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The Importance of Small Hydro Power Plant Development in Advancing Sustainable Energy Solutions: Methodology and Case Study of Bistrica Majstorovina SHPP

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Abstract – Small hydropower plants (SHPPs) have evolved in a sustainable way, providing clean, renewable and reliable electricity with minimal impact on the environment. This paper looks at the methodology for planning SHPPs, with a detailed case study of the Bistrica Majