A Pilot Plant for Energy Harvesting from Falling Water in Drainpipes. Technical and Economic Analysis

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Abstract. Renewable energy sources are currently object of great attention from the scientific community involved on the matter, in the general context of the ongoing climate change and related implications. In this work, we investigate the costs needed to implement a technical solution to harvest energy from drainpipes. To this aim, a pilot plant was built at the Laboratory of Environmental and Maritime Hydraulics (LIDAM), University of Salerno, Italy.

The driving idea consists in the possibility of collecting rainwater at the roof of a building, storing it in tanks. In this way, the established hydraulic head can be converted into kinetic energy at the bottom of the building as can be easily explained by applying the Bernoulli's principle. Here, a water jet of mean velocity of up to tens of m/s is formed at the pipe outlet as it is provided with a nozzle. The stream is directed against a Pelton turbine where the rotational kinetic energy is finally converted into electrical energy by means of a DC brushed motor turned as generator.

The analysis of the investment and management costs of the pilot plant provides useful economic parameters for implementing the project in practice.

Keywords: Hydropower · Pelton · Drainpipes · Cost analysis

1 Introduction

The presence of water in the form of water bodies, aquifers, glaciers, rainfalls and runoff is the result of state changes, i.e. evapotranspiration, condensation, sublimation/desublimation, ice melting, thanks to the energy transferred by the sun on the atmosphere and the earth's surface. Solar irradiation, highest at the equator and lowest at the poles, determines non-equilibrium thermal conditions, yielding air masses which originate spatial and temporal meteorological events. The result is the water cycle, also called hydrologic cycle, involving the continuous circulation of water in the Earth-atmosphere system making its presence continually changing from one form to another [1–3].

Every year sun irradiation takes away from the oceans the equivalent of un meter of water depth, that is 875 km^3 equivalent in volume. Others 160 km^3 evaporate from the continents. Water evaporation varies depending mainly on the season and geographic latitude.

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Precipitations vary as well, with annual average values of 1140 mm and 720 mm for oceans and continents, respectively. Globally, the average annual rainfall is 1020 mm, 970 mm for the Italian peninsula. Italy is the first country for water consumption in Europe, the third worldwide, after Canada and United States. The water resource is not equally distributed among the Regions. The availability decrease from North to South with Puglia, Sicilia and Sardegna Regions receiving only 40 to 50% less precipitations than the ones falling in the North.

The exploitation of water as a source of energy has its origins back in time, when Greeks and Romans used watermills for irrigation, grind corns for bread or olives for olive oil [4, 5]. Today, hydropower is among the first renewable source to be produced, attaining a percentage of 18% worldwide [6]. The energy is harvested thanks to the existence of a difference in height through which water gains pressure and kinetic energy or by means of run-of-the-river generation plants. Anyway, the power output is generated by connecting the turbine axis to an alternator, according to an energy conversion efficiency η being the ratio between the useful output of an energy conversion machine and the input, in energy terms. Actually, the tendency is toward the creation of small (SHPs) or micro (MHPs) or pico-hydropower (PHPs) plants due the availability of water flowing, providing power to isolated homes or to small communities [7–9].

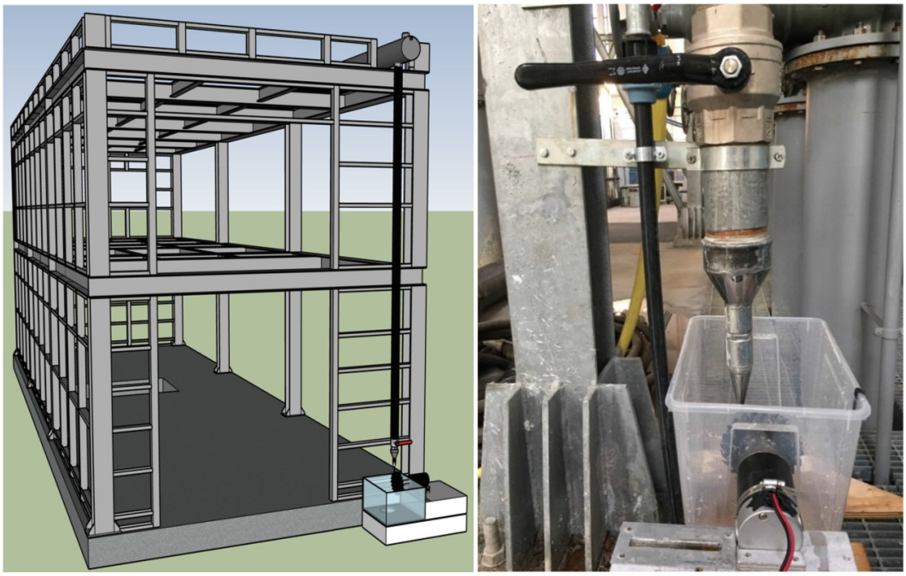
The experimental study carried out at the Laboratory of Environmental and Maritime Hydraulics (LIDAM), University of Salerno, Italy, consisting of a pilot plant for energy harvesting from falling water in drainpipes, is the basis for technical and economic analysis next presented.

