WATER MILLS REFURBISHMENT FOR INCREASING THE HYDROPOWER CAPACITY: AN ITALIAN CASE STUDY

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ABSTRACT

The energy sector is undergoing considerable changes in both energy production and utilization in the view of an optimal management of renewable energy resources. Europe is currently pushing for the deployment of renewables to achieve emissions reduction targets set by 2030. In 2023, Photovoltaics (PV), wind, hydropower, and bioenergy added capacity accounted for 359 GW, 141 GW, 28 GW, and 11 GW, respectively. Focusing on hydropower, the small-scale plants look promising for further enhancing their share, especially considering the so-called hidden hydropower. In this sense, several old water mills in Europe have been abandoned, but they could be an interesting energy resource if properly refurbished. This paper deals with a water mill in the center of Italy that has been converted into a hydropower plant. A rated flow rate of 0.65 m^3/s and a gross head of 9 m can be exploited in the site under investigation. In particular, two hydraulic turbines have been analysed and designed for being installed on site: a Cross-flow (Banki) and a Francis one. Finally, the Francis turbine type has been chosen since it reaches a higher power output of 46.48 kW than the Cross-flow (Banki) one and can lead to a yearly energy production of nearly 150 MWh. From an economic perspective, the capital cost for the overall refurbishment was equal to 200 k€ and, considering a yearly expense coming from the Operation and Maintenance (O&M) of the plant along with a revenue of 24 k€ due to the energy sold to the electricity market, a worst-case PayBack Period (PBP) of 10 years might be achieved which is quite long. This result should make government institutions and policymakers aware of providing further incentives for deploying these kinds of interventions, thus being more affordable, profitable, and interesting for attracting potential investors and stakeholders. Furthermore, these interventions might preserve rivers and avoid the accumulation of debris which is the main cause of river floods.

1 INTRODUCTION

Renewable energy is an alternative to fossil fuels for decarbonising several sectors since it does not emit polluting substances or alter the climate. Among them, the most important and used renewables worldwide are solar (e.g., PV), wind, hydropower, and biomass (International energy Agency (IEA), Renewables 2023). However, one of the biggest drawbacks of renewable energy is its intermittent nature which does not allow it to constantly fulfil the required energy demand. For this reason, the coupling of some of them (e.g., solar and wind) and the introduction of energy storage systems are the keys to making renewables the future pathway for producing clean energy constantly (Cosgrave *et al.*, 2023). Focusing on hydropower, in the same year, the share of its total capacity was about 30% of all

https://doi.org/10.52202/077185-0207

the renewables, and there is still considerable room for its increase by focusing on small-scale plants, especially those consisting of the so-called hidden hydropower (McNabola *et al.*, 2022). Hidden hydropower stands for the exploitation of water potential in those sites where hydraulic energy has not been used so far; for instance, weirs are installed to limit the debris transport downstream of the rivers and stabilise the watercourse from erosion (Hemmati and Daraby, 2019). At the same time, weirs can act as small dams where a low-head micro-hydropower plant could be installed to recover hydraulic energy. The weir-type structures mostly prevail in Eastern Europe, especially in Bulgaria (98.6%) and Romania (89.7%). Meanwhile, 78.0% and 63.3% of the total sites are in Ireland and the United Kingdom, respectively. The largest numbers of weirs are identified in Poland (5,261) and France (3,577) (Punys *et al.,* 2023). Some applications related to the hydraulic potential of weirs are currently operative. Verbeek *et al.* (2021) proposed installing a tidal turbine in a hydraulic structure such as a weir. The hydraulic machine has been designed, downscaled, and tested in labs. The dimensionless analysis has been performed to extend the turbine performance in a real environment. In particular, they found out that the power coefficient increased by 40% when the turbine was repositioned from the upstream to the downstream of the hydraulic structure, thus increasing the machine's power output as well. Brown *et al.* (2023) designed a low-head, in-stream turbine which is considered an alternative and ecologically friendly option. Numerical simulations of this machine have been performed, showing that it can operate with low risk to the surrounding aquatic environment regarding physical strike, pressure, shear, and turbulence. In particular, the highest power coefficient of 0.26 has been achieved, and relative velocities at different span locations have been analysed to study the fluid dynamic behaviour of the hydraulic turbine, showing a good agreement between designed and numerical results.

