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FEASIBILITY, EFFICIENCY AND ECOLOGICAL ASPECTS OF LOW HEAD HYDROPOWER PLANTS

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Abstract. *With the increasing energy demands, especially for renewable and easily accessible energy sources, a real engineering challenge is in finding new solutions for using available resources, while considering three main aspects: feasibility, efficiency and ecology. One of the solutions can be found in small hydropower plants operating with a very low hydraulic head, from 0.8 to 3 m, and power in the range of 5 to 500 kW. Although some of technical solutions are environmentally friendly, so far low head hydropower plants constitute a largely unused potential source of renewable energy. The main reason for the low utilization of these potentials is because there are still many engineering problems that are not fully resolved. Conventional turbines are not suitable for many of the existing locations with such a low hydraulic head, and increased ecological demands must be considered. One of the best solutions for the exploitation of low head hydropower is the newly designed Archimedean screw turbine, which is eco-friendly and usually does not require large investments. Two suitable locations on the territory of the southeast Republic of Serbia are analyzed in the paper, giving recommendations for the selection of main power plant parameters, such as: flow duration curve, installed capacity, dimensions, issues and operating principles, environmental considerations, scheme costs, revenue and return.*

Key words: *Archimedean screw turbine, Hydropower, Low head, Eco-friendly.*

1. INTRODUCTION

Hydropower energy is a renewable energy source, which has been used since ancient times. This is the largest and most widely used renewable energy source, accounting for 16% of global electricity consumption [1]. Hydro energy is a reliable and cost-effective way to generate electrical energy. It has a long life, usually operating for more than a

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century, therefore is considered an excellent investment. Hydropower can provide both energy and water solutions, and contributes to the fields of water distribution, irrigation, flood control. Therefore, hydropower can promote economic and social development [2].

With the increasing energy demands, especially for renewable and easily accessible energy sources, the main task is to find and utilize every available hydro resource, always considering three main aspects: feasibility, efficiency and ecology.

Small hydropower (SHP) refers to hydro-power plants with an installed capacity of up to 10 MW, and contributes around 8% of electricity production in Europe. There is no uniform classification of SHP for smaller installed power, yet different sources provide some guidelines. Therefore, small hydro can be classified as: pico (5<kW), micro (5÷100 kW), mini (100 kW÷1 MW) and small (1 MW÷10 MW (up to 25 MW)) [3, 4]. Small hydropower plants are mainly run-of-river, without any substantial storage.

There is still a large potential for small hydropower, even though SHP potential has been greatly affected by environmental legislation [5]. Natura 2000 and the Water Framework Directive give environmental frameworks and standards, which should protect biodiversity and Europe's most valuable species and their habitats and establish a framework for protection of all surface waters and groundwater in order to reach good status [6]. Consequently, in some countries economically feasible potential was reduced significantly. To take advantage of the remaining potential, SHP must be designed for each location, site by site, in order to comply with all the environmental requirements. Growing environmental requirements for SHP are very restrictive, sometimes even reducing production hours, lowering profitability and increasing the investment cost [6].

The Joint Research Centre conducted a technical assessment of the National Renewable Energy Action Plans, in order to verify the achievement of an overall EU27 target of 20 %, to compare the proposed renewable resources with resource estimates, and to make a comparative analysis between the data reported and the technically and environmentally available and economically competitive resources [7, 8]. Hydropower installed capacity in Europe was projected to increase up to 127 GW in 2020 [9]. The European Commission (EC) introduced the Guidance on the requirements for hydropower concerning EU Nature legislation, making a framework for hydropower operation following ecology requirements, i.e. requirements of the Habitats and Birds Directives [10].

In November 2018, the European Commission released its "Long Term Strategy" for decarbonizing the European economy, and this meets Europe's 2030 Renewable Energy and Energy Efficiency targets of 32% and 32.5%, respectively [11]. The possible pathways of further development of the mini and small hydropower production systems based on run-of-river hydropower schemes are presented by Bodis et al. (2014), estimating and analyzing the technical potential for exact geographical locations [12].

France, Italy, Sweden, Austria and Spain produce almost 70% of the total hydro energy in the European Union [13]. The Balkan countries are also trying to follow the frameworks and standards of the European Union. Bosnia and Herzegovina and Serbia are countries with the highest technical potential. Serbia has about 50% utilization rate, but still a lot of potentials, especially for low hydropower.

When talking about small hydropower plants, three groups of aspects are considered: economic, social and environmental [14]. Economic aspects have the following advantages: low operation and maintenance costs, long life, fast regional development, high energy efficiency, while the disadvantages are high investments. The advantages of social aspects are tourist and recreational facilities and all infrastructure, irrigation potential, flood protection, engaging the local community and improving their living conditions. Also, new jobs can increase the local population and change the environment. Environmental changes can also happen with the change of the river flow, modification of river hydrology, building a dam, impact on animals, etc. On the other hand, it is important to emphasize that hydropower does not produce air, water or ground pollution.

2. CASE STUDIES

2.1 Hydropower technologies

There are two main types of conventional hydropower technologies [15]:

- Installations with a reservoir, which may be:
  - Storage power plant or impoundment facility, with a dam to store river water, usually for large hydropower plants;
  - Pumped storage, with a storage reservoir and a pump station for pumping water back to the reservoir;
- Run-of-river or diversion type, using a canal or penstock for water supply.

The dam creates a reservoir that allows flexibility in the electric energy generation, since the reservoir can store the river in order to utilize water as needed to meet baseload as well as peak load demands. However, most of the dams are not built for the needs of generating electricity, but for the purpose of flood control, water supply, irrigation etc. From an environmental point of view, dams change the environment dramatically, interrupting the flow of rivers and changing habitats for all living creatures in the site, including humans.

Pumped storage facilities are not very common since they require a site with appropriate topography. When electricity consumption is low, usually during the night, water is transported from the lower to the upper reservoir by pumps, storing the energy. During the day, when electrical consumption is higher, stored water is used to generate electricity.

A Run-of-river hydropower facility (ROR) should have less impact on the environment than previous types of hydro facilities if designed properly. It can also have a small dam and a small reservoir. The main concern with such facilities is the occurrence of low water levels, which can also cause the turbine unit to shut down.

In order to make better use of the available hydro potential, it is necessary to use new concepts of hydroelectric power plant construction and find better technical solutions for exploiting low head locations [16].

In addition to the conventional solutions, other solutions are also considered, such as in-stream hydropower scheme, with a small dam inside the riverbed, applied for low head locations. This type of hydropower plant is also used for offshore and tidal power plants [15]. Basically, an in-stream hydropower function like a ROR scheme, but the river flow is not diverted. This type of hydropower scheme can be used for low head locations, to optimize the existing weirs, barrages, canals or falls. Usually, low head turbines or hydrokinetic turbines are installed at such locations.

There is no specific definition of low head hydro sites. Projects with a head up to 5 m can be considered as low head sites, but for a net head less than 2.5 m conventional turbine aggregates are not available. There are many hydro sites available, with very low heads from less than 1 m and up to 3 m, with power up to 1000 kW, waiting to be utilized. So far, such sites have been mostly neglected, due to very low efficiency. An additional problem is the negative impact of conventional small-scale turbines on the environment.

The current situation in which there is a desire to develop all sources of renewable energy has attracted and still attracts many researchers and inventors who try to overcome the technical difficulties connected with the exploitation of low head hydropower [17, 18]. New technologies have been developed to take advantage of very low heads, despite all obstacles. These technologies are often referred to as hydrokinetic, taking advantage of the kinetic energy [19] and are not considered in this paper. During the last decade several old and new turbine units have been proposed and developed. As a result, the area of low head hydropower has attracted the attention of many researchers to use and develop a new and efficient, environmentally friendly Archimedean screw turbine (AST).

Keeping in mind the important role of environmental aspects, efficiency, initial costs and maintenance requirements, Archimedean turbines can be widely adopted at low head hydro sites. For a more detailed explanation, the two suitable (different in flow duration curve) locations on the territory of the southeast Republic of Serbia are analyzed. The procedure for analysis of possible locations is given in the paper with detailed recommendations for the selection of main power plant parameters, investment cost and return on investment (ROI).

2.2 Archimedean turbine

The Archimedean screw is one of the two oldest hydraulic machines known to man. The creation of the water screw is probably based on the study of the spiral, for which Archimedes wrote a treatise entitled “On Spirals” in 225 B.C. The Roman engineer Vitruvius gave a detailed and informative description of the construction of an Archimedean screw in his “De Architectura” [20].

A system with an Archimedean turbine is based on the principle of an ancient pump, the so-called Archimedean screw pump, but running in reverse. In 1997, after a four-year research program, the first screw turbine in the world was manufactured in the Czech Republic.

Archimedean screw turbines can also be used as an additional unit at existing hydropower plants by utilizing overflow energy (minimal residual flows), or they can even replace old existing turbines completely.

Fig. 1a shows a typical power generation unit, with the screw running in a metal trough. The Archimedean screw turbine (AST) consists of a rotor which can be situated in a metal or concrete trough and it is fixed in an upper and lower bearing, with a gearbox and an asynchronous generator.

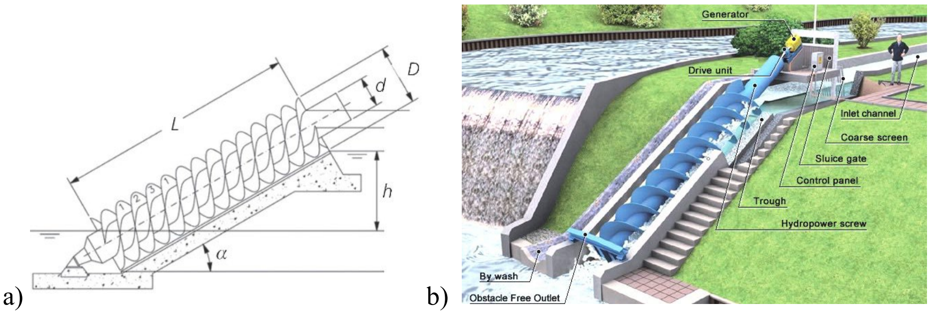

Fig. 1 AST: a) main dimensions and b) hydropower plant on site (Photo Landustrie)

Archimedean screw turbine technology does not need any special regulation method, all it needs is an emergency gate valve and an overflow from the trough in which the screw is positioned. The asynchronous generator, with a properly designed gearbox, ensures connection to the public network with sufficient output optimization in the range 10÷100%.

