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Research paper

INFLUENCE ANALYSIS OF SELECTED TURBINE TO WORKING CHARACTERISTICS OF SMALL HYDRO POWER PLANTS

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Abstract: *Small Hydro Power Plants (SHPPs) represent a very important renewable energy source and is becoming more and more expensive in the world. Unfortunately, this is not the case in our country. The choice of turbine SHPP is an extremely complex task because it has a decisive influence on the performance characteristics of the SHPP (efficiency, impeller power, average annual production of electricity, impeller RPM, dimensions, price,...).*
In this paper, the methodology for selecting the SHPP turbine is defined based on the most important parameters. The methodology has been applied to the specific location located on the Mlava River, but it is most important that it can be applied at any other location. At the end of the paper, conclusions and directions for further research is given.

Key words: *small hydro power plant, turbine selection, turbine characteristics working analysis*

1. INTRODUCTION

One of the efficient, but still insufficiently exploited renewable energy sources are SHPPs. There is no exact boundary in the world that defines the category of small hydropower plants. Upper limit of SHPPs is influenced by many parameters, such as: level of country economic development, electricity greed development, available and usable water resources, natural conditions of topography and geology, level of industry development, richness in coal, oil derivatives and other energy raw materials, size and area of the settlement, or population density... Some countries such as Portugal, Spain, Ireland, Greece and Belgium have accepted 10 MW as the upper limit of the installed capacity. In Italy, the limit is 3 MW, in Sweden 1.5 MW, in France 8 MW, in India 15 MW. In countries with large hydropower plants and high consumption, such as Canada and the United States, a SHPP means a plant below 30 MW [1]. However, the upper limit of up to 10 MW is increasingly being accepted in Europe and the European Small Hydropower Association (ESHA). According to the existing Law on Energy, in Serbia under small hydroelectric power plant is meant an energy facility for electricity generation of installed power up to 10 MW [2].
The construction of a small hydropower plant is not a simple assignment, because a large number of businesses, engineering, financial, legal and administrative aspects should be taken into account in different stages of development, starting from the construction site selection to the operational phase of the SHPP. In the construction of SHPP essential components are machine and electrical equipment, whose construction depends on the type of hydroelectric power plant, local conditions, accessibility of building materials, etc.
The viable use of hydropower in the Republic of Serbia is reduced to the construction of small storage and flow hydroelectric power plants. These power plants are most commonly comprised of dams, gutters, waterways, drains, overpasses, channels, pressure pipelines and machine buildings [1]. The machine building of SHPP is reduced practically to only one room with an aggregate. The small hydro power plant's aggregate consists of turbine, generator, control cabinet and regulator.
Certainly, the key element of the SHPP is the turbine. The most commonly used are Pelton, Turgo, Banks, Francesis, Kaplan and tubular turbines.
The choice of a turbine is not a simple and clearly defined process. It is based on recommendations from literature, manufacturer recommendations, previous experiences, etc. On the other hand, the choice of the turbine significantly influences the performance characteristics of the SHPP, such as: turbine shaft power, turbine utilization rate, average annual production of electricity, turbine speed, turbine impeller dimensions, production costs, ...
An impact analysis of selected turbine type was performed in the framework of this paper for one SHPP in Serbia.

2. BASE CHARACTERISTICS OF ANALYZED SHPP

The location for the construction of SHPP is located on the river Mlava, upstream from Ribare, and downstream of the bridge in the settlement Izvarica (Figure 1).
The hydrological analysis of the watercourse is the most important basis for the proper design of the project. Based on previously mentioned criterias selection of all components of the small hydroelectric power plant is carried out.
Hydrological data obtained by measuring at the adopted location have the following values:
- Area of the basin F_{sl}=408,8 km^2;
- Average precipitation P_{sr}=800 mm;
- Average flow Q_{sr}=4,29 m^3/s;
- Annual inflow W_{god}=135,21 hm^3,
- Specific drain 10,5 l/sec/km^2;

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- Evacuation large water level Q_{ev}= 550 m^3/s;
- Minimum flow Q_{ec}≈0,4 m^3/s;
- Maximum installed flow Q_t=6,44 m^3/s;
- Gross drop H_b=11 m [3].

