The techno-economic analysis of small hydropower plants installed parameters for three different mountain watercourses

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Abstract: In the last decade, hydrological data measurements, acquisitions and analyses of various Montenegrin mountain watercourses were carried out comprehensively. The data were analyzed respecting the hitherto known approaches in determining the small hydropower plant (SHPP) installed parameters. The SHPP installed parameter K_i is the ratio of the design flow and averaged perennial flow obtained from the flow duration curve at the planned water intake location. Due to the specifics of the rivers, it was not possible to define the installed parameters easily and clearly. For this reason, an improved multidisciplinary approach was conducted, which would lead to clearer general guidelines for quality and efficient determination of the SHPPs installed parameter respecting environmental requirements for each of them. The range of SHPP installed parameters is determined according to the technical and economic criteria. In this paper, the conclusions for three different SHPPs are presented comparing the calculated results and in-situ ones.

Keywords: small hydropower plant, design flow, installed capacity, techno-economic parameters.

1. INTRODUCTION

The small hydropower plant (SHPP) with an installed capacity of up to 10 MW is one of the most cost-effective energy technologies on a small scale due to its predictable energy characteristics, long-term reliability and reduced environmental effects [1]. The optimum design of SHPP should provide optimum net present value (NPV) taking into consideration technical conditions and tariff of electric energy during the lifetime of the SHPP project [2]. The proper choice of the optimum SHPP design flow is the fundamental goal for maximizing both the cost-effectiveness of the investment and the hydro energy utilization of water resources [3]. Up to date, there has been no straightforward way to determine the design flow for SHPP. Due to this fact, an improved multidisciplinary approach was developed, which would lead to clearer general guidelines for efficient determination of the SHPPs installed parameter respecting environmental requirements for each of them [4]. Karlis and Papadopoulos [5] developed a numerical model for the systematic assessment of the technical feasibility and economic viability of SHPPs. They pointed out that NPV and internal rate of return (IRR) are, among the other economic factors, the most used ones in the field of hydropower. Montanari [6] presented a method based on the use of NPV which is calculated using design flow, net head and hydrology characteristics from the location investigated. Kaldellis et al. [7] presented the study on the systematic investigation of the techno-economic viability of SHPPs. It was shown that the IRR value of SHPP installation is higher than 18% for most cases and that the IRR value reaches its maximum after 10 to 15 years of plant operation. Santolin et al. [8] took into consideration seven technical and economical parameters, the annual energy production, NPV and IRR among the others, in order to make a proper capacity sizing of SHPP. They concluded that simultaneous analysis of technical and economic aspects can lead to optimum design based on the desired performance, profitability and feasibility of the plant. Mishra et al. [9] concluded that net head and installed capacity are usually used as cost-influencing parameters for cost determination of SHPPs, and advised that more parameters, such as flow, turbine speed, runner diameter and setting of the turbine, should be used for improving cost correlations. Barelli et al. [10] proposed a design approach for SHPPs that was applied to three torrential rivers in Italy and optimum design flow was found out for the cases investigated.

The main aim of this paper is to contribute to the comprehensiveness of the analysis of the design flow determination in SHPPs using methodology developed by Vilotijević et al. [4] where their detailed description is given.

The process of the new SHPPs development campaign in Montenegro began with the adoption of the Small Hydropower Development Strategy in 2006 [11]. During 2010 and 2011, flows on 65 small watercourses were measured under the project named the Registry of Small Rivers and Potential Locations of SHPPs at Municipality Level for Central and Northern Montenegro, and relevant flow duration curves (FDCs) have been obtained [12]. This Registry was enhanced during 2018 and 2019 [13] and obtained data can serve as input for the design of SHPPs.

2. METHODOLOGY

In this paper, 3 (three) small rivers on the territory of Montenegro, where small hydropower plants with capacity below 1 MW were already designed, have been investigated. Flow duration curves with determined averaged perennial flow for each river are known [12,13]. Based on hydrology data, the ecological flow is determined, i.e. the minimum amount of water that must remain in the river in order to preserve the natural balance of aquatic ecosystems and ecosystems related to water [14].
The SHPP installed parameter is defined as the ratio of the design flow and averaged perennial flow according to the following equation,

$$K_i = \frac{Q_d}{Q_{av}} . \quad (1)$$

According to the rules for calculating the purchase price of energy from the SHPPs [15], the incentive energy prices are determined depending on the capacity at the plant's threshold (P_{SHPP}) in the manner defined in Table 1. It should be noted that SHPPs with capacity below 1 MW and above 8 MW have constant values of incentive price.

Table 1. Electricity prices depending on the capacity of the power plant [14]

Hydro power plant capacity [MW]	**Incentive price [c€/kWh]**
$P_{SHPP} < 1$ MW	10.44
$1 \leq P_{SHPP} < 3$ MW	$10.44 - 0.7 \cdot P_{SHPP}$
$3 \leq P_{SHPP} < 5$ MW	$8.87 - 0.24 \cdot P_{SHPP}$
$5 \leq P_{SHPP} < 8$ MW	$8.35 - 0.18 \cdot P_{SHPP}$
$8 \leq P_{SHPP} \leq 10$ MW	6.8

With the increase of capacity on the threshold of the power plant, the incentive price decreases from the maximum value of 10.44 c€/kWh for power plants with a capacity less than 1 MW to the value of 6.8 c€/kWh for power plants with capacity larger than 8 MW. The total decrease in the incentive price with an increase in capacity at the power plant threshold is about 35%. By varying the design flow $Q_d = K_i \cdot Q_{av} = \{1.0 \div 2.5\} \cdot Q_{av}$, capacity, annual energy production, gross income, NPV, IRR and PB are calculated for every design flow [4, 16], where Q_{av} is averaged perennial flow. The net present value (NPV) represents the value of the net cash flow during the exploitation period of SHPP discounted back to its present value and it is calculated according to the next equation [8,17],

$$NPV = \sum_{t=1}^{T} \frac{R(t) - C(t)}{(1+d)^t} \quad (3)$$

where is, R – annual net income of the SHPP, C – annual costs of the SHPP (in the first year this is total investment costs of the project and in all the following years this is the operation and maintenance costs), d – discount rate (d = 8% for Montenegro), T – the lifetime of the project, equal to concession period of 30 years. The total investment costs of the plant are computed as the sum of the cost of the different parts and components i.e. civil works including penstock, electro-mechanical and hydro-mechanical equipment, connection to the electrical network, project design and supervision.

The internal rate of return (IRR) is the discount rate that reduces the present value of the net project cash flow to zero in a discounted cash flow analysis and can be calculated from eq. (2), as the value of d corresponding to a NPV = 0 [8,17].

The payback period (PB) is the period of time it takes to recover the cost of an investment and it is obtained by dividing total investment costs with a net annual income of SHPP. The developed methodology is applied to proposed rivers and obtained results are compared with the in-situ ones.

3. RESULTS AND DISCUSSION

Three investigated plants with their basic parameters are shown in Tables 2, 3 and 4. Table 2 shows calculated and designed maximum annual electricity production and income as well as main designed parameters Q_d, H_n and P_{SHPP}, where H_n is the net head. Table 3 shows the calculated and designed economic parameters IRR, NPV. Table 4 shows calculated values of K_i depending on applied techno-economic criteria. In addition, designed K_i is also presented. It can be observed that the value of K_i = 2.5 gives the maximum annual electricity production and the maximum income. This is not the case for NPV and IRR where the installed parameter range is $K_i = \{1.7 \div 2.5\}$. Therefore, it can be noticed that if the annual production and annual income are considered as a decision parameter, a practically unambiguous value of K_i = 2.5 is obtained for the considered power plants. The situation is quite different if economic parameters are considered as decision criteria. The payback period corresponds to the maximum value of IRR and its range is very wide i.e. PB = {5.4÷14.4} years. For plants investigated, the range of K_i is narrowed from initially $K_i = \{1.0 \div 2.5\}$ to $K_i = \{1.7 \div 2.5\}$. Maximum values of IRR and NPV are obtained for Umski SHPP and they are IRR = 18.94% and NPV = 1,466.40 kEUR.

Table 2. Maximum annual production and income (* - constructed plant parameters)

SHPP Name	Annual electricity production [GWh]	Annual income [kEUR]	Q_d [m³/s] (*)	H_n [m] (*)	P_{SHPP} [kW] (*)	Annual electricity production [GWh] (*)	Annual income [kEUR] (*)
Rmuš	1.59	166.8	0.178	186.60	293.26	1.33	138.40
Hridska	2.18	228.0	0.426	180.11	601.89	1.69	177.02

Umski	3.01	314.4	0.601	140.67	746.46	2.25	232.36

Table 3. Internal rate of return, net present value, payback period (*- constructed plant parameters)

SHPP Name	IRR [%]	NPV [kEUR]	PB for max IRR [year]	IRR [%] (*)	NPV [kEUR] (*)	PB for max IRR [year] (*)
Rmuš	6.38	-225.1	14.4	5.52	-291.97	15.7
Hridska	11.63	507.9	8.7	10.18	248.49	9.7
Umski	18.94	1,466.4	5.4	17.26	976.06	6.01

It should be noticed that Rmuš SHPP and Hridska SHPP have the same value of the SHPP installed parameter for all considered parameters and Umski SHPP has all three different values of the SHPP installed parameter (Table 4).

Table 4. Values of SHPP installed parameter (*- designed values of SHPP installed parameter on these constructed plants)

SHPP Name	K_i for max electricity production and max income	K_i for max IRR [%]	K_i for max NPV	PB for max IRR [year]	K_i (*)
Rmuš	2.5	2.5	2.5	14.4	1.1
Hridska	2.5	2.5	2.5	8.7	1.5
Umski	2.5	1.7	2.3	5.4	1.8

Rmuš SHPP has the K_i = 2.5 obtained from all parameters which means that for this plant maximum value of K_i gives the best performance from both technical and economical points of view. Rmuš SHPP started with a capacity of 293.2 kW for K_i = 1.0 and finished with 742.7 kW for K_i = 2.5 having a constant incentive price for all capacities (Table 1). Due to this fact, annual electricity production and annual income have permanent and the same behaviour rise (Fig. 1). Fig. 2 shows the change in NPV, IRR and PB as a function of K_i. NPV and IRR continuously increase from minimum to maximum value with NPV having slightly sharper growth. On the other hand, as expected, PB decreases with the increase in these parameters. The total investment is 1.50 mEUR and the payback period is PB = 14.4 years.
Designed values of SHPP installed parameter on constructed Rmuš SHPP is K_i =1.1. For these values annual electricity production is 1.33 GWh, annual income is 138.40 kEUR, NPV is -291.97 kEUR, IRR is 1.7% and PB is 15.7 years. It is interesting to note that NPV has negative values for all ranges of K_i and Rmuš SHPP is also designed with negative NPV which is a very unusual decision in business practice. It seems that this plant is designed and constructed without a serious approach or with wrong input data.