The first tests of the Archimedean screw turbine were conducted by Brada [21], for D=1050 mm, L=4.7 m. Experimental results were obtained by measurement on a 30º inclined screw with three turns and gave efficiencies of 80%. Another test conducted by Hellmann [22] with the same angle resulted in efficiencies of 84.5%. Very recently, the first theory of the Archimedean screw was developed by Muller and Senior [23], and the theory indicates that the maximum possible efficiency is a function of the geometry; efficiencies decrease with steeper angles and with wider turns. High efficiency for a wide range of flow rates makes these turbines very suitable for small hydropower plants. Some manufacturers claim that efficiency of AST is up to 88%.

The geometry of AST, especially the screw diameter, is responsible for the maximum flow rate of a turbine. Different manufacturers have agreed that the diameter of the smallest screws is 1 m up to 5 m, which are designed for hydraulic head in the range of 1 m to 12 m, operating with flow rates (0.1÷20) m^3/s. Archimedean screws typically rotate with small rotational speed (about 26 rpm). Therefore, increasing the rotational speed is necessary to achieve the rotational speed of commercial generators. If possible, it is always recommended to use variable-speed turbines, in order to adjust the rpm speed to the variable turbine operating mode. In this way, the efficiency of the turbine unit is significantly increased.

2.3 AST advantages and disadvantages

The most important advantages of hydropower plants with AST are:

- Operating with a very low head (1 m) and low flow rate (0.1 m^3/s)
- Simple to install, use and maintain
- No major construction works
- Fine screen is not required (debris tolerance)
- Fish-friendly, due to screw geometry and small rpm
- Very cost-effective compared to other turbines
- Good efficiency at partial loads
- Long bearings due to low rotation speeds
- Wear-resistant and reliable

- Screws can be coated with composite materials to increase wear resistance.

The most important disadvantages are:

- Constant changes of hydraulic head during the year cause changes in electricity production
- High power requires high flow rates
- No electricity production during the low water period
- Require a gear box, which reduces the overall efficiency
- To obtain maximal efficiency of the system, the variable speed is required.

Sensitivity to water height requires special attention to the choice of design flow and reduces the possibility of full utilization of the available water resources. This problem can be solved by placing a few parallel turbines, but in such a case, the investment costs increase.

2.4 Main parameters of AST

The optimum exchange of energy in the Archimedean turbine cannot be uniquely resolved, given that it depends on many interlinked factors, such as energetic factors (turbine head, flow rate, rotational speed), as well as constructive factors (diameters, number of blades, number of screws and their shape, pitch, length of the turbine (screw), angle of inclination, etc.).

Some empirical formulas are available in the literature [24] as guidelines for the determination of geometric parameters of an AST:

- Outer diameter: $D = 2 \cdot ((k_a \cdot Q)/(k_1 \cdot k_s \cdot k_p)))^{3/7}$.
- Inner diameter: $d = (0.5 \div 0.54) \cdot D$.
- Inclination coefficient: $k_\alpha = tg(\alpha) = 0.176 \div 1.192$.
- Coefficient $k_1 = 10.362 \div 11.606$.
- Pitch coefficient: $k_s = (k_\alpha \cdot S)/(\pi \mathrm{D}) = -0.3947 \cdot z_k^{-0.2699} + 0.5191$,

where: S – pitch of the Archimedean screw, z_k – number of blades.

- Loading coefficient: $k_p = V_n/(\pi D^2 s = 0.04865 \cdot z_k^{-0.2657} + 0.2331$.
- Gap: $s = 0.0045\sqrt{D}$.

Certain recommendations for designing Archimedean screw turbines are obtained by experimental investigations [25, 26]. There are still not enough theoretical and practical data related to dimensioning and optimization of the Archimedean turbines.

Therefore, there have been attempts in recent years to obtain relevant conclusions by performing numerical simulations [27, 28].

Recommended values for the diameter size of the AST according to its operating parameters, obtained by Spaans and Babcock, is presented in Fig. 2.

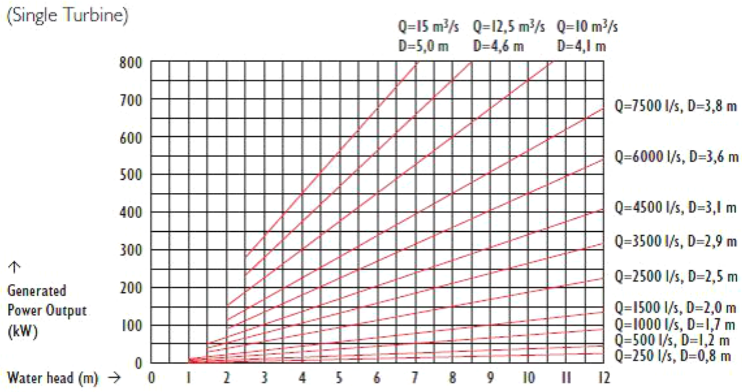

Fig. 2 Indicative sizes, flow, head and output (Photo credit Spaans and Babcock)

2.5 Other equipment

An Archimedean screw is usually equipped with the upper and lower bearings to support the screw. The lower bearing should be sealed for life to minimize maintenance and risk of oil leakage into the river. Also, the upper bearing must be sealed against high flood events. It is recommended to install the turbine brake system, which is used as a backup in the case of the intake control gate failure.