Fig.1. Location position [4]

Based on the field topography and technical data, a schematic diagram of the hydroelectric power plant can be adopted, Figure 2.

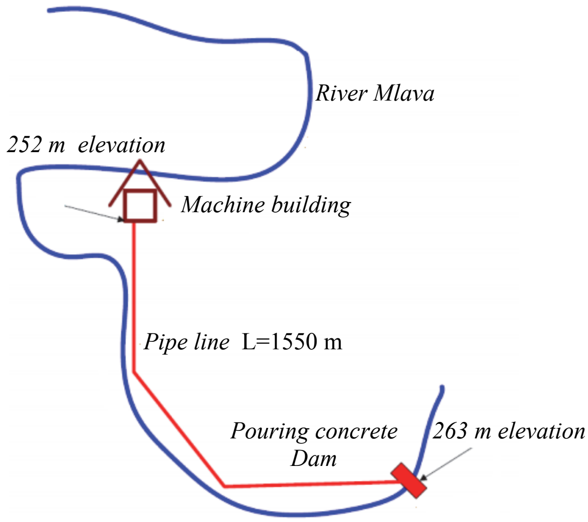


Fig.2. SHPP schematic view [4]

3. BASIC CRITERIA FOR TURBINE SELECTION

The choice of turbines for SHPP depends on the available net drop and flow, the price of the plant, the number of generators, maintenance requirements and other criteria. Therefore, the hydro turbine should be selected to suit the conditions that occur at a specific location, with the aim of achieving the expected high efficiency. Different falls and available flows occur in different locations, and the number of flow and fall combinations is practically equal to the number of locations, and only by chance the same turbine, with all of the same dimensions and characteristics, can be efficiently used in multiple locations.

In order to compare the basic parameters of different turbines, the same net drop H_n = 10,255 m will be used and the maximum flow Q_t = 6,44 m^3/s, in order to select the most suitable turbine for the aforementioned location.

The choice of the type of turbine is made based on recommendations from the literature in the function of the net drop of H_n and the turbine flow Q_t. The available literature contains different types of recommendations (most often in the form of diagrams), so it must be taken into account whether the recommendations refer to the selection of a turbine of a pico, micro, mini, small or large hydroelectric power plant. In addition, on such diagrams there are areas of overlap, so several types of turbines can be selected for the same location. Therefore, for the further selection of the turbine, other factors are taken into account (efficiency, turbine power, costs, etc.).

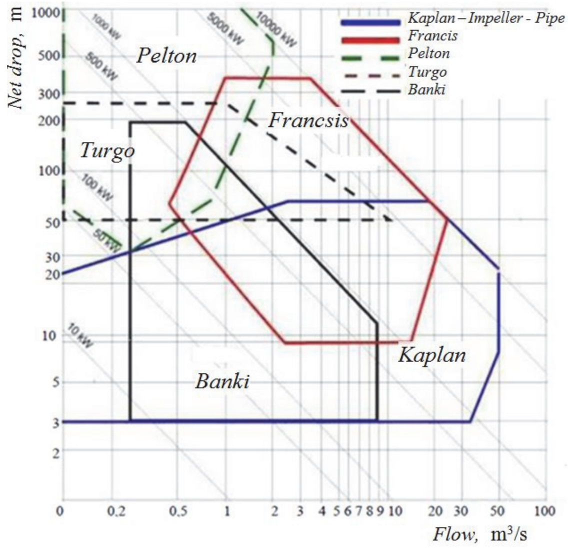


Fig.3. Usage filed of different turbines related to flow and net drop [5]

For the chosen location (Figure 3) Francis, Kaplan or Banki turbine can be used.

These three different types of turbines has a different efficiency, Figure 4.

