Hydroenergy harvesting in Alviela River weir: technical and economic analyses

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The current paper aims at the development and application of a methodology for assessing the potential of hydroenergy harvesting in water systems and for selecting the most adequate technology taking into account both technical and economic aspects. The methodology is a five-step procedure: i) data collection and analysis; ii) technology identification; iii) energy harvesting assessment; iv) economic analysis; and v) final recommendation of the technological solution. The methodology is demonstrated with the case study of the Alviela River weir, located near the Alviela water, in Portugal. The potential of energy harvesting is assessed for three turbines types, adequate for the 2.5 m available head: two propeller turbines, with and without adjustable blades, and the Archimedes screw turbine (AST). Results show that the most feasible solution is the AST, with 3 m^3/s rated discharge and 55 kW rated power, being the internal rate of return above 10% and a payback period of 8 years. This low-cost solution has a major potential for energy harvesting in low head sites, like river weirs or wastewater treatment facilities, operating for a wide range of discharges and in fluids with transported solid material.

Keywords: Hydropower energy, Archimedes screw turbine, energy harvesting, technical-economic analysis.

1 Introduction

Residential, commercial, and industrial water consumers rely on water supply systems (WSS) to collect, treat, and distribute water from sources to maintain their daily activities [1]. In the water collection, treatment and distribution processes, WSS consume around 7% of the global energy consumption [2]. Optimization techniques, focusing on minimizing the costs of the system, are commonly used in the planning and design of large scale and complex WSS [3, 4]. As a result, optimized implementation techniques support the decisions of WSS managers in meeting daily operational objectives: minimizing the energy and the chemical usage, the sludge disposal, and the greenhouse gas (GHG) emission [5-8].

Many water or wastewater utilities have already minimized energy consumption in the most energy-demanding processes, such as pumping and treatment, and a very small margin exists for energy efficiency improvement. Still, utility managers, concerned with the environment and with the planet sustainability, are still looking for measures and opportunities of becoming more sustainable and eco-friendlier [9-12].

A very promising solution is the recovery of the energy in excess existing in control valves or at the inlet of storage tanks by means of the construction of mini (100 kW-1MW) or micro-hydropower plants, MHP, (5-100 kW). These solutions should be considered in locations that combine available physical space, excessive head and, if possible, high discharges [13]. The MHP converts the potential energy in free-surface flows or pressure-head in pressurized systems into kinetic energy and then, into electric energy. Examples of locations with energy in excess in water and wastewater systems are: at the inlet of storage tanks, at locations with pressure reducing valves and at the inlet, outlet or between processes in wastewater treatment plants [14].

Several hydro-turbine technologies can be used in MHP that can be divided in impulse turbines, which operate at atmospheric pressure (e.g., Pelton, Cross-flow, or Archimedes screw turbines), and reaction turbines, which operate under pressure (e.g., Francis, propeller with fixed blades, Kaplan, and pumps running as turbines). The turbine selection must attend to the available head and the range of discharges. Turbines are characterized by hill-charts with efficiency curves that specify the range of pressure head and discharge operation [15]. The turbine selection should consider the best type and size to meet the discharge variation of the location since it influences the annual energy production, and consequently, the economic results of the project [16-18].

WSS are complex systems in which the head and discharge vary continuously and, for this reason, the chosen turbine efficiency range must fit these variations [19], being of the utmost importance to consider discharge variation and the respective effect on available head and on the turbine efficiency [20].

A very cost-effective technological solution for energy harvesting in water systems with low available head and a wide range and large discharges is the Archimedes screw turbines (AST). This solution is particularly adequate in sites with low heads (up to 10 m), very large flow rates (up to 10 m³/s per turbine), with a large space for construction and for liquids with solid material in suspension [13, 21].

The current paper aims at the development and demonstration of an innovative technical-economic feasibility study of installing an Archimedes screw turbine in a river source in Portugal. The paper includes a description of the proposed methodology for assessing the potential of energy harvesting and predictable capital costs and revenues. The methodology is applied to a real-life case study located in a 2.5 m height weir in Alviela river. The AST solution is compared with other technologies typically used to energy harvesting for small heads. Several economic indicators are calculated. The main conclusions are drawn concerning the use of this solution in systems with low available heads.