Intake screen: Usually, a coarse screen with 75 to 100 mm bar spacing is provided to prevent debris entry to the turbine during the operation. This screen is sufficient for an Archimedean screw considering the turbine design and proposed operating speeds. Small debris can pass through the turbine to the tailrace and back to the river.

Control gate: Immediately upstream the inlet channel of an Archimedean screw the control gate is installed. The best option for the control gate drive (opening or closing) is by hydraulic pump pressure and cylinders. The second solution is the AUMA drive for small control gates. In both cases the gate must be closed quickly upon an urgent shutdown or power failure - loss of load on the generator. Special attention must be given to the water protection of the control gate actuator.

Generator and drive: In the presented analysis a fixed speed drive is used. In the case of variable speed control, the cost will be higher but in some cases the advantages can outweigh the disadvantages. At the peak power output a variable speed drive slightly lowers the overall efficiency of turbine aggregate. In the case of less favorable flow and level conditions the variable speed drive increases overall efficiency and for each case a detailed analysis should be conducted in order to determine the best economic choice.

Level sensors: In order to control the Archimedean screw, a level sensor should be placed at minimum three locations in the inlet channel before the bar screen for the river level measurement. The second sensor is usually placed after the bar screen to provide the information of head loss and to give the actual intake level. This sensor is also used as a backup and alarm for cleaning of the intake screen. The third sensor is placed at the downstream outlet side or in the lower river level. The purpose of this sensor is to measure the actual head or to give the information in the case of the turbine outlet blockage.

2.6 Analysis of potential hydropower locations

In the area of southeastern Serbia, some rivers of the South Moravian basin were considered as sites suitable for setting up Archimedean turbines. In order to analyze the available hydropower potential of certain locations for which it is possible to install Archimedean turbines, the authors of this paper have performed the analysis of many locations in the southeast of Serbia in the previous period. Locations where the application of conventional turbine aggregates is not possible are primarily analyzed. Secondly, analyzed locations can be used without significant construction work on the riverbed and with almost no impact to the environment. In addition to the mentioned features of the locations under consideration, the two selected ones are characterized by similar net heads and different types of flow duration curves, which makes the analysis more interesting.

The selected locations are on the river Nišava and river Vlasina. The first location is on the river Nišava, near the village Ostrovica (Fig. 3a), and the second location is on the river Vlasina, near the village Boljare (Fig. 3b).

Both locations are connected by existing roads to the neighboring settlements, leading to the highway E80 and E75, respectively. High-voltage lines are in the immediate vicinity of the locations, as well as mid voltage electricity transmission networks.

An analysis of potential mini hydro sites using an Archimedean screw turbine is the main aim of this paper. The design flow for selected location (and the max power) has been limited by the largest diameter screw which can perform efficiently with the small head available. To exploit more flow (hence higher max power), this scheme could be doubled (with twin screws).

a) b)

Fig. 3 Analyzed locations: a) on the river Nišava; b) on the river Vlasina;

2.7 Hydrological data of the locations

In order to analyze the hydroelectric potential of one location, it is necessary to have the following studies:

- Monthly and daily flow duration curve based on a minimal period of 20 years
- Available gross head at the location with the analysis of the lower water level as function of the river flow
- Available Archimedean screws for defined location head and different flow rates
- Archimedes screw efficiency as function of the installed flow rate percentage
- Generator efficiency as function of the load

- General dimensions of the Archimedean screw and number of units
- Estimated annual energy production for the chosen solution
- Estimated investment cost for the chosen solution.

Hydrological analysis of the rivers is presented in Fig. 4 and Fig. 5.

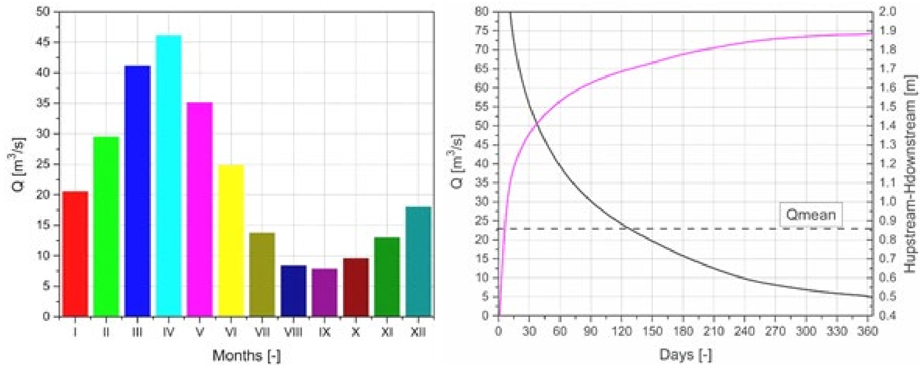

Fig. 4 Hydrological data for the river Nišava location

In the following diagram, the dependence of the minimal turbine head and the installed turbine flow is presented, according to many manufacturers' data for the Archimedean turbines. It should be noted that such a diagram is designed to optimally exploit locations with a small head, and not as the best solution for choosing a turbine generator.