2 Materials and Methods

The pilot plant (Fig. 1a) consists of a steel tank, 1001 of capacity, placed at 4,90 m above ground to reproduce a single level building. At its bottom, a vertical pvc pipe is bolted, reproducing a drainpipe of 0,09 m of inner diameter with an hydraulic capacity of 8,11/s. The tank is fed with the local water supply to the aim of reproduce the recharge as a consequence of a meteoric event. A solenoid valve connected to a float prevents the inlet of water once the tank reaches 60% of its capacity, that is 601. A Pelton micro-turbine connected to a 36 V generator is placed at the lower end where an adjustable nozzle, that is a reduction of two consecutive truncated cones, see Fig. 1b, produces a water jet. The hydroelectric energy produced is then stored in a 2–12 V, 250 A/h battery. Two nozzles have been tested with lower diameters of 3 mm and 5 mm, respectively.

In order to fix the Pelton turbine to the generator, the horizontal shaft was turned on a lathe and a central hole was performed on the runner wheel (Fig. 2a), shaped the axis (Fig. 2b) and finally two holes are pierced to ensure the generator-turbine connection by means of tightened screws (Fig. 3).

An off-the shelf DC brushed motor (Fig. 3) was turned as generator to produce electricity. As the expected output voltage is of the order of 10^0 V, a 36 V model is taken into account to prevent power failures. In the Table 1 are given the related technical specifications.



a. *b.*

Fig. 1. *a.* Sketch of the pilot plant built at the Laboratory of Environmental and Maritime Hydraulics (LIDAM), University of Salerno, Italy. *b.* A particular of the adopted nozzles assisted with the shut-off valve.



a. *b.*

Fig. 2. *a.* Execution of the central slot on the runner wheel with a precision drill. *b.* Axis shaping.

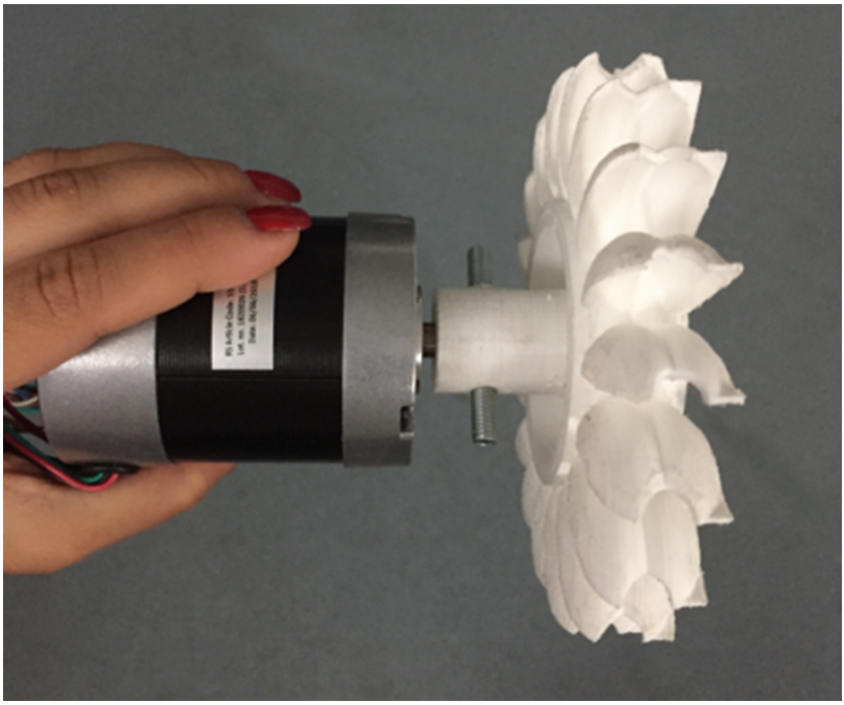


Fig. 3. Final assembling of the Pelton turbine on the generator axis.