The key innovative features are i) the proposed methodology for energy harvesting assessment applicable to water systems considering data records of available head and discharge, as well as the turbine discharge-head-efficiency curves, ii) the demonstration of the methodology for three technological solutions (i.e., AST, Kaplan and the propeller) for low-heads; and iii) the discussion of the advantages and drawbacks of each technological solution.

2 Methodology

A comprehensive methodology for assessing the potential of hydroenergy harvesting in water systems and for selecting the most adequate technology considering both technical and economic aspects is proposed herein. The methodology is a five-step procedure (Fig. 1): i) data collection and analysis; ii) technology selection; iii) energy harvesting assessment; iv) economic analysis; and v) final recommendation.

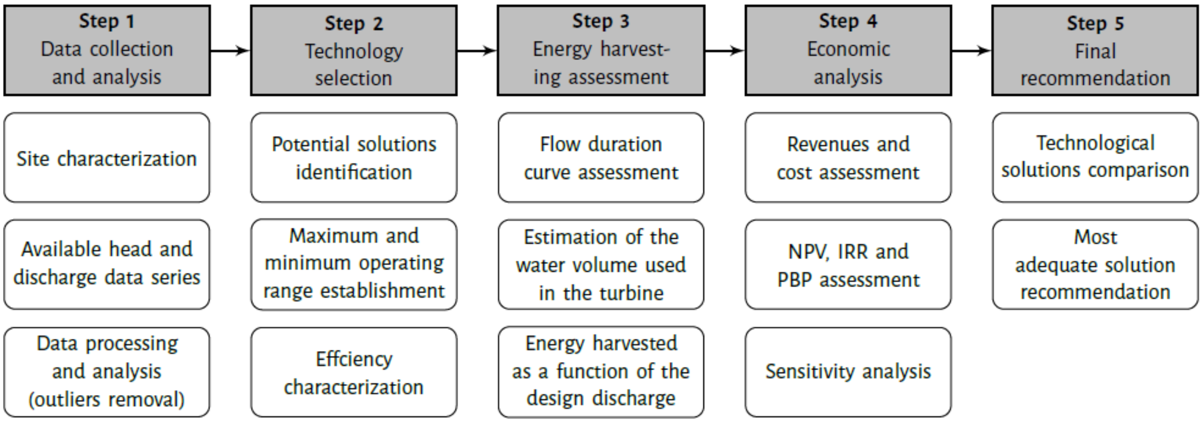

Figure 1. Proposed methodology for energy harvesting assessment and technology selection.

Step 1, data collection and analysis, consists of identifying the primary purpose of the system, the main characteristics, and the potential locations for harvesting energy, which must combine excessive head, large discharges, and sufficient available space to install the powerhouse and the turbine. For the identified locations, data of available head and discharge must be collected and should include at least three representative years of the system operation. If necessary, it should be identified as a derived flow rate that cannot be turbined. Above all, the construction of MHP cannot compromise the primary purpose of the water system.

Step 2 focuses on the selection of the possible technological solutions based on the available head and discharges range and the technical features of each turbine. For this purpose, Fig. 2a) which presents the performance characteristics of possible solutions, can be used. Usually, the best solutions are: for low-heads (1-20 m), the Archimedes screw, the Kaplan, PAT, Cross-flow, and waterwheel turbines [22]; for medium heads (20-100 m), the PAT, Francis and Cross-flow turbines; and for high heads (>100 m), Francis and Pelton turbines. For each solution, the maximum and minimum operating ranges of head and discharge, as well as the efficiency curve *vs* discharge, should be defined. Fig. 2b) presents the variation of the turbine efficiency with the percentage of maximum discharge.