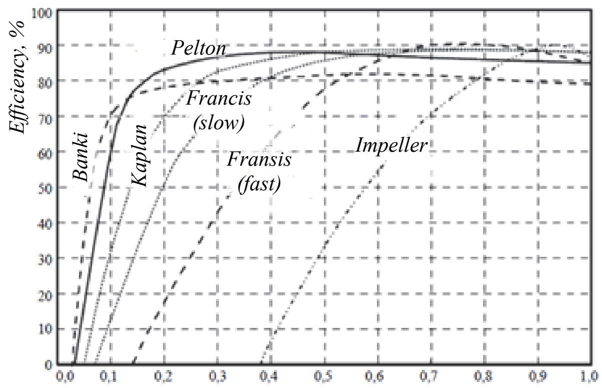


Fig.4. Efficiency of different types of turbines in relation to decreased flow [5]

For the relation of maximum and average flow Q_{sr} / Q_t = 0,666, efficiencies are show in figure 5.

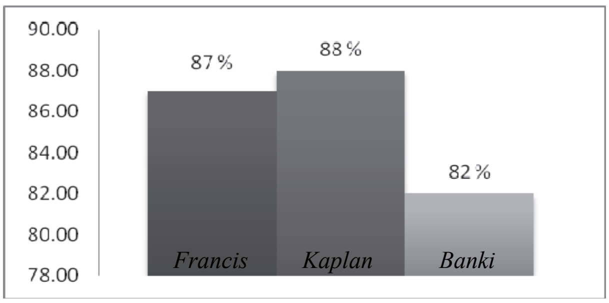


Fig.5. Efficiencies for the different types of turbines for the selected location

Power on the impeller shaft P_t can be calculated by following expression [6]:

$$P_t = \eta_t \cdot 9{,}81 \cdot Q_t \cdot H_n \text{ kW} \quad (1)$$

where are:

Q_t m^3/s - turbine flow,

H_n m - net drop,

η_T - turbine efficiency.

The calculated power for different types of turbines is given in Fig 6.

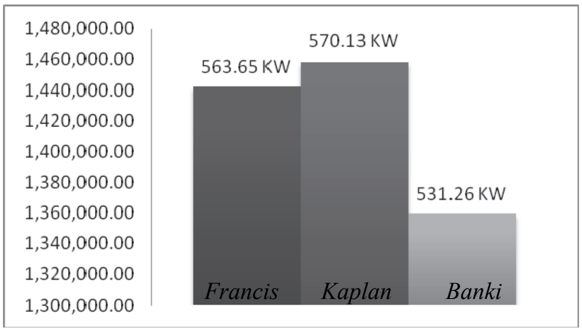


Fig.6. Power of the impeller shaft P_t for different turbine types for the selected location

Turbine efficiency η_t also affects the average annual electricity production E_{yr}:

$$E_{yr} = \frac{P_G}{\cos\phi} \cdot T = \frac{\eta_g \cdot \eta_t \cdot 9{,}81 \cdot Q_{sr} \cdot H_n}{\cos\phi} \cdot T \text{ kWh} \quad (2)$$

where are:

$\eta_g = 0{,}96$ - the efficiency of synchronous generator with six poles pairs,

$T = 4000$ h – annual working hours,

$\phi = 0{,}80$ - a nominal power factor that determines the ability of the generator to produce reactive power.

Figure 6 shows the values of average annual electricity production for analyzed turbines.

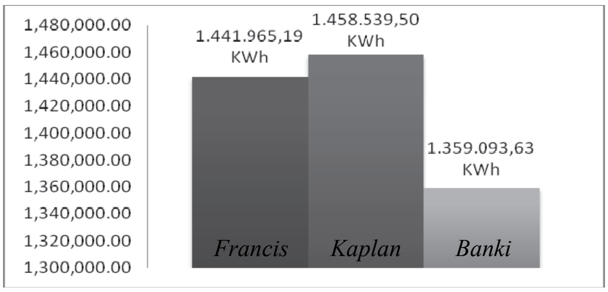


Fig.7. Average annual electricity generation E_{yr} for different turbine types for the selected location

Hydro turbines are very expensive machines, and before the construction of the turbine itself, the laboratory models are tested. These models are based on similarity theory based on parameters such as: net drop, flow, water density, speed, earth acceleration, etc. One of the important parameters for testing the turbine is the dimensional specific n_{QE} RPM. It is defined by the equation [6]:

$$n_{QE} = \frac{n_t \cdot \sqrt{Q}}{60 \cdot E^{3/4}} \quad (3)$$

where are:

n_t min^{-1} – turbine RPM,

$E = H_n \cdot g$ J/Kg – specific hydraulics energy.