Old water mills are very interesting and promising among the potential hidden hydropower sites. Historic watermills prevail in Austria, Greece, the Netherlands, Italy, Germany, Belgium, and the Czech Republic and vary between 93 and 100% of all the recorded micro-hydro sites in these countries. Most of the watermills are located in Italy (4,965), Germany (4,850), France (4,403), Greece (2,940), and Belgium (2,392). The distribution of the number of micro-hydropower capacities shows that France, Poland, Germany, and Italy have about 24,000, 8,000, and 5,000 sites with a potentiality of up to 300 kW, respectively, being worth to be investigated for their future reuse (Punys *et al.,* 2023).

This work aims to present an Italian case study of a water mill that has been transformed into a micro-hydropower plant. This investigation can help in identifying the feasibility and the profitability of such interventions and suggest possible support schemes. Knowing the rated flow rate and head, the design of two hydraulic turbines suitable for the site under investigation has been performed, namely a Cross-flow (Banki) and a Francis one. An economic analysis of the overall investment has been carried out as well.

The paper is structured as follows: Section 2 describes the methodology used to design the hydraulic machines. The design procedure is already reported in detail in other documents to which the reader is referred (Quaderni del COSV sulle Tecnologie Appropriate, 1984), (Hoeg Sundfor, 2017). Section 3 briefly describes the site under investigation. Section 4 provides information on the design values of the two turbines along with the economic analysis considering the installation of a Francis turbine along with two turbines design values, the economic analysis considering the installation of a Francis turbine, and the required works (e.g., civil, electrical, and mechanical). Finally, Section 5 sums up the main findings of the work.

2 METHODS

Two different types of turbines have been analysed: a Cross-flow (Banki) and a Francis one. The hydraulic machines were designed considering the same rated conditions of flow rate (Q) equal to 0.65 m^3/s and head (H) equal to 9 m.

The characteristic speed, velocity triangle, and all the data required for evaluating which kind of turbine would be more suitable for the site under investigation were calculated to get the power output.

The characteristic speed value of a turbine is the speed of a geometrically similar turbine which would produce unit power under unit head. The manufacturer gives the characteristic speed of a turbine along with other ratings, and always refers to the point of maximum efficiency.

https://doi.org/10.52202/077185-0207

The velocity triangle represents the various components of velocities of the working fluid in a turbomachine. The vector nature of the velocity is used in the triangles, and its most basic form consists of a crank, a relative, and an absolute velocity that make up the triangle's three sides. Velocity triangles may be drawn for the inlet and outlet sections of any turbomachine, although for the Cross-flow (Banki) only the inlet velocity triangle can be defined.

2.1 Cross-flow (Banki) turbine design

Unlike most water turbines with axial or radial flows, the water in a Cross-flow (Banki) turbine passes through it transversely. Similarly, to a water wheel, the water enters the turbine's edge. After passing to the inside of the runner, it leaves on the opposite side, going outward. Passing through the runner twice, an additional efficiency is achieved. When the water leaves the runner, it also helps clean from small debris and pollution. The Cross-flow turbine is well suited for locations with low-head but relatively high flow rates. The formula used for the calculation of the main technical characteristics of a Cross-flow (Banki) turbine (e.g., characteristic speed and velocity triangle) has been reported in the manuscript. At the same time, the other values have been calculated according to the procedure in (Quaderni del COSV sulle Tecnologie Appropriate, 1984) and not reported here since the technology is well-known along with its design procedure.
The rotational speed (n) of the Cross-flow (Banki) turbine has been fixed at 3,000 rpm; indeed, by keeping fixed both the rated flow rate and head, it is possible to get i) a typical characteristic speed (n_c) for this kind of turbine between 18 and 50, and ii) a runner diameter between 0.2 m and 0.4 m according to (Quaderni del COSV sulle Tecnologie Appropriate, 1984). The characteristic speed value is calculated through Equation (1):

$$n_c = n \cdot \frac{\sqrt{Q}}{\sqrt[4]{H^3}} \tag{1}$$

The inlet velocity triangle consisting of the crank (u_1), relative (w_1), and absolute (v_1) velocity, along with their vector decomposition in tangential ($_t$) and radial ($_r$) directions, at the inlet section has been calculated through Equations (2), (3), and (4) according to (Quaderni del COSV sulle Tecnologie Appropriate, 1984), respectively. Furthermore, in this case, the inlet absolute angle (α_1) should vary between 15 and 25°, a value of 16° has been chosen as suggested by (Quaderni del COSV sulle Tecnologie Appropriate, 1984).

$$v_1 = 4.34 \cdot \sqrt{H} \, \left[\frac{m}{s}\right] \tag{2}$$

$$u_1 = 1/2 \cdot v_1 \cdot cos\, \alpha_1 \left[\frac{m}{s}\right] \tag{3}$$

$$w_1 = \sqrt{w_{1t}^2 + w_{1r}^2} \, [\frac{m}{s}] \tag{4}$$

Finally, the power output (P_o) of this turbine is calculated with Equation (6) by knowing the hydraulic power (P_h), obtained through Equation (5), and the turbine efficiency (η).

$$P_h = \rho \cdot g \cdot Q \cdot H \, [W] \tag{5}$$

$$P_o = \eta_g \cdot \eta_{tu} \cdot P_h \, [W] \tag{6}$$

Where ρ is the water density in kg/m^3 and g is the gravity acceleration.

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2.2 Francis turbine design

Most equations are used for designing a Cross-flow (Banki) turbine such as Equations (1), (5), and (6) have been employed in the Francis one as well.

The rotational speed (n) of a Francis turbine has been chosen equal to 500 rpm to obtain a typical characteristic speed for this kind of turbine, which varies between 60 and 300, according to (Hoeg Sundfor, 2017). Since the technology is well-known along with its design procedure, further details on the geometry and velocity triangle calculations at the inlet and outlet sections used in this work can be found in (Hoeg Sundfor, 2017).

3 CASE STUDY

The water mill under investigation is located in the center of Italy and is crossed by the Marena River. The exploitable flow rate and head for hydropower production equals 0.65 m^3/s and 9 m, respectively. A view of the site from above is shown in Figure 1 (source: Google Maps: 43.38, 12.84).

Figure 1: A view of the site under investigation (coordinates from Google Maps: 43.38, 12.84)

4 RESULTS AND COMMENTS

4.1 Technical results

Technical end economic results of the water mill's refurbishment are reported in this section; firstly, those from the design phase of the hydraulic turbines suitable for the site under investigation, namely a Cross-flow (Banki) and a Francis one, are reported. Regarding the former, the inlet velocity triangle, along with its values, are shown in Figure 2 and listed in Table 1, respectively. As previously said, only the inlet velocity triangle of the Cross-flow (Banki) one can be defined. Table 2 lists the main geometric, physical, and operating characteristics of the Cross-flow (Banki) turbine. It is worth noting that an efficiency of 0.7 has been chosen for this kind of turbine according to (Quaderni del COSV sulle Tecnologie Appropriate, 1984).

https://doi.org/10.52202/077185-0207

Table 1: The inlet velocity triangle of the Cross-flow (Banki) turbine

MAGNITUDE [UNIT OF MEASURE]	VALUE
$v_1\ \left[\frac{m}{s}\right]$	13.02
$u_1\ \left[\frac{m}{s}\right]$	6.25
$w_1\ \left[\frac{m}{s}\right]$	7.21
α_1 [°] (red angle)	16
β_1 [°] (black angle)	150

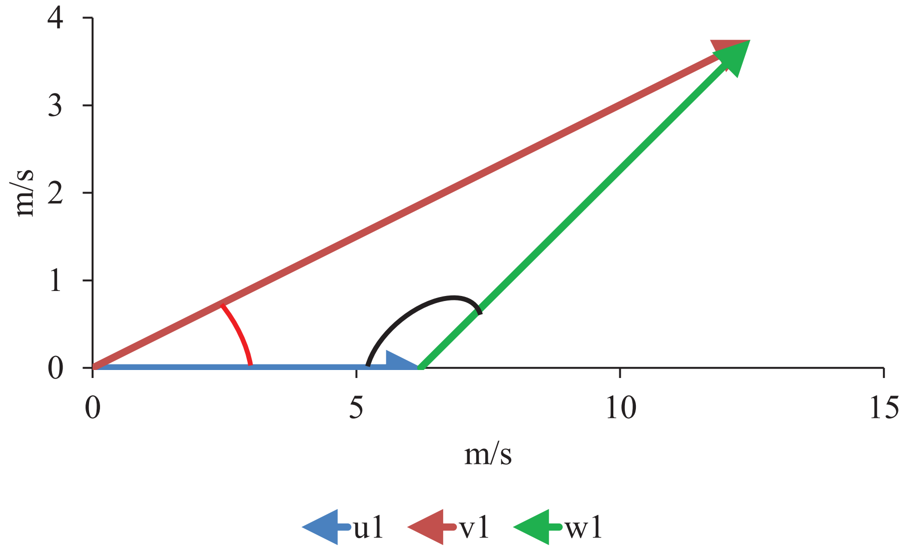

Figure 2: Cross-flow (Banki)'s inlet velocity triangle

Table 2: Geometric, physical, and operating characteristics of the Cross-flow (Banki) turbine

MAGNITUDE [UNIT OF MEASURE]	VALUE
n_c	48.7
$D_1\ [m]$	0.38
$D_2\ [m]$	0.25
$\#\ of\ blades$	24
η	0.7
$P_o\ [kW]$	40.17

Regarding the Francis turbine, its inlet and outlet velocity triangles are shown in Figures 3 and 4, respectively, along with their values in Table 3. Table 4 lists the main geometric and operating characteristics of the Francis turbine. It is worth noting that an efficiency of 0.81 has been chosen for this kind of turbine according to (Hoeg Sundfor, 2017).

https://doi.org/10.52202/077185-0207

Table 3: The inlet and outlet velocity triangles of the Francis turbine

MAGNITUDE [UNIT OF MEASURE]	NUMERICAL VALUE
$v_1\ \left[\frac{m}{s}\right]$	9.54
$u_1\ \left[\frac{m}{s}\right]$	12.57
$w_1\ \left[\frac{m}{s}\right]$	5.57
α_1 [°] (red angle)	17.40
β_1 [°] (black angle)	52.54
$v_2\ \left[\frac{m}{s}\right]$	3.97
$u_2\ \left[\frac{m}{s}\right]$	9.16
$w_2\ \left[\frac{m}{s}\right]$	9.98
α_2 [°] (purple angle)	90.00
β_2 [°] (yellow angle)	23.43