Table 1. Technical specification of the adopted brushed motor.

DC motor type	*Brushed*
Length	*135* mm
Shaft diameter	*90* mm
Current rating	*9.8* A
Dimensions	*157* mm
Maximum output torque	*0.68* Nm
Output speed	*2,800* RPM
Supply voltage	*36* V

In the following the pilot plant is analysed both from a technical and financial point of view, taking into account the investment and maintenance costs. The results, next presented in Sects. 3 and 4, are derived following the fundamentals of orifices for the technical analysis, whereas financial aspects are tackled with the Appraisal methodology. Latter elaborations are the result of the studies carried out at the Project Evaluation Laboratory (PEL) at the Department of Civil Engineering of the University of Salerno.

3 Results of the Technical Analysis

The operating height H_a = 4.45 m is obtained by considering the vertical distance between the nozzle outlet and the lower end of the tank. In the definition of the expected flow rate Q two aspects are therefore not taken into account, specifically:

- the maximum water depth h_t = 0.24 m reached at the tank is neglected, in order to obtain a conservative estimate of the outflow discharge Q (see Table 2);
- the vertical distance between the nozzle outlet and the contracted section is neglected as it is of order of 10^{-2} m or less.

Two nozzles are taken into account, with outlet diameters $d_u = 5\ 10^{-3}$ m and $d_u = 3\ 10^{-3}$ respectively. The efflux of water from the orifice can be evaluated with the following:

$$Q = \mu\sigma\sqrt{2g\ H_a} \tag{1}$$

being $\mu \in [0.6, 0.99]$ the efflux coefficient. Here, $\mu = 0.8$, nearly coincident with the contraction coefficient C_c, because of the particular configuration of the adopted nozzle.

$$\sigma = \frac{\pi d_u^2}{4} \tag{2}$$

The expected flow rate Q is compared with the measured flow rate Q_m derived with the bucket method [10]. A bucket of known volume (Vol = 10 l) is taken as reference for the measure of Q_m. The time to fill the bucket is 57 s and 152 s for $d_u = 5\ 10^{-3}$ m and $d_u = 3\ 10^{-3}$ respectively. In the following Table 2, the expected volume flow rate Q, the corresponding velocity at the contraction section V_c and the measured flow rate Q_m are given, showing a good agreement under the hypotheses above stated.

Table 2. Expected $Q(d_u)$ and measured $Q_m(d_u)$ volume flow rates. The mean velocity at the contraction section V_c is derived for Q.

d_u [mm]	Q [cl/s]	V_c [m/s]	Q_m [cl/s]
3	5.3	10.61	6.6
5	14.68	10.19	17

3.1 Measurement of Output Voltage V and Intensity I with the Brushed Motor

Measurements of the output voltage V and current intensity I are taken with the 2460 High Current SourceMeter® Source Measure Unit (SMU) Keithley Instrument (Fig. 4). The developed output power P_{out} is then derived by the following:

$$P = \frac{V^2}{R} \tag{3}$$

since there is no phase shift between voltage and intensity signals, that is the adopted generator is of direct current type.



Fig. 4. The 2460 Keithley 100 V, 7 A, 100 W high current SourceMeter® unit (SMU) instrument

Since the theoretical power is given by

$$P_t = \gamma Q H_a \tag{4}$$

the efficiency η is calculated as:

$$\eta = \frac{P_{out}}{P_t} \tag{5}$$

In the Table 3 are given V, P_{out}, P_t and η.

Table 3. Output Voltage V, power P_{out}, theoretical power P_t and efficiency η.

d_u [mm]	V [V]	P_{out} [mW]	P_t [mW]	η [-]
3	2.3	384	2,970	13%
5	6.5	3,420	7,670	45%

4 Estimate of the Pilot Plant Costs

With reference to the pilot plant for energy harvesting from falling water in drainpipes, technically described in the previous paragraphs, market surveys are carried out aimed at estimating investment and management costs [11, 12]. The retrieval of merchant

information from specialized magazines and directly from operators in the sector makes it possible to apply the direct procedure to pass forecast judgments.

The investment cost, to be sustained for the concrete implementation of the intervention in the Campania Region (Italy), depends on the expenditure items for the purchase and installation of the plant components:

- 100 l cylindrical container in stainless steel;
- 2 V–12 V 250 A/h battery;
- brushed motor;
- Pelton turbine,
- inverter,
- connection elements.