Also, the specific n_{QE} RPM can also be determined from the relationship of similarity between the model and the actual turbine. All simulation rules are strictly defined by international standards IEC 60193 and 60041 [6].

Based on the large number of static tests on a large number of models, the correlation between the specific number of rotations and the net drop for each type of turbine was established [6,7], Table 1. These values should not be considered as final because they are relatively variable due to further testing. Also, these static formulas should be used only for preliminary studies, since only manufacturers can give the actual dimensions and characteristics of the turbine.

Tab. 1. Specific RPM for different turbine types

Turbine type	Preliminary equation
Pelton turbine with one nozzle	$n_{QE} = \frac{0{,}0859}{H_n^{0{,}243}}$
Francis turbine	$n_{QE} = \frac{1{,}924}{H_n^{0{,}512}}$
Kaplan turbine	$n_{QE} = \frac{2{,}294}{H_n^{0{,}486}}$
Banki turbine	$n_{QE} = \frac{1{,}107}{H_n^{0{,}2998}}$
Impeller turbine	$n_{QE} = \frac{2{,}716}{H_n^{0{,}5}}$
Pipe turbine	$n_{QE} = \frac{1{,}528}{H_n^{0{,}2837}}$

The calculated values of the specific n_{QE} RPM for different turbine types are given in Figure 8.

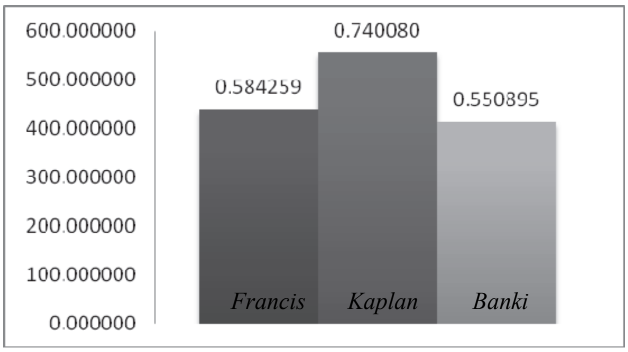


Fig.8. Specific n_{QE} RPM for different turbine types for the selected location

When the specific n_{QE} RPM is known, based on expression (3), it is easy to calculate the turbine speed n_t. The calculated values are shown in Figure 9.

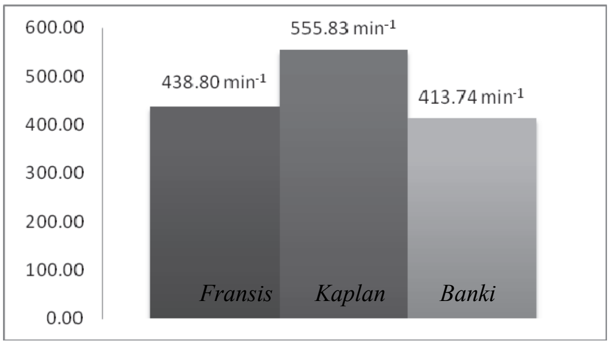
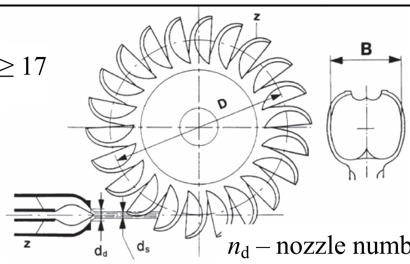
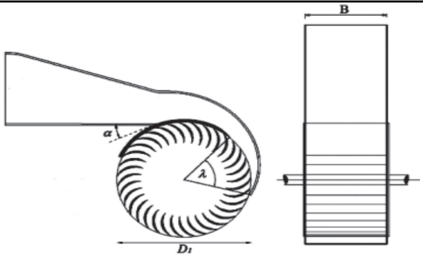
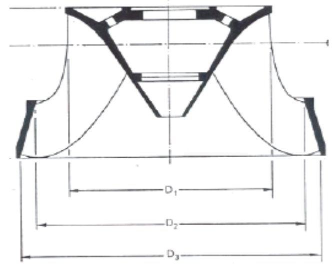
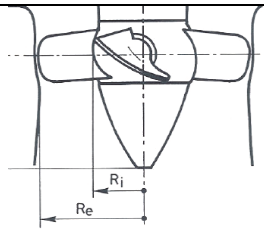


Fig.9. Impeller RPM n_t for different turbine types for the selected location

Also, by knowing the specific number of n_{QE} RPM, the number of turbine rotations n_t, and based on the expressions obtained by the tests on the scaled models, the basic dimensions of the turbine impellers can be preliminarily determined (Table 2) [6,7,8,9]. The calculated values of the impeller dimensions are given in Figure 10.