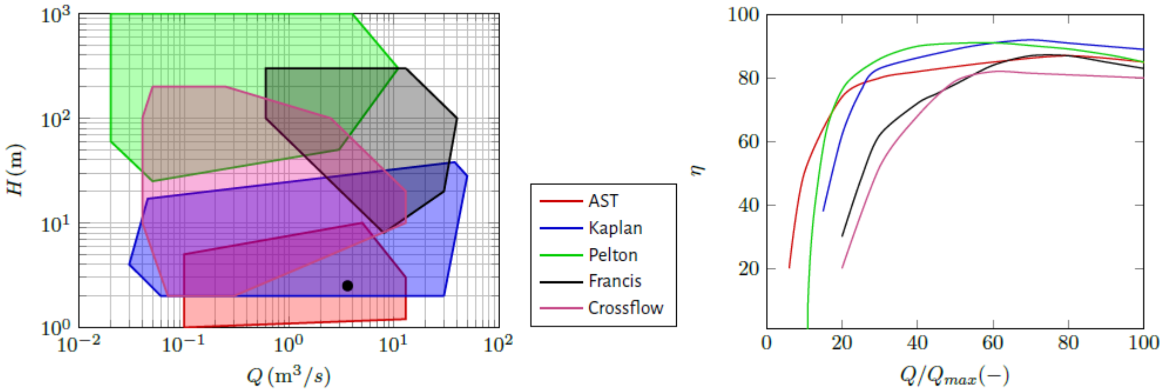

Figure 2. Turbine a) performance characteristics, and b) efficiency curves (adapted from [18]).

Step 3 consists of determining energy harvesting as a function of the design discharge. The proposed method requires the following input data: the pressure head and discharge data; the interval of acceptable design discharges; and the discharge range of operation of the turbine [Q_{min}, Q_{max}], typically described in terms of design discharge (Fig. 2a). Then, the discharge probability of occurrence curve is calculated over the assessment period (e.g., three years). Different design discharges, Q_d, are considered defined within the specified interval.

The energy harvesting is calculated for each design discharge, Q_d, and for each discharge of the probability of occurrence curve, $Q(t)$, considering the following rules: i) if $Q(t) \geq Q_{max}(Q_d)$, the turbine will only use $Q_{max}(Q_d)$ to generate power and the remaining discharge will be derived through a bypass; ii) if $Q(t)$ is between [Q_{min}, Q_{max}], the turbine will use $Q(t)$ for energy production; and iii) if $Q(t) \leq Q_{min}(Q_d)$ the turbine will not operate.

The annual water volume used by the turbine for each design discharge, V_t (Q_d), is calculated by the time integration of the discharge used by the turbine divided by the number of years. The annual harvested energy, E (kW.h), for each design discharge Q_d is calculated by

$$E(Q_d) = \frac{\gamma V_t H_n \eta}{3600 \times 1000} \tag{1}$$

being γ the specific weight of water (9800 N/m³), H_n is the net head (m), η is the global efficiency of the turbomachine. The total installed power P (kW), is calculated as a function of the design discharge:

$$P = 9.8QH_n\eta \tag{2}$$

The variation of the annual volume used by the turbine, of the harvested energy and of the total power should be plotted as a function of the design discharge.

Step 4 consists of the economic analysis of the project-based of the annual energy harvested for each design discharge. Capital costs, operation and maintenance (O&M) costs, and gross and net revenues are calculated. Three economic indicators are typically used to evaluate the feasibility of the project: the net present value (NPV), the payback period (PB) and the internal rate of return (IRR) for the design discharge for each selected turbine. The additional input data to calculate these indicators are the discount rate, t_a ; the project lifetime, n (years), the unit energy cost, Cu (€/kWh); O&M costs described as a percentage of the capital cost (CC). The CC include the equipment control, management, civil work, and turbine generator setup. The civil works and equipment costs can be estimated by using empirical equations or using estimations per MW, based on previous projects. The turbine cost can be assumed as a percentage of the total cost of the project and then estimated the CC [17, 23].

The capital costs, net revenue, accumulated revenues and the referred economic indicators should be calculated for each design discharge, and for each technological solution. These indicators will contribute to finding the best solution.

A sensitivity analysis to the main uncertain parameters, such as the unit of capital cost, the O&M costs, or the discount rate, is recommendable to assess its impact on the results.

Step 5 consists of the comparison of selected technological options to establish the best technical and economical solution for energy harvesting in the water system. The main parameters to be compared for each design discharge scenario are energy recovered, CC, PBP, NPV and IRR.

The final solution is the one that leads to the highest NPV with an acceptable IRR (>10%) and an adequate payback period (< 10 years) [24]. The project is feasible if the NPV is higher than zero, it means that the investment is recovered within the project lifetime. If the NPV is equal to zero, the investment cost is retrieved, and the minimum rate of return of capital is achieved, so the profitability of the project is doubtful. If the NPV is negative, the project is financially impractical.

It should be highlighted that the project design discharge depends not only on the energy harvested but also on the economic analysis since higher flow rates not only lead to higher revenues but also to higher capital and O&M costs.

A computational tool has been implemented for carrying out described calculations.

3 Case study: Alviela river source

3.1 Data collection and analysis

Empresa Portuguesa de Águas Livres (EPAL), the water utility responsible for supplying Lisbon is the concern with the environment and aims to be increasingly more a Zero-Energy consumer. EPAL has identified the Alviela river source as a potential location with a high seasonal discharge, available head and space to install a MHP to harvest energy.

Alviela river source, located in Santarém district, Portugal, is currently managed by EPAL. The Alviela transmission system, built-in 1880, was a significant source of water to Lisbon and other bordering councils 40 years ago. The system includes the Alviela transmission system, with over 100 km of length and a transport capacity of 0.8 m^3/s. This system reduced its contribution to the Lisbon supply when another transmission system located closer to Lisbon, Castelo de Bode system, was built in 1987 [25]. Currently, the Alviela source is not operational; however, it maintains the ecological discharge in the river of 0.1 m^3/s (EPAL protocol, DRGN 1992). Nowadays, the created reservoir area is used for recreational purposes, as a fluvial beach.

During this study, a topographic survey of the Alviela source area (Fig. 3a). The Alviela river source has two small reservoirs (R1 and R2) and two weirs (1 and 2). Reservoir R1 has a weir (1) that discharges to the recreational area and the inlet of a 50 m pipe (3) that connect R1 to the transmission system chamber, controlled by a sluice-gate. The chamber has a valve to control the water that goes to the transmission system (4) and a weir (2) that discharges the water in excess. The location to install the MHP is in the second weir (2) that has 2.5 m of available head between the inlet chamber and the reservoir R2. Since the chamber elevation is greater than that of R2, the water used in energy production cannot be reused for the transmission system.

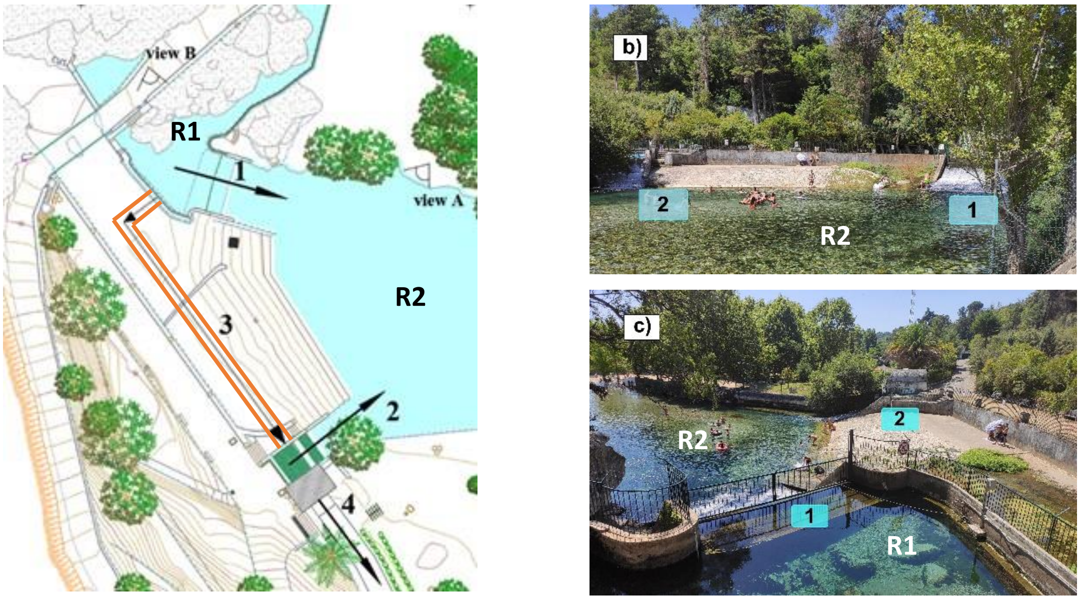

Figure 3. Alviela river source a) catchments scheme; (b) view A and (c) view B (1−Weir 1; 2−Weir 2; 3−Pipeline; 4−Alviela aqueduct Inlet; R1−Upstream reservoir; R2−Downstream reservoir).

The analysis of the discharge data series between 2004-2019 provided by EPAL has shown that the period of 2016-2019 had an anomalous behaviour (Fig. 4a), thus, only the period 2004-2015 is analysed herein.