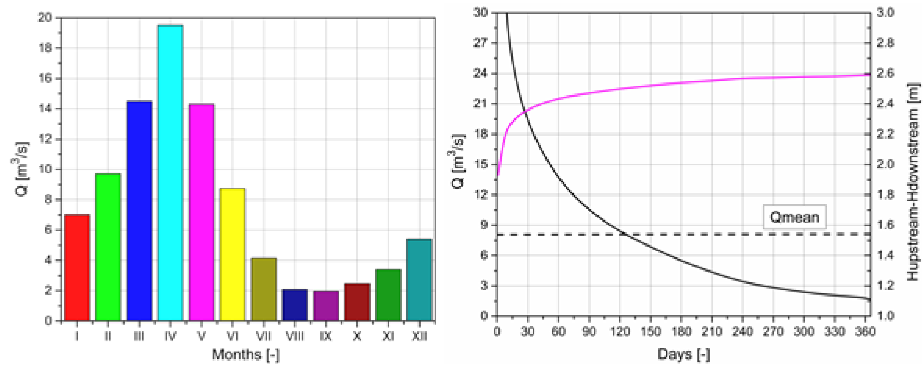

Fig. 5 Hydrological data for the river Vlasina location

In addition, a diagram showing the orientation values of the turbine aggregate rotational speed, depending on the diameter of the turbine impeller and the inclination angle of the turbine aggregate, is presented in Fig. 6.

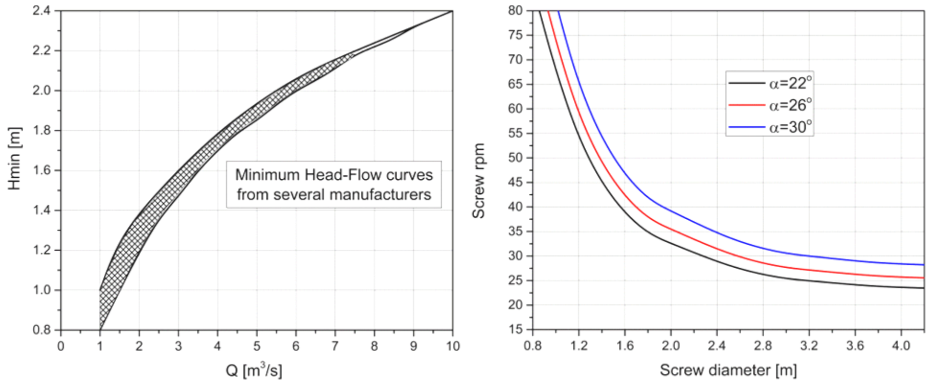

Fig. 6 Recommended operating parameters and geometric dimensions of an Archimedean screw turbine which operates with a very small head

According to the diagrams given in Fig. 6, it is possible to select the installed capacity of the Archimedean turbine, depending on the available hydraulic head. Based on the installed capacity, the inclination angle of the turbine and the adopted rotational speed, it is possible to define the approximate value of the turbine diameter (Table 1).

Table 1 Values of the parameter k, for turbines with 3 and 4 screws

d/D	α=22°		α=26°			α=30°	
	S=1.0·D	S=1.0·D	S=0.8·D	S=1.2·D	S=1.2·D	S=1.0·D	S=0.8·D
0.3	0.331	0.335	0.274	0.287	0.286	0.246	0.245
0.4	0.350	0.378	0.285	0.317	0.323	0.262	0.271
0.5	0.345	0.380	0.281	0.317	0.343	0.319	0.287
0.6	0.315	0.351	-	0.300	0.327	-	0.273

The diameter of the Archimedean turbine can be estimated using the following formula:

$$D = \left(\frac{Q}{k \cdot n}\right)^{1/3} \tag{1}$$

where: Q - installed flow [m^3/s], n - rotational speed [s^{-1}].

The dimensions of the turbine can also be checked by using the following expressions:

$$n = \frac{0.85}{D^{2/3}},\ \mathrm{L} = \frac{\mathrm{H}}{\sin(\alpha)},\ \mathrm{d} = \frac{L}{10}. \tag{2}$$

The data obtained in such a manner, coupled with the values of the installed flow and power of the turbine generator, are a very good basis for estimating the price of equipment and work at the hydroelectric power plant, but they are not values obtained from detailed calculations.

3. RESULTS AND DISCUSSION

3.1 Analysis of location I

The analysis of the considered locations required a solution that involves the application of one to three turbine aggregates (n=1÷3) at a site, where the AST have different installed flows (solutions I, II and III). The installed flow rate of the turbine aggregate was chosen based on the available net head fluctuation curve on the site, which is a function of the river flow rate. For the purpose of further analysis, a computer program was developed that enabled the calculation of all operating parameters of the hydropower plant (HPP).