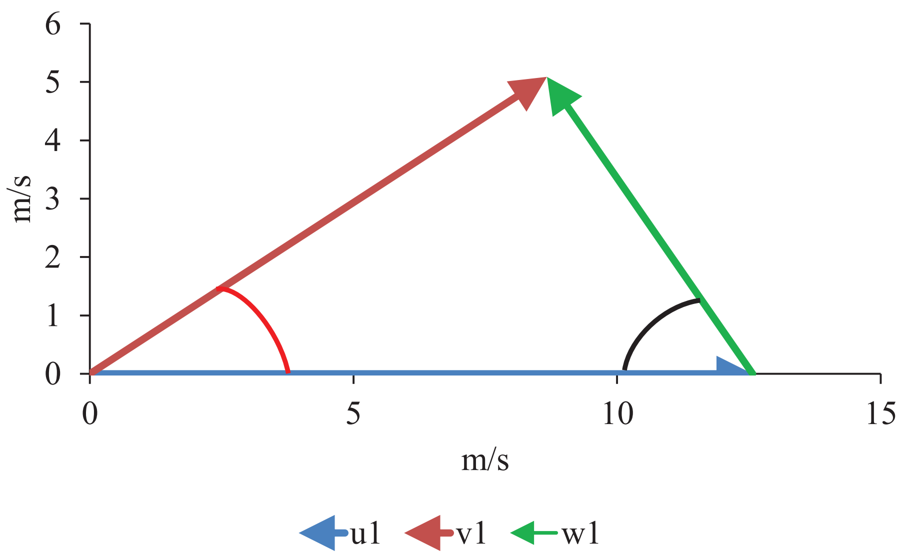

Figure 3: Francis's inlet velocity triangle

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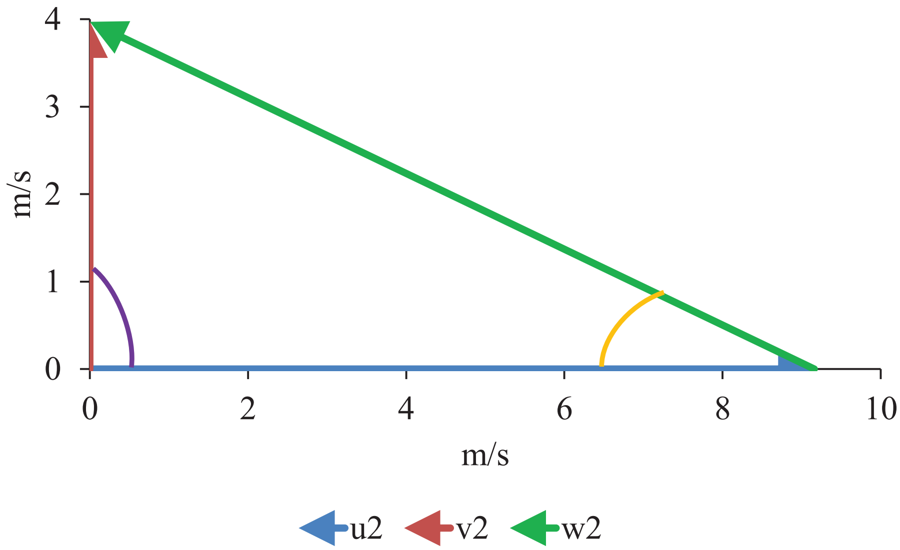

Figure 4: Francis's outlet velocity triangle

Table 4: Geometric, physical, and operating characteristics of the Francis turbine

MAGNITUDE [UNIT OF MEASURE]	NUMERICAL VALUE
n_c	77.6
D_1 $[m]$	0.48
D_2 $[m]$	0.35
$\#\ of\ blades$	16
η	0.81
P_o $[kW]$	46.5

The Francis turbine achieves a power output of 46.5 kW that is higher than the Cross-flow (Banki) one (40.17 kW). To have a better picture of the results, Table 5 compares the main technical characteristics of the two turbines, while Figure 5 shows a 3D model of the turbine.

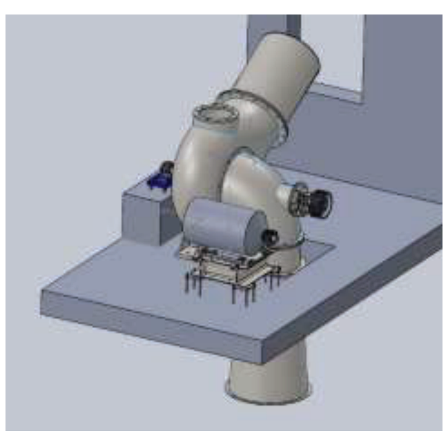

Figure 5: 3D model of the Francis turbine

https://doi.org/10.52202/077185-0207

Table 5: Main technical characteristics of both the Cross-flow (Banki) and Francis turbine

Q [m³/s]	H [m]
0.65	9

CROSS-FLOW (BANKI) TURBINE		FRANCIS TURBINE
0.7	η	0.81
57.4	P_h [kW]	57.4
40.17	P_o [kW]	46.5
3,000	n [rpm]	500
48.7	n_c	77.6
24	# of blades	16

4.2 Economic results

Once the hydraulic turbine has been chosen, the economic analysis for refurbishing the old water mill has been carried out. A detailed cost breakdown of the last kind of expenses is reported in Table 6. It is worth noting that the cost of the Cross-flow (Banki) turbine has been evaluated according to (Quaranta *et al.*, 2022), while the remaining cost breakdowns have been assumed the same for both turbines' typologies.

Finally, the micro-hydropower plant can produce 150 MWh/year and, considering an electricity sales price equal to 177.5 €/MWh (Gestore dei Servizi Energetici - Prezzi minimi garantiti, 2024), 24 k€/year are gained. It is worth noting that this last value also embeds the Operation & Maintenance costs (O&M) that are equal to 1.3% of the capital cost according to (Lorenzoni and Bano, 2007). The PayBack Period (PBP) of the investment has been obtained with interest rates of 5, 6, and 7% according to (SCHEDA INFORMATIVA CONTENENTE LE INFORMAZIONI CHIAVE SULL'INVESTIMENTO - WATERFALL ENERGY S.R.L., 2023) and (Impianto idroelettrico "Agri 9" a Grumento Nova (Basilicata), DOMANDA DI CONCESSIONE DI DERIVAZIONE ACQUA PUBBLICA PRESSO UFFICIO CICLO DELL'ACQUA - R2K SRL, 2015): in all the cases, the PBP ranges between 9 and 10 years as shown in Figure 6.