Four scenarios were considered for the water derived to the transmission system that could not be used for energy harvesting. The derived discharge is described as a percentage of the maximum capacity of the aqueduct (0.81m^3/s), for dry and for wet seasons. Scenario 0 considers that no water is derived. Scenarios 1, 2 and 3 consider the derived discharge equal to 15%, 25% and 50%, respectively, in the wet season, and 30%, 50% and 75%, respectively, in the dry season. Only Scenario 2 results will be presented herein.

The probability of occurrence curves obtained for the total discharge in the period 2004-2015, and for the available discharge for Scenario 2 are depicted in Fig. 4b). Minor differences are observed between these two curves since derived discharges to the transmission system (0.20 m^3/s in the wet season and 0.41 m^3/s in the dry season) are small when compared with average discharge values (4 m^3/s).

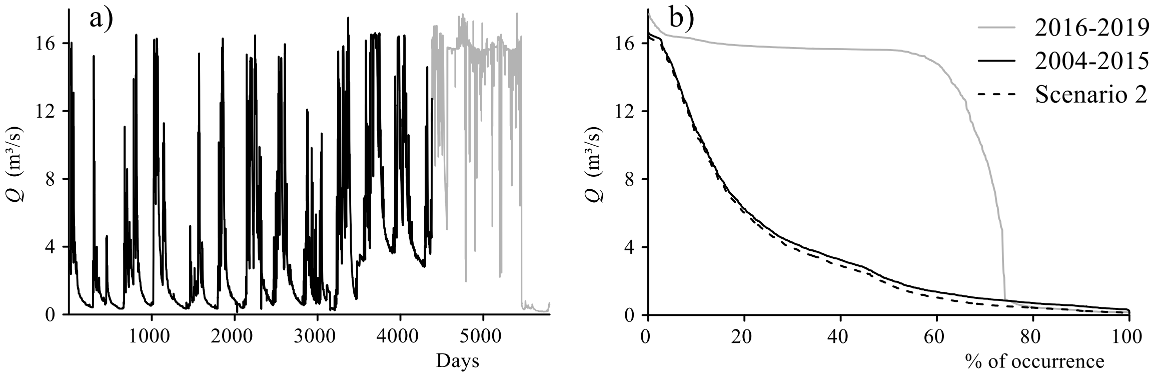

Figure 4. a) Discharge data series; b) Flow duration curves.

3.2 *Technology selection*

The technological solutions adequate for the available head (H=2.5 m) and the available discharge range for Scenario 2 (0.5-16 m³/s) can be obtained using Fig. 2a): (see black circle), resulting in Kaplan, propeller, and Archimedes screw turbines.

Based on manufacturers' catalogues, the AST turbine efficiency is maintained high (80-85%) for a wide range of discharges (40-100% Q_d); however, experience shows lower efficiencies (ca. 75%) [20, 26]. Therefore, a constant efficiency of 75% is considered for 40-110% Q_d; additionally, the AST does not operate for discharges lower than 20% Q_d, and in between 20-40% Q_d the efficiency varies linearly from 20-75%. The Kaplan turbine part-flow efficiency was estimated also based on manufacturer catalogues: the turbine can maintain a high efficiency (90%) for discharge ranges from 110% to 30% of the rated discharge. The propeller has a high efficiency (90%) around the rated discharge; however, this efficiency drops very fast when the discharge deviates from this value. The three turbines efficiency curves are plotted in Fig. 2b).

3.3 *Energy harvesting assessment*

The developed model is applied to estimate the harvested energy, considering the design discharges between 1.5 to 15 m³/s. The annual harvested energy, *E*, and the respective turbine operating time are presented in Fig. 5a) for each design discharge. The maximum value of harvested energy (*E*=472 MWh/year) corresponds to a design discharge of 12 m³/s and 2242 hours of operation.

Despite $Q_d = 12$ m³/s leading to the maximum energy harvesting, the optimal design discharge also depends on capital costs and on O&M costs.

Figure 5b presents the available power, γQH, probability of occurrence curves. An AST with a design discharge of 1.5 m³/s and a maximum power of 30 kW can operate for more than 80% of the time/year, while a turbine with $Q_d = 15$ m³/s with a full power of 273 kW can operate for less than 40% of the time. The frequency occurrence of 50% corresponds to a design discharge of 9.0 m³/s and a maximum power of 182 kW.