Tab. 2. Preliminary values of the basic impeller dimensions

Turbine type	Preliminary equation and scheme
Pelton turbine	z ≥ 17  n_d – nozzle number $D = 0,68 \cdot \frac{\sqrt{H_n}}{n_t}$ $B = 1,68 \cdot \sqrt{\frac{Q}{n_d} \cdot \frac{1}{\sqrt{H_n}}}$ $d_s = 1,178 \cdot \sqrt{\frac{Q}{n_d} \cdot \frac{1}{\sqrt{g \cdot H_n}}}$
Banki turbine	 $D_1 = 40 \cdot \frac{\sqrt{H_n}}{n_t}$ $B = \frac{Q_t \cdot n_t}{50 \cdot H_n}$
Impeller turbine	$D = 4,511 \cdot \left(\frac{Q_t}{n_t}\right)^{0,3393}$
Pipe turbine	$D = 4,181 \cdot \left(\frac{Q_t}{n_t}\right)^{1,4233}$
Francis turbine	 $D_3 = 84,5 \cdot \left(0,31 + 2,488 \cdot n_{QE}\right) \cdot \frac{\sqrt{H_n}}{n_t}$ $D_1 = \left(0,4 + \frac{0,095}{n_{QE}}\right) \cdot D_3$ $D_2 = \frac{D_3}{0,96 + 0,3781 \cdot n_{QE}}$
Kaplan turbine	 $D_e = 84,5 \cdot \left(0,79 + 1,602 \cdot n_{QE}\right) \cdot \frac{\sqrt{H_n}}{n_t}$ $D_i = \left(0,25 + \frac{0,0951}{n_{QE}}\right) \cdot D_e$

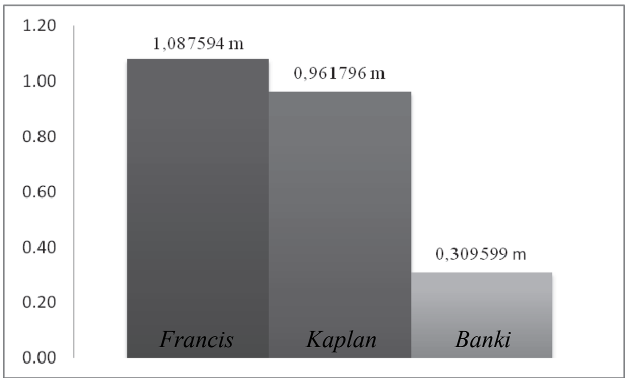


Fig.10. Different turbine impeller diameters for the selected location

A very important parameter in choosing a turbine is its price. In the literature, it is difficult to find a reliable expression for calculating costs that take into account the type of turbine, [10, 11, 12, 13,14]. Most of these preliminary expressions are in the function of the net drop of H_n and the installed power of P_t. Since each turbine has a different efficiency η, the turbine prices differ for the minimum difference due to the different value of efficiency η_t [15,16]. Only *Papantonis* [17] estimates the costs of Kaplan, Frances and Pelton turbines based on data analysis from different manufacturers.

The turbine price is influenced by impeller manufacturing, the material, the enclosure of the impeller, the conducting apparatus, the introductory chamber, the generator mounting, etc., so there are certain bands. To a certain size, depending on the manufacturer, the Kaplan and Francis turbine impellers are one-piece castings. For larger diameters, the impeller is made by welding blades the hub. In cases of very large duty impellers, the production is made from parts.