The evaluations results are detailed in Table 4. The total investment cost, equal to € 1,563.49, is the sum of the expenditure for the plant components purchase (€ 1,341.13) and the installation works cost (€ 222.36). It should be noted that the monetary amounts relating to purchases are gross of Value Added Tax (VAT), assuming that private individuals make the investment.

For the installation works, concerning the adaptation of the system to the downpipe and the assembly, the data are taken from price lists, also confirmed in the light of the direct information.

Table 4. Pilot plant investment costs.

Expenditure items		***Amount***	
100 litre cylindrical container in stainless steel		*200.00*	*€*
2V-12V 250A/h battery		*735.00*	*€*
Brushed motor		*215.13*	*€*
Pelton turbine		*74.00*	*€*
Inverter		*17.00*	*€*
Connection elements		*100.00*	*€*
	(a)	*1,341.13*	*€*
Installation work			
- worker (4h × 23,59 €/h)		*94.36*	*€*
- electrician (4h × 32,00 €/h)		*128.00*	*€*
	(b)	*222.36*	*€*
	TOT. (a)+(b)	***1,563.49***	***€***

The management costs of the pilot plant relate to ordinary and extraordinary maintenance. Routine maintenance consists of checking the battery and mechanical components wear. The photovoltaic battery used at 2 V continuously has a cycle of 20 years; for the study system it lasts about 30 years.

The turbine is made of PVC and is tested for a cycle of 5 years of continuous work. In the plant, in relation to the use of about 1 month each year, the turbine has a cycle of about 60 years.

The inverter, which rectifies and redistributes the energy from the motor to the battery, lasts about 15 years, after which it shall be replaced.

Starting from the technical information on the parts of the pilot plant, even considering the reliability levels, the annual ordinary and extraordinary maintenance takes place in verification operations, therefore of cleaning/replacing the filter of the container and cleaning the mechanical system, for average total cost of € 30/year.

5 Discussion and Future Perspectives

The experimental campaign, here presented, shed light on some aspects of technical nature. First of all, it is evident that the developed output power strongly depends on the adopted nozzle, changing from P_t = 384 mW to P_t = 3420 mW when the output diameter passes from $d_u = 3\ 10^{-3}$ m to $d_u = 5\ 10^{-3}$. Consequently, the global efficiency undergoes to a variation from 13% al 45%. The limited number of the used nozzles suggest the use of new ones of different output diameter d_u, with the aim of identifying an optimum point in terms of efficiency. The system can be optimized by varying the geometry of the Pelton turbine as well. In particular, the number and shape of the buckets has shown to sensibly influence the results [7]. In addition, it is of interest to investigate the use of generators of brushless type. Preliminary results, not included in the present memory, have shown that higher efficiencies could be reached. It is, however, worth nothing that if one considers an operating height doubled (i.e. H_a = 9.00 m) and a nozzle with an output diameter one order of magnitude greater (let's say $d_u = 4\ 10^{-2}$ m), flow rates of up two order of magnitudes can be attained, that is tens of litres per second.

From an economic point of view, it appears that the cost of the intervention is limited. This both in terms of initial investment, in total of € 1,563.49, and with regard to the management cost, on average equal to € 30/year. This leads to the prospect of the real feasibility of the plant. The need to extend the research by implementing the Cost-Benefit Analysis and perhaps also employing a multi-criteria economic assessment technique should be considered where it is intended to estimate not only the strictly monetary effects of the project, but also those social and environmental [13–17].

6 Conclusions

In this work, we have discussed about the possibility of harvest energy from drainpipes. To this aim, a pilot plant was built at the Laboratory of Environmental and Maritime Hydraulics (LIDAM), University of Salerno, Italy. Production depends on several factors, namely the random nature of rainfall precipitations, spatially and temporally varying over the globe, geometry of the nozzle and Pelton turbine, available hydraulic heads. Anyway in a social context in marked by a strong focus for the environment, the rational use of available energy along with the production of clean forms is

fundamental in terms of energy saving and environmental protection. The residential sector can contribute in a significant way with the realization of micro-production at a diffuse scale with the possibility of use the energy harvested locally. In this regard, the economic analysis shows a low cost of the intervention, both in terms of initial investment (€ 1,563.49) and with regard to the management cost (€ 30/year). Which shows the real feasibility of the plant. Furthermore, the studies in progress within the Project Evaluation Laboratory (PEL) at the Department of Civil Engineering of the University of Salerno provide for an extension of this research through the implementation of both Cost-Benefit Analysis, both of multi-criteria economic evaluation techniques. The aim is to estimate not only the closely monetary effects but also the social and environmental impacts of the hydraulic system.

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