Table 2 Hydro power plant data and annual production at location I

Hydro power plant data and annual production – Location I							
Q_{mean} (m^3/s)		Q_{95} (m^3/s)		Q_{95}/Q_{mean} (-)		QFP -fish pass (m^3/s)	
22.9		5.56		0.243		1.146	
Solution	Q_{HPPin} design flow (m^3/s)	Q_{HPPin}/Q_{mean}	Net head range (m)	Turbine efficiency (%)	Turbine start up flow Q_{suf} (m^3/s)	Maximum HPP power (kW)	Annual production (MWh)
number of turbines n=1							
I	2.5	0.109	1.37-1.89	86.5	0.375	36.95	279.54
II	3.5	0.152	1.46-1.89	86.5	0.525	51.71	360.93
III	4.5	0.196	1.73-1.89	86.5	0.675	66.17	334.04
number of turbines n =2							
I	5.0	0.218	1.37-1.89	86.5	0.375	73.52	551.45
II	7.0	0.304	1.46-1.89	86.5	0.525	101.9	662.47
III	9.0	0.393	1.73-1.89	86.5	0.675	129.68	527.24
number of turbines n =3							
I	7.5	0.327	1.37-1.89	86.5	0.375	109.18	761.86
II	10.5	0.456	1.46-1.89	86.5	0.525	148.93	861.04
III	13.5	0.589	1.73-1.89	86.5	0.675	188.40	604.38

Results related to the first location (on the Nišava River) are presented graphically (Fig. 7) and in tabular form (Table 2).

Fig. 7 shows a graphic representation of the operating curves for three different solutions of turbine aggregates, during the year.

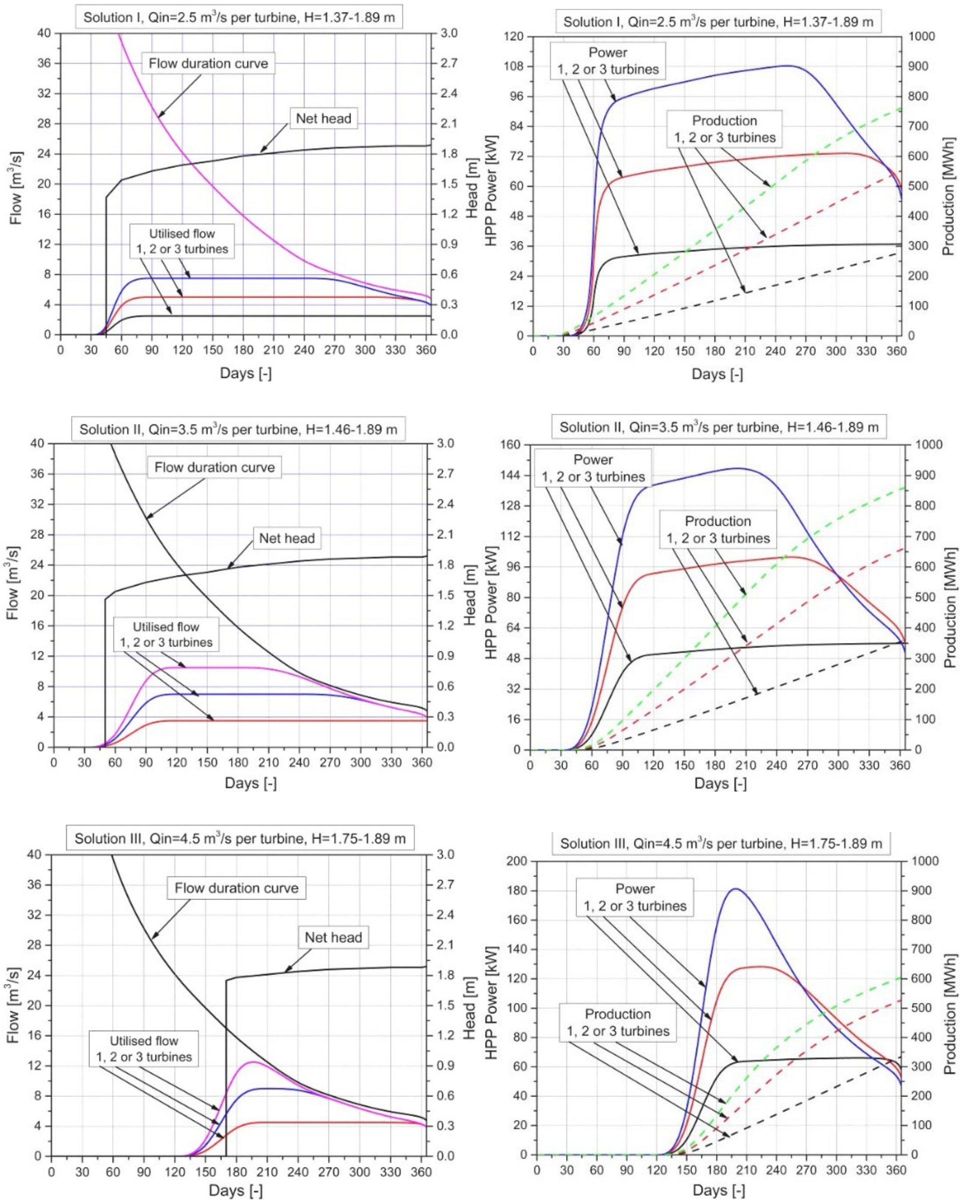

Fig. 7 Graphic representation of the operating curves for three different solutions of turbine aggregates, during the year

At location I, three different installed turbine flows (solutions I, II and III) were analyzed, and for each of these variants, number of turbines at the location can be one, two or three (n=1, 2 or 3). According to the results of the turbine aggregate operation analysis, i.e. different solutions of turbine aggregates at location I, economic analysis of the small hydropower plant can also be carried out. The result of an economic analysis for location I is presented in Table 3, giving a comparative overview of the prices for all variants (three different solutions) as well as the investment payback time.