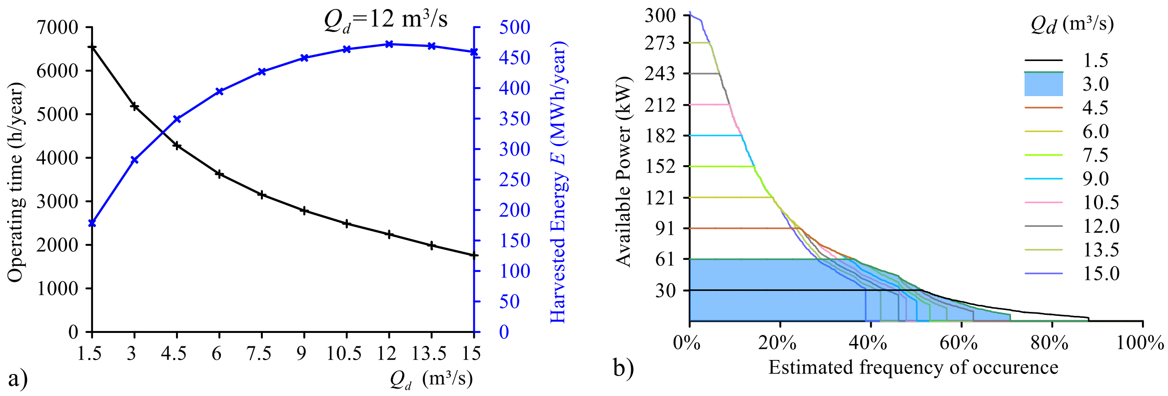

Figure 5. a) AST operating hours (dark line) and produced energy (blue line) as a function of design discharge and; b) available power probability of occurrence curves for several design discharges.

3.4 *Economic analysis*

In addition to the construction of the hydropower plant, it is necessary to reinforce the pipeline between reservoir R1 and the transmission system chamber. The existing pipe has 755 mm diameter and a maximum discharge of 1.5 m³/s. For design discharges higher than this value, it is necessary to build a new ductile iron pipeline with 50 m.

Economic analysis requires the calculation of the capital and O&M costs, gross and net revenue, as well as several economic indicators, such as Net Present Value (NPV), payback period (PB), and Internal Rate Return (IRR). Several assumptions are considered herein: (i) discount rate = 5%; (ii) project lifetime = 20 years; (iii) unit energy cost = 0.08753 €/kWh; (iv) capital cost = 2 M€/MW plus the reinforcement of the pipeline cost, which depends on the design discharge; (v) O&M = 0.5% of the capital cost, excluding the pipeline cost. The discount rate, project lifetime, and unit energy cost are typical current values used by EPAL. Capital and O&M costs are estimated based on EPAL previous experience and considering the location characteristics.

The NPV, the PB and the IRR for the AST solution are presented in Fig. 6 as a function of the design discharge. The discharge that leads to the maximum NPV for the AST over 20 years is 3 m^3/s, a value significantly smaller than the one that allows the maximum energy harvesting (12 m^3/s). The corresponding PB is 8 years (lower than 10 years, established as a threshold by EPAL) and the IRR is 13.74% (higher than 8%).