Costs Kaplan turbine C_K are defined for two flows Q_t in m^3/s. For a range of 0.5 to 5 m^3/s, the turbine cost can be estimated based on the expression:

$$C_{K1} = 15000 \cdot (Q \cdot H)^{0,68}, €$$

or

$$C_{K1} = 3500 \cdot (KW)^{0,68}, €$$

For flow range from 5 to 30 m^3/s, costs are calculated by using the expression:

$$C_{K2} = 46000 \cdot (Q \cdot H)^{0,35}, €$$

or

$$C_{K2} = 14000 \cdot (KW)^{0,35}, €$$

Costs of the Francis turbine C_F are defined in 3 flow ranges Q_t in m^3/s. For the flow range from 0,5 do 2,5 m^3/s, costs can be estimated by expression:

$$C_{F1} = 142000 \cdot \left(Q \cdot H^{0,5}\right)^{0,07}, €$$

or

$$C_{F1} = 122000 \cdot \left(KW / H^{0,5}\right)^{0,07}, €$$

For the higher flow range from 2,5 to 10 m^3/s it is used:

$$C_{F2} = 282000 \cdot \left(Q \cdot H^{0,5}\right)^{0,11}, €$$

or

$$C_{F2} = 223000 \cdot \left(KW / H^{0,5}\right)^{0,011}, €$$

For the flow range greater than 10 m^3/s, turbine cost can be estimated by following expression:

$$C_{F3} = 50000 \cdot \left(Q / H^{0,5}\right)^{0,52}, €$$

or

$$C_{F3} = 16500 \cdot \left(KW / H^{0,5}\right)^{0,52}, €$$

Pelton turbine costs can be calculated by expressions:

$$C_P = 8300 \cdot (Q \cdot H)^{0,54}, €$$

or

$$C_P = 2600 \cdot (KW)^{0,54}, €$$

However, for the production of the Pelton turbine, the costs remain generally the same [14].

The costs of Fransis and Kaplan turbines manufacturing are given in Figure 11.

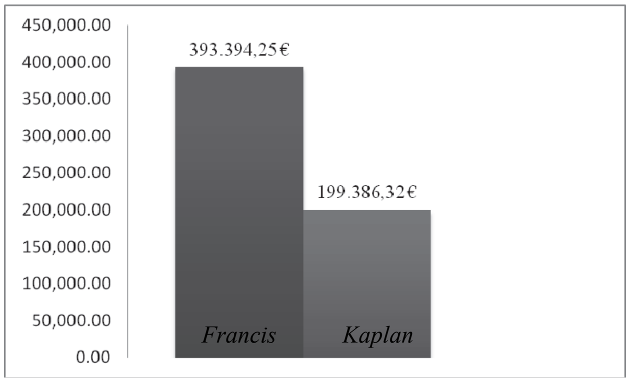


Fig.11. Turbine expenses for the selected location

4. CONCLUSION

Small hydroelectric power plants represent outstanding energy potential, but unfortunately, in our country it is still under-exploited. The performance characteristics of SHPP are significantly influenced by the choice of turbine, which is usually done based on recommendations from literature, manufacturer recommendations, previous experiences etc. However, the choice itself is not a simple and clearly defined procedure. The limits of the use of certain types of turbines are not clearly defined, so the overlap fields appear.

In this paper, an impact analysis of the selected turbine on the performance characteristics of the SHPP was performed for one specific location in Serbia (the Mlava River, upstream from Ribare) [18]. Three types of turbines (Francis, Kaplan and Banki) are analyzed and for each of them: efficiency, power on the impeller, average annual production of electricity, specific RPM, impeller RPM, dimensions and costs.

For the selected location, Kaplan's turbine has the highest efficiency, and thus the highest power. This also applies to the average annual electricity production, which affects the total annual SHPP revenue from the sale of electricity. Kaplan turbine has the highest number of revolutions for maximum flow in the rainy period. However, in a dry period, with a decrease in flow, the speed of the impeller decreases. The smallest diameter of the impeller has a Banki turbine, and Francis is the largest. It should be noted that, besides the small diameter of the impeller, the Banki turbine have is the longest. The dimensions of the impellers are very important because they directly affect the size of the machine building. Kaplan turbine is the most affordable and costs-friendly.

Having in mind all the above, the best solution for the selected particular location is Kaplan's turbine.