Table 3 Economic analysis of the HPP with Archimedean screw turbine at location I

Economic analysis – Location I					
Solution	Turbine, gearbox, generator, sluice gates	Civil works, access, installation, commissioning	Control and ancillaries, logging, monitoring, electrical connection	Gross Revenue (Euro)	Simple Payback (years)
number of turbines n=1					
I	108,256 €	128,130 €	38,664 €	34,663 €	8.85
II	159,440 €	140,488 €	55,091 €	44,755 €	8.63
III	215,622 €	150,665 €	71,954 €	41,422 €	11.59
number of turbines n =2					
I	216,511 €	206,021 €	56,358 €	68,380 €	7.39
II	319,885 €	227,029 €	80,825 €	82,147 €	7.99
III	431,243 €	244,331 €	106,163 €	65,378 €	12.65
number of turbines n =3					
I	324,767 €	266,293 €	74,052 €	94,472 €	7.32
II	479,827 €	294,097 €	106,559 €	106,769 €	8.53
III	644,373 €	316,997 €	140,372 €	74,943 €	15.44

3.2 Analysis of location II

Results related to location II (Vlasina) are presented in Fig. 8 and Table 4.

Table 4 Hydro power plant data and annual production at location II

Hydro power plant data and annual production – Location II						
Q_{mean} (m^3/s)		Q_{95} (m^3/s)		Q_{95}/Q_{mean} (-)		QFP -fish pass (m^3/s)
22.9		5.56		0.243		1.146
Solution	Q_{HPPin} design flow (m^3/s)	Q_{HPPin}/Q_{mean}	Net head range (m)	Turbine efficiency (%)	Turbine start up flow Q_{suf} (m^3/s)	Maximum HPP power (kW)	Annual production (MWh)
number of turbines n=1							
I	2.5	0.3125	1.93-2.59	86.5	0.375	50.26	400.52
II	4.0	0.50	1.93-2.59	86.5	0.60	79.83	557.70
III	5.5	0.687	1.95-2.59	86.5	0.825	109.36	681.29
IV	7.0	0.875	2.12-2.59		1.05	138.15	757.26
number of turbines n =2							
I	5.0	0.625	1.93-2.59	86.5	0.75	99.42	651.46
II	6.5	0.8125	1.93-2.59	86.5	0.975	128.28	763.38
III	8.0	1.0	1.93-2.59	86.5	1.20	156.68	847.79

At location II, four different installed turbine flows (solutions I to IV) were analyzed with one turbine aggregate (n=1).

Also, three different installed flow rates were analyzed (solutions I to III), for the case of two identical turbines installation (n=2).

Fig. 8 shows graphic representations of the operating curves for the three different solutions of Archimedean screw aggregates during a single year period, where the head and power curves, for different turbine flow rates are analyzed.

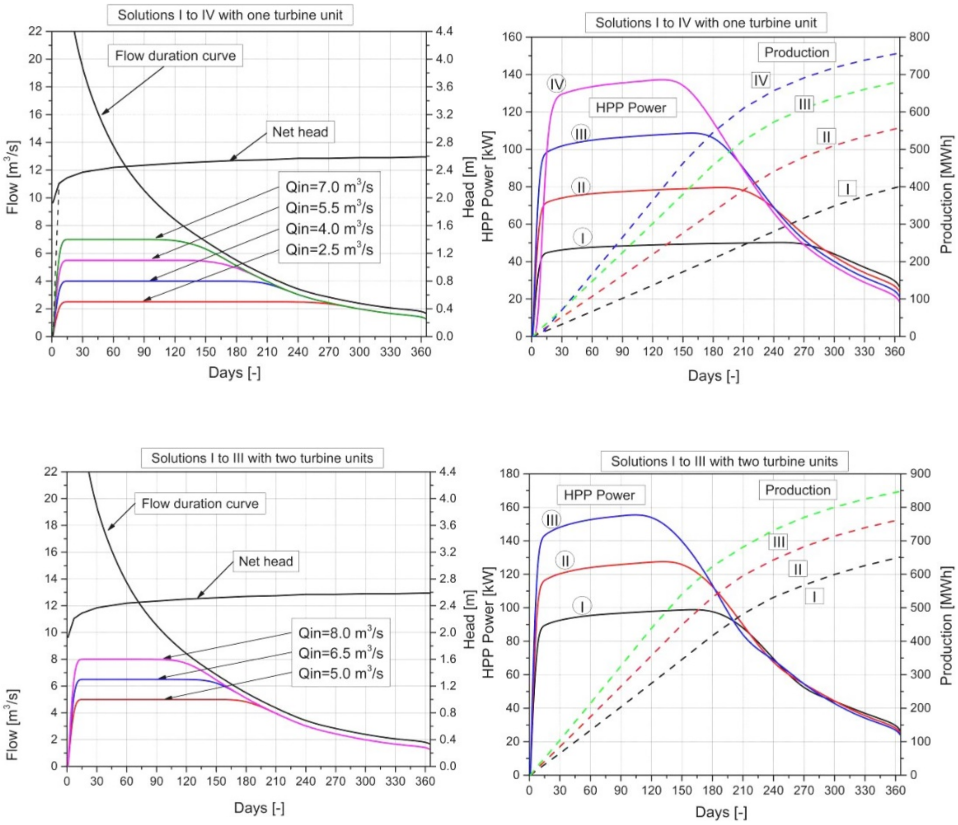

Fig. 8 Graphic representation of the operating curves for the three different solutions of turbine aggregates, during the year

In the same way as in the previous location, economic analysis for location II was performed.