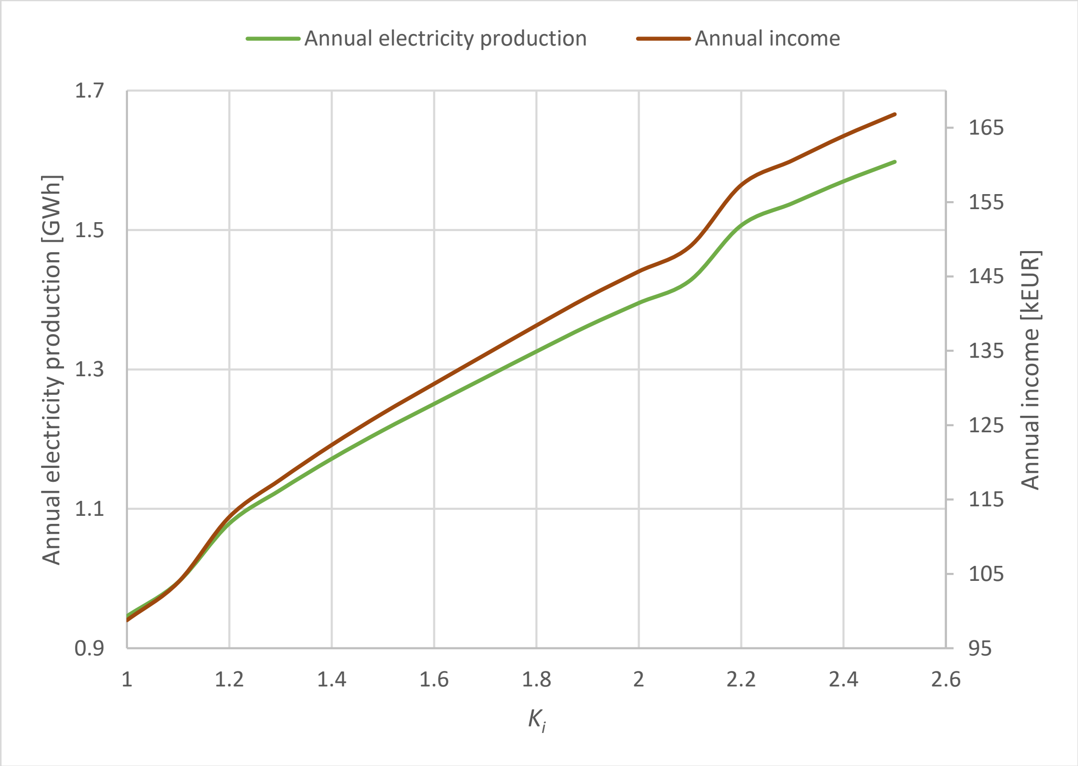

Fig. 1. Annual electricity production and income – Rmuš SHPP

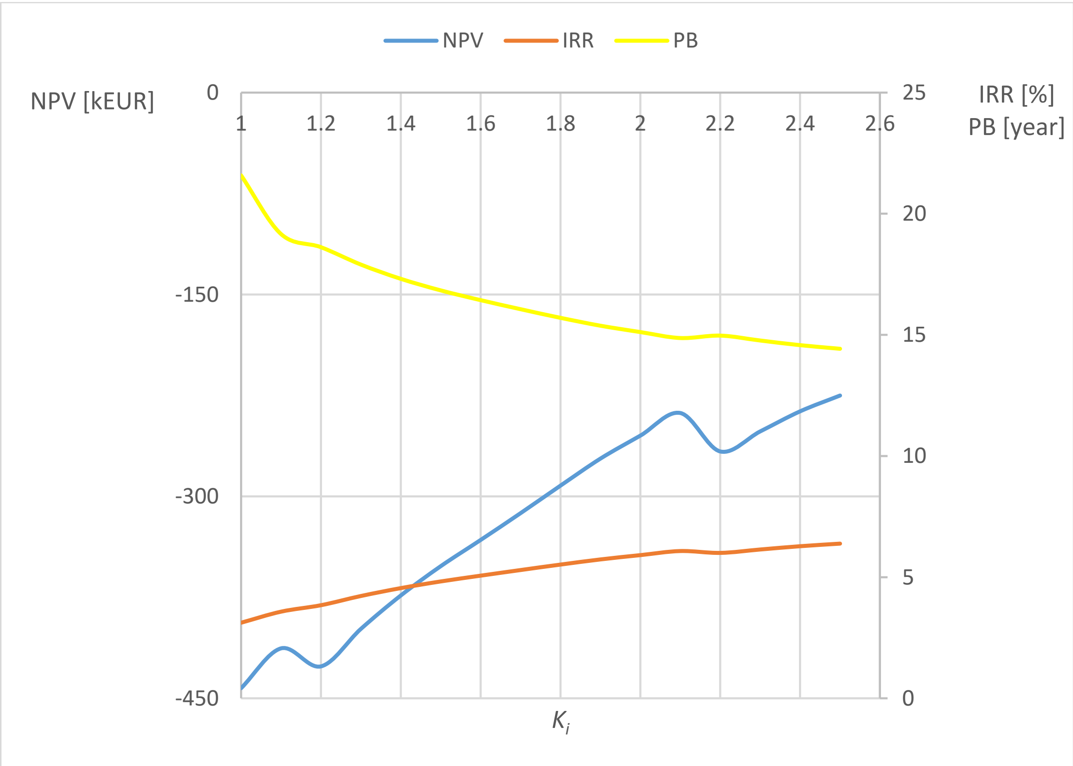

Fig. 2. NPV, IRR and PB – Rmuš SHPP

Hridska SHPP has the $K_i = 2.5$ obtained from all parameters, which means that this plant's maximum value of K_i gives the best performance regarding both the technical and economical view. Hridska SHPP started with a capacity of 412.8 kW for $K_i = 1.0$ and finished with 999.8 kW for $K_i = 2.5$ having, for all capacities, a constant incentive price (Table 1). Due to this fact, annual electricity production and annual income exhibit permanent and similar rising behavior (Fig. 3). Fig. 4. shows the change in NPV, IRR, and PB as a function of K_i. NPV and IRR continuously increase from minimum to maximum value, with NPV having a slightly sharper growth. On the other hand, as expected, PB decreases with the increase in these parameters. The total investment is 1.37 mEUR, and the payback period is PB = 8.7 years.

The designed value of K_i on constructed Hridska SHPP is 1.5. For this value, annual electricity production is 1.69 GWh, annual income is 177.02 kEUR, NPV is 248.49 kEUR, IRR is 10.18% and PB is 9.7 years. When SHPP installed parameter is K_i = 2.5, the annual electricity production and annual income are 1.3 times higher than electricity production and annual income for SHPP installed parameter K_i = 1.5. The pay-back period given by methodology is shortened by one year. Comparing the results obtained by applying the developed methodology, it was shown that the developed methodology gives better parameters with the designed parameters of the power plant.