As it can be noticed, the PBP is quite long and, for this reason, it would be suggested to further incentive hydropower to support investors and stakeholders invest in this kind of technology since it allows not only to produce energy, but also to preserve the river and avoid the accumulation of debris which is the main cause of river floods.

https://doi.org/10.52202/077185-0207

Table 6: Cost breakdown of the expenses for the refurbishment of the water mill

ITEM	COST [*k*€]
Cross-flow (Banki)/Francis turbine	**71/65**
Electric generator	**8.5**
Electric works	35
Civil works	45
Mechanical works	46.5
TOTAL	**206/200**

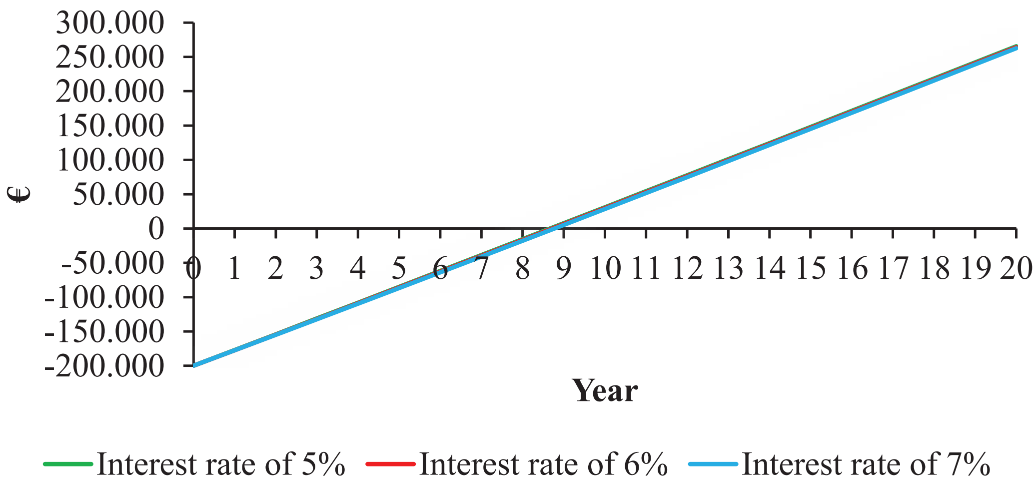

Figure 6: PBP of the overall investment

5 CONCLUSIONS

This paper deals with of refurbishing an old water mill located in the center of Italy which has been turned into a 47-kW micro-hydropower plant. In Italy thousands of these infrastructures can be recovered for building up small-scale hydropower plants to enhance the hydropower capacity. The revamping of the old water mills consisted in: i) turbine analysis, design, choice, and manufacturing, and ii) other works required for its operation. In particular, two different hydraulic turbines have been investigated: a Cross-flow (Banki) and a Francis one. A Francis turbine has been chosen for being installed in the site under investigation since it achieves a power output of 46.5 kW which is higher than the Cross-flow (Banki) one (40.17 kW). Finally, an economic analysis for refurbishing the old water mill has been conducted. The capital cost was equal to 200 k€. The micro-hydropower plant can produce 150 MWh/year and 24 k€/year are gained for selling the produced energy. The PBP ranges between 9 and 10 years, which is quite long. It is recommended to further incentive hydropower to let investors and stakeholders invest in this kind of technology since it allows not only to produce energy, but also to preserve the river and avoid the accumulation of debris which is the main cause of river floods.

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NOMENCLATURE

α	absolute angle	(°)
β	relative angle	(°)
η	efficiency	(-)
ρ	density	(kg/m^3)
D	diameter	(m)
g	gravity acceleration	(m/s^2)
H	head	(m)
n	rotational speed	(rpm)
n_c	characteristic speed	(-)
O&M	Operation and maintenance	
P	power	(W)
PBP	Payback Period	(year)
PV	Photovoltaic	
Q	flow rate	(m^3/s)
u	crank velocity	(m/s)
v	absolute velocity	(m/s)
w	relative velocity	(m/s)

Subscript

1	inlet section
2	outlet section
c	characteristic
g	electric generator
h	hydraulic
m	mechanical
o	output
r	radial direction
t	tangential direction
tu	turbine

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