The results obtained are presented in Table 5, showing a comparative overview of the prices for all solutions at location II and the investment payback time.

Such economic analysis is essential for the selection of an appropriate optimal turbine aggregate.

Table 5 Economic analysis of the HPP with Archimedean screw turbine at location II

Economic analysis – Location II					
Solution	Turbine, gearbox, generator, sluice gates	Civil works, access, installation, commissioning	Control and ancillaries, logging, monitoring, electrical connection	Gross Revenue (Euro)	Simple Payback (years)
number of turbines n=1					
I	146,126 €	128,130 €	52,984 €	49,665 €	7.10
II	251,673 €	145,789 €	86,979 €	69,155 €	7.39
III	368,244 €	159,427 €	122,261 €	84,480 €	8.04
IV	494,977 €	170,762 €	158,698 €	93,900 €	9.13
number of turbines n =2					
I	292,252 €	206,021 €	77,231 €	80,781 €	7.46
II	393,693 €	222,198 €	102,261 €	94,660 €	7.89
III	501,792 €	236,042 €	127,979 €	105,127 €	8.53

3.3 Return on investment (ROI)

In order to obtain a more detailed analysis of the economic feasibility of certain analyzed solutions, an analysis of long-term return on investment (ROI) was conducted.

The graphs in Fig. 9 show the analysis of both locations where the analyzed solutions are indicated on the x-axis while the y-axis indicates ROI for the period of 12, 18 and 24 years.

The first period of 12 years was taken as a reference because in Serbia this is a period of the privileged status, i.e. feed-in tariff for renewable energy sources.

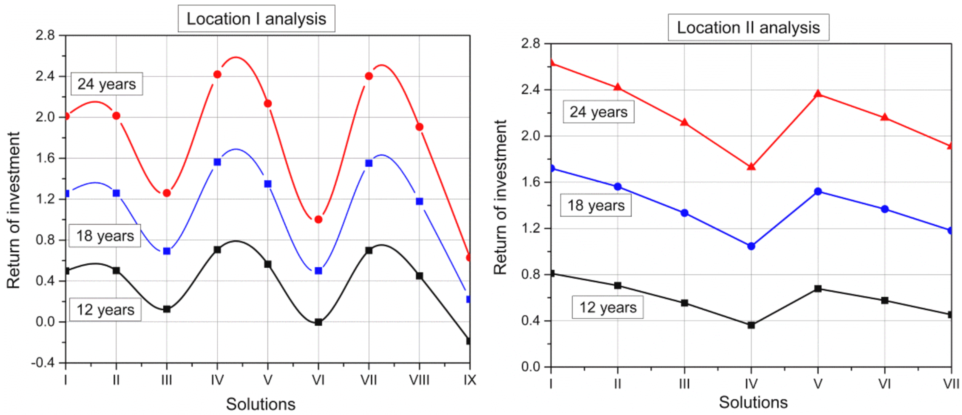

Fig. 9 Return on investment

For location I, solutions I to III are with single but changing turbine unit (different installed flow), solutions IV to VI are with two turbine units, and solutions VII to IX are with three turbine units.

For location II, solutions I to IV are with single but changing turbine units (different installed flow), and solutions V to VII are with two turbine units.

Parameter analysis of SHP was carried out by calculating net present cost of the project by computing capacity factor, power, number of hydro turbines, turnkey cost and subsidizing impact. The price of electricity was taken as the present feed-in tariff in Serbia, where hydro facilities can count on purchases of 12.6 € cents per kilowatt for systems of up to 200 kW. When analyzing the total investment for equipment and regulation, the prices of European equipment manufacturers were taken, while the prices of domestic companies were taken for construction works. Since the average electricity price in Europe is higher than the aforementioned feed-in tariff in Serbia, and the escalation of electricity prices has not been taken into account, one can expect better economic feasibility and ROI of small head projects with AST in the near future.

4. Conclusion

Based on the obtained results, the following conclusions can be made. For locations with extremely low heads and larger amounts of water (as on location I), it is a more cost-effective solution to choose a larger number of Archimedean turbines of smaller capacity, which can work with extremely low net heads. A long-term solution with a higher number of same aggregates gives the best results both from the energy and economic point of view. For another location with a somewhat higher turbine head, but with smaller available flows (as on location II), the best solution is to choose one Archimedean screw turbine from an economic point of view. In order to make better use of the available energy potential, it is possible to choose a solution with the maximum of two AST.

The conclusion drawn from both analyses is that the shape of flow duration curve and net head change significantly influence the choice of the optimal solution for sites with a small hydraulic head. As it is shown in the given example for the two cases, it is necessary to perform the presented analyses for each location individually.

In-stream hydropower scheme with AST is a highly recommended solution for low head locations. This solution is in line with the European regulations (EIA and WFD), and enables the use of hydroelectric potential which is difficult to use otherwise and in an economically viable way. Finally, but equally importantly, solutions with AST for utilization of small hydraulic heads have no negative impacts on the environment.

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