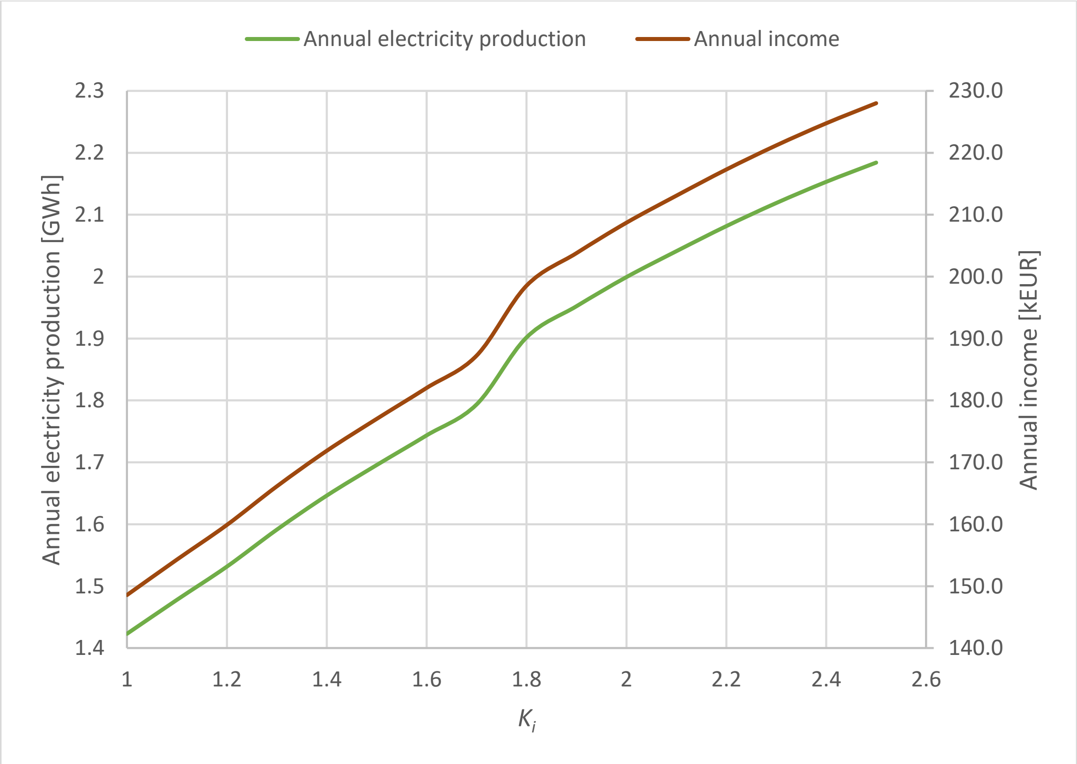

Fig. 3. Annual electricity production and income – Hridska SHPP

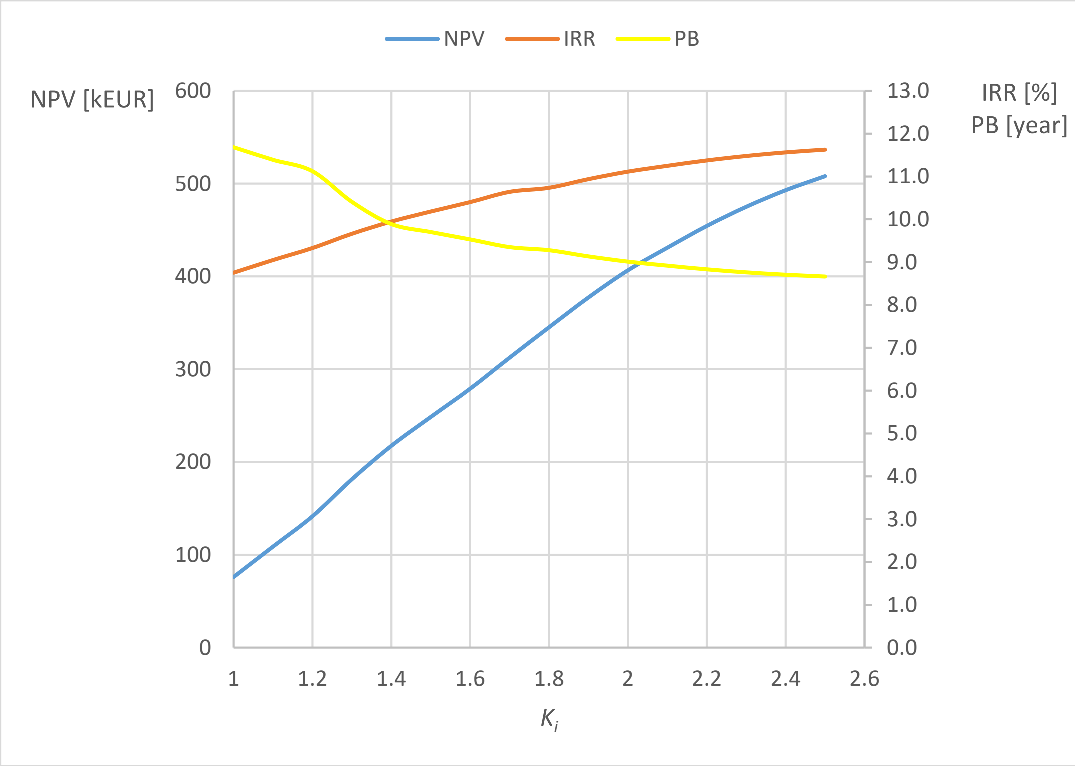

Fig. 4. NPV, IRR and PB – Hridska SHPP

Fig. 5 and 6 show electricity production, income, NPV, IRR and PB in the function of K_i for Umski SHPP. This SHPP started with a capacity of 413.79 kW for K_i = 1.0 and finished with 999.88 kW for K_i = 2.5. The annual electricity production and income permanently rise to K_i = 2.5 with a total investment of 1.28 mEUR and a payback period of 5.7 years. On the other hand, maximum values of NPV (1466.35 kEUR) and IRR (18.94%) are obtained for K_i = 2.3 and K_i = 1.7 respectively (Fig.6). Total investment for maximum NPV is 1.25 mEUR and 1.10 mEUR for maximum IRR with corresponding payback periods of 5.6 and 5.4 years.