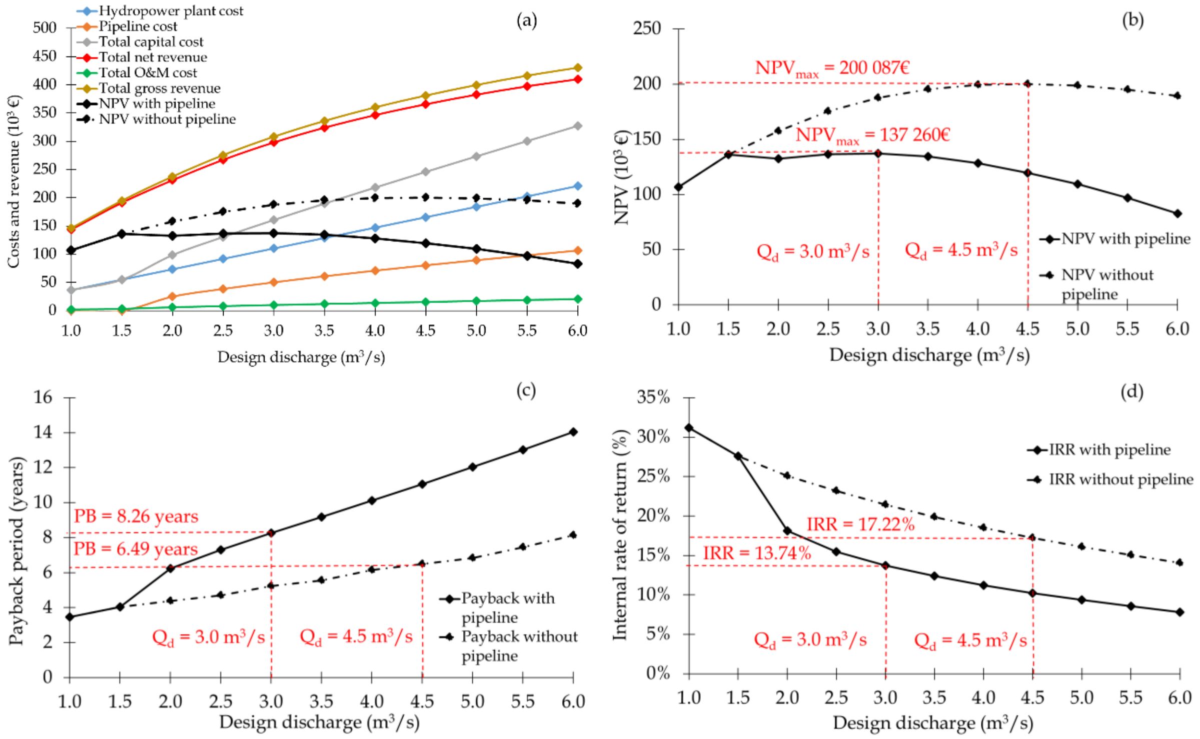

Figure 6. Results of the AST economic analysis as a function of the design discharge with and without the pipeline cost: (a) capital cost, O&M costs, revenues, and net present value; (b) Net Present Value; (c) Payback Period; (d) Internal Rate of Return.

3.5 *Final recommendation*

The AST solution is compared to the other two solutions, Kaplan, and propeller turbines. These technologies have a higher efficiency but are more costly, so the capital cost considered in the comparison was 3 M€/MW for the propeller and 4 M€/MW for the Kaplan. The O&M cost per year considered for the propeller was 2% of the capital cost and 4% for the Kaplan. The efficiency adopted for both turbines are represented in Fig. 2a).

Results are presented in Fig. 7. The maximum NPV (Fig. 7a) occurs at different design discharges for each technology, namely Q_d=3 m^3/s (for AST) for Q_d=1.0 m^3/s (for Kaplan) and Q_d=1.5 m^3/s (for propeller). The Archimedes screw and the propeller turbines are the options that fulfil the 10 years maximum payback period (Fig. 7a) established by the water utility; thus, the Kaplan turbine solution is discarded. The AST is the one that has the highest capital cost, but also the highest NPV at the end of the project lifetime.

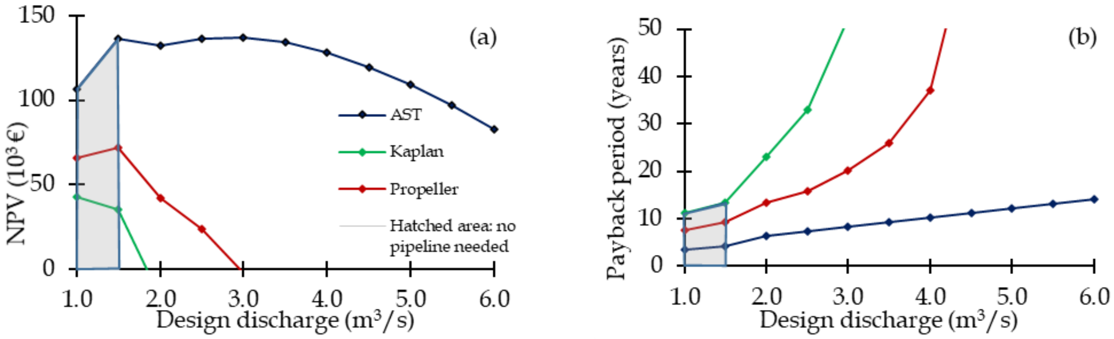

Figure 7. Parameters comparison between AST, Kaplan, and propeller turbines; (a) NPV; (b) Payback period.