The procedure defined in this paper can also be applied to any other location.

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REFERENCES

[1] Ivanović D. (2007). *Hydroenergy,* Engineering Chamber of Montenegro, ISBN 978-9940-669-00-3, Podgorica

[2] *** (2014) http://www.eps.rs – Law on Energy, Official Gazette RS, br. 145/2014, Accessed on: *2018-03-17*

[3] *** (2009) http://mhe.mre.gov.rs/Katastar MHE/76-ribare zagubica-mlava.tif - Cadastre of small hydropower plants in the Republic of Serbia, 1991, Accessed on: 2018-03-18.

[4] Jovanović B., Parović M. (2010). Development of the project and preparation of project documentation for the small hydroelectric power plant Ribare, Jefferson Institute

[5] Fraenkel P., Paish O., Bokalders V., Harvey A., Brown A., Edwards R. (1991). *Micro-Hydro Power: A Guide for Development Workers,* Practical Action, ISBN 1853390291, London

[6] ESHA (1994). Guide book on how to develop a small hydro power plant - Part II, Available from: *https://energypedia.info/wiki/File:Part_2_guide_on_how_to_develop_a_small_hydropower_plant-_final-21.pdf*, Accessed on: 2018-03-18.

[7] C.S.K. Kpordze, C.C. Warnick, Civil Engineering Department, *Experience Curves For Modern Low-Head Hydroelectric Turbines*, Idaho Water and Energy Resources Research Insitute Univesity of Idaho, 1983.

[8] Chica Arrieta E. L., Flórez S. A., Sierra N. I. (2013). Application of CFD to the design of the runner of a propeller turbine for small hydroelectric power plants. *Revista Facultad de Ingeniería Universidad de Antioquia*, Vol. 2013, No. 69, (December 2013), pp.181-192, ISSN 0120-6230

[9] Nasir B. A. (2013). Design of High Efficiency Cross-Flow Turbine for Hydro-Power Plant. *International Journal of Engineering and Advanced Technology*, Vol. 2, No. 66, Februar 2013., pp. 308-311, ISSN 2249-8958

[10] Elbatrana A.H., Yaakobb O.B., Ahmedac Y.M., Shabaraa H.M. (2015). Operation, performance and economic analysis of low head micro-hydropower turbines for rural and remote areas: *A review. Renewable and Sustainable Energy Reviews*, Vol. 43, No.4, (November 2014), pp 40-50, ISSN 1364-0321

[11] Kittner N., Gheewala S.H., Kammen D.M. (2016). Energy return on investment (EROI) of mini-hydro and solar PV systems designed for a mini-grid. *Renewable Energy,* Vol. 99, No. 39, (July 2016), pp 410-419, ISSN 0960-1481

[12] Agugliaroa F. M., Tahera M., Sierraa A.Z.,Juaidia A., Montoyaa F.G. (2017). An overview of research and energy evolution for small hydropower in Europe. *Renewable and Sustainable Energy Reviews,* Vol. 75, No. 40, (November 2016), pp 476-489, ISSN 1364-0321

[13] Okot D. K. (2013). Review of small hydropower technology. *Renewable and Sustainable Energy Reviews,* Vol. 26, No. 39, (July 2013), pp 515-520, ISSN 1364-0321

[14] Aggidis G.A., Luchinskaya E., Rothschild R., Howard D.C. (2010). The costs of small-scale hydro power production: Impact on the development of existing potential. *Renewable Energy*, Vol. 35, Issue 12, (December 2010), pp 2632-2638, ISSN 0960-1481

[15] Gordon J.L., Penman A.C. (1979). Quick estimating techniques for small hydro potential. *Water Power and Dam Construction*, vol. 31, pp. 46–55, ISSN 0306-400X

[16] Matthias H.B., Doujak E., Angerer P. A. (2001). A contribution to ecological-economic aspects of hydro power plants. *Hydropower in new millennium*, Proceedings of the 4th international conference on hydropower development hydropower'01, Bergen, ISBN 90 5809 195 3

[17] Papantonis D. (2001). Small hydro power stations. Simeon

[18] Vasić M. (2017) Small hydro power plants, Master thesis, Faculty of Engineering, Kragujevac, Serbia