Designed value~~s~~ of K_i on constructed Umski SHPP is 1.8. For this value annual electricity production is 2.25 GWh, annual income is 232.36 kEUR, NPV is 976.06 kEUR, IRR is 17.26% and PB is 6.01 years. Comparing the results obtained by applying the developed methodology with the designed parameters of the power plant, it was shown that applying the developed methodology for the adopted SHPP installed parameter K_i = 1.7 gives the maximum value of IRR. The constructed SHPP installed parameter is K_i = 1.8 and it gives almost the same parameter values as the K_i = 1.7. This design~~ed~~ solution seems to be well chosen if the economic aspect is to be observed.

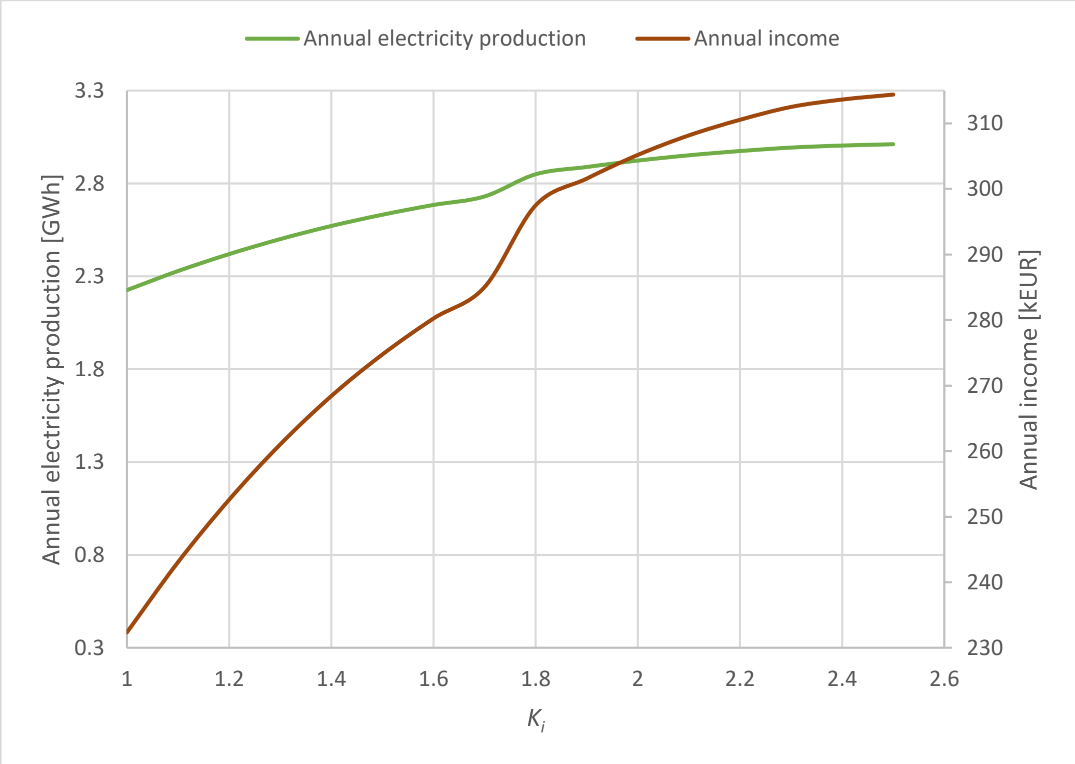

Fig. 5. Annual electricity production and income – Umski SHPP

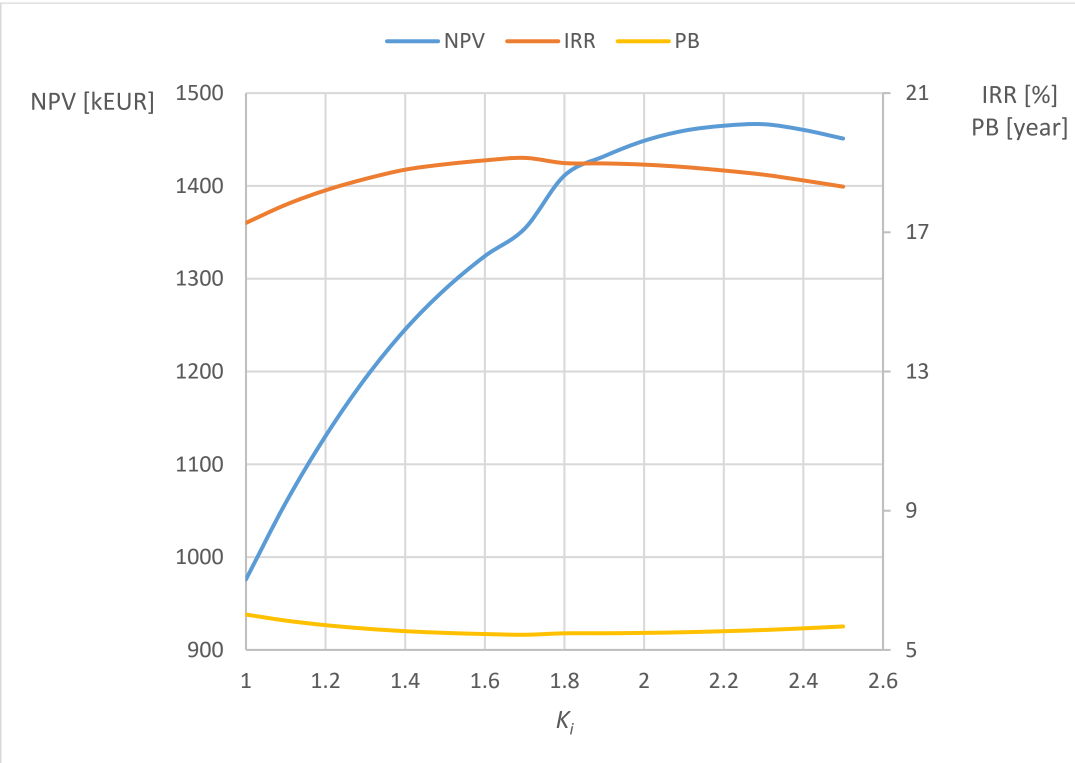

Fig. 6. NPV, IRR and PB – Umski SHPP

Fig.7 illustrates the normalized values of NPV for the three investigated power plants. The normalized values were obtained by dividing calculated values with optimal ones given with chosen K_i for every plant. Parameter NPV was chosen as an example in this case but also other techno-economic parameters can be used. With relative