The best solutions obtained for each technology are presented in Table 1. The Kaplan turbine is the technology that operates more time, due to its wide range of discharges, yet, due to its high capital and O&M costs, it has the lowest NPV, the highest payback period, and the lowest IRR. The propeller turbine solution recovers almost the same energy as AST, but operates fewer hours, due to a limited range of flow rates. The AST solution is the one that has the lowest capital cost, the highest NPV and IRR and the lowers payback period. The AST with a design discharge of 3.0 m³/s leads to an NPV of 137 260 € in 20 years with a PB of 8.26 years and an IRR of 13.74% (Fig. 6). This solution corresponded to an AST with a nominal power of 55 kW and recovered energy of 282 MWh per year, and a capital cost of 160 734 €. Figure 5b) shows that the turbine can work with a maximum power of 61 kW for 36% of the time and decrease gradually until stops working in 71% of the time. This means that the turbine will not be used for 29% of the time.

Despite the lower efficiency, the AST has a lower capital (2M€/MW) and O&M costs (0.5% CC/year) than the impulse turbines. The gain in harvested energy of Kaplan and propeller turbines due to the higher efficiency is not compensated by the increase in the investment when comparing to the AST (Fig. 2a).

Table 1. Technical and economic parameters comparison of optimal solutions for each turbine

Turbine	Q_d (m^3/s)	H (m)	P (kW)	E (MWh/year)	Operation hours (h/year)	V (hm^3)	Capital Cost (M€/MW)	Pipeline cost (€)	Capital Cost (€)	O&M Cost (% of CC)	O&M Cost (€/year)	Net Revenue (€/year)	NPV (€)	Payback (years)	IRR (%)
AST	3.0	2.5	55	282	5 183	55.98	2	50 372	160 734	0.5	804	23 912	137 260	8.26	13.74
Kaplan	1.0	2.5	22	160	7 326	26.37	4	0	88 290	4	3 532	10 506	42 634	11.10	10.19
Propeller	1.5	2.5	33	179	5 479	29.58	3	0	99 326	2	1987	13 724	71 705	9.13	12.51

The technical analysis results in higher discharges that maximize the harvested energy than the economic analysis that maximize the net results (revenues minus costs) since the capital cost increases with the turbine power. Despite the produced energy increasing with the discharge until it reaches 12.0 m³/s, the capital cost increases faster. The final design discharge should be decided by the water utility manager based on the overall analysis.

Concerning the physical characteristics of the Archimedes screw turbine, based on manufacturer information for an AST of 3.0 m³/s, the diameter varies from 2.6 m and 2.8 m for an angle with the horizontal of 22° and 30°, respectively. The values for length and angle depend on the local characteristics and on the manufacturer. In Alviela, according to the topographic survey, the weir width is 4.20 m, and the available length is around 13.00 m so that the AST can be installed in any of the referred diameters or angles.

4. Conclusions

This work proposes a methodology for assessing the technical and economic feasibility of energy recovery in urban water systems. Energy harvesting in the water industry is a growing area, as seen in the many recent pieces of research and projects. This is due to the existing energy potential and the need for making the industry more sustainable and energy efficient.

The most promising technology for the case study of Alviela is the Archimedes screw turbine, which is a relatively new technology, when using it as a turbine and not as a pump, especially in Portugal. This solution has never been used by AdP Group (the company responsible for water supply in most of the Portuguese territory).

The recommended solution is the Archimedes screw turbine with a rated power of 55 kW, a rated discharge of 3 m^3/s and a rated head of 2.5 m. Assuming an average efficiency of 75%, this turbine can harvest 282 MWh of energy per year, even when observing a considerable discharge variation.

Despite the Archimedes screw turbine lower efficiency in comparison to the other turbines (Kaplan and propeller) and the need for more space for installation, this turbine can operate for a wide range of discharges and is available for use on very-low heads, making it a desirable option for many water supply systems and wastewater treatment plants. Additionally, this solution has lower unit costs and lower O&M costs compared to Kaplan and propeller turbines, which are the other options for locations with these characteristics, making it a promising technology in Portugal, to explore the energy harvesting potential in the many existing water systems.

The Archimedes screw turbine is an option that is worth considering to harvest energy in low head locations, like river weirs or wastewater treatment plants, with a wide range of flow rates and with solid material transported with water.

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