values, we are able to check results on the same level and compare different plants. Vertical lines mean constructed K_i and cross points with NPV lines give constructed NPVs. For Rmuš SHPP, NPV is negative all the time and this implies its relative NPV values range from 1 to 2. For Umski SHPP, the constructed relative NPV value is close to unity, which means that constructed K_i is well chosen. For Hridska SHPP, it is obvious that constructed relative value of NPV = 0.5 is far away from the optimum solution.

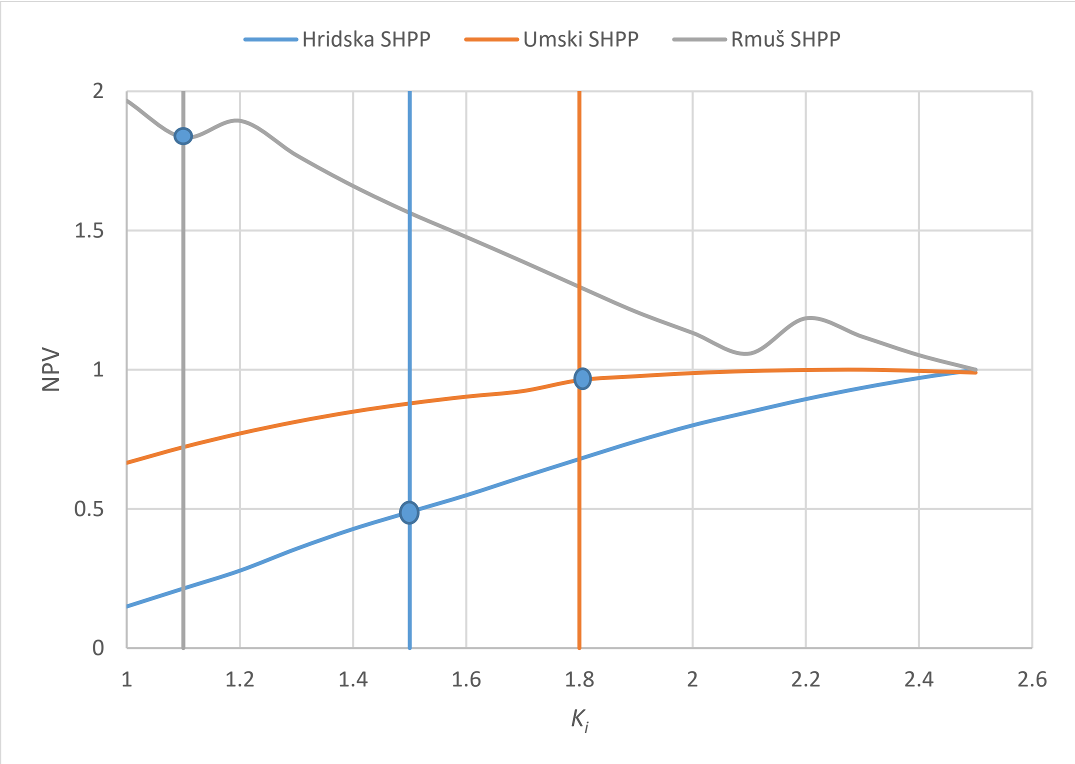

Fig. 7. Normalized values of NPV

4. CONCLUSION

The determination of the SHPP installed parameter is one of the main goals during the design of small hydropower plants. Previous experiences show that the range of SHPP installed parameter is very wide. Therefore, there is the need to determine the SHPP installed parameter in a more precise and improved way. The main intention of this paper is to contribute to the comprehensiveness of the design flow determination analysis in small hydropower plants using techno-economic parameters. For the examined plants with capacity below 1 MW, the following conclusions can be drawn:

1. Annual electricity production and annual income give the highest examined value of $K_i = 2.5$ as the optimal solution for all considered plants.
2. The economic parameters NPV and IRR narrow the initial value of SHPP installed parameter range to $K_i = \{1.7 \div 2.5\}$.
3. It can be noticed that NPV and IRR have more influence on the choice of SHPP installed parameter.

The comparison of the results obtained by applying the developed methodology with the designed parameters of power plants showed that higher annual electricity production and higher annual income are obtained this way. NPV and IRR values are also higher, and the PB period is shorter. Comparison of relative values of NPV answers whether the constructed values are chosen properly or differ significantly from the optimum.

Finally, it can be concluded that the developed methodology can serve as a guide for designers and investors of small hydropower plants.

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REFERENCES

[1] Kilama Okot, D., Review of small hydropower technology, *Renewable and Sustainable Energy Reviews*, 26 (2013), 515-520.

[2] Lopes de Almeida, J.P.P.G., Nenri Lejeune, A.G., Sa Marques, J.A.A., Conceição Cunha. M., OPAH a model for optimal design of multipurpose small hydropower plants, *Advances in Engineering Software*, 37 (2006), 236-247.

[3] Anagnostopoulos, J.S., Papantonis, D.E., Optimal sizing of a run-of-river small hydropower plant, *Energy Convers. Manag.,* 48 (2007), 2663-2670.

[4] Vilotijević, V., Karadžić, U., Vujadinović, R., Kovijanić, V., Božić, I., An Improved Techno-Economic Approach to Determination of More Precise Installed Parameter for Small Hydropower Plants, *Water*, 13 (2021), 2419.

[5] Karlis, A., Papadopoulos, D., A systematic assessment of the technical feasibility and economic viability of small hydroelectric system installations, *Renewable Energy*, 20 (2000), 253-262.

[6] Montanari, R., Criteria for the economic planning of a low power hydroelectric plant, *Renewable Energy*, 28 (2003), 2129–45.

[7] Kaldellis, J., Vlachou, D., Korbakis, G., Techno-economic evaluation of small hydropower plants in Greece: a complete sensitivity analysis, *Energy Policy,* 33 (2005), 1969–1985.

[8] Santolin, A., Cavazzini, G., Pavesi, G., Ardizzon, G., Rosetti, A., Techno-economical method for the capacity sizing of a small hydropower plant, *Water Resources and Management*, 52 (2011), 2533-2541.

[9] Mishra, S., Singal, S., Khatod, D., A review on electromechanical equipment applicable to small hydropower plants, *Int. J. Energy Res*, 36 (2012), 553–571.

[10] Barelli, L., Liucci, L., Ottaviano, A., Valigi, D., Mini-hydro: A design approach in case of torrential rivers, *Energy*, 58 (2013), 695–706.

[11] Ministry of Economy, Strategy for development of small hydropower plants in Montenegro, Podgorica, Montenegro, 2006.

[12] Vodni zdroje, a.s., Blom, Sweco Hydroprojekt CZ, a.s., Sistem doo, HMZCG, Registry of Small Rivers and Potential Locations of SHPPs at Municipality Level for Central and Northern Montenegro, European Bank for Reconstruction and Development (EBRD) and Ministry of economy, Podgorica, Montenegro, 2011.

[13] Vodni zdroje as, Sweco Hydroprojekt CZ as, Enhancement of Registry of Small Rivers for Small Hydropower Projects Potential of up to 10 MW, European Bank for Reconstruction and Development (EBRD) and Ministry of economy, Podgorica, Montenegro, 2019.

[14] Regulation on the approach of estimating the ecologically acceptable surface water flow, Ministry of Agriculture and Rural Development, Podgorica, Montenegro, 2015.

[15] Government of Montenegro, Regulation on the Tariff System for Determining the Feed Cost of Electricity from Renewable Energy Sources and High-Efficiency Cogeneration. Podgorica, Montenegro, 2015.

[16] Vilotijević V., Karadžić U., Božić. I., Ilić. J., Design discharge determination for SHPPs with capacity below 1 MW, *14th International Conference on Accomplishments in*

Mechanical and Industrial Engineering, Banja Luka, Republic of Srpska, BiH, 24-25 May 2019.
[17] Basso, S., Botter, G., Streamflow variability and optimal capacity of run-of-river hydropower plants, *Water Resources Research*, 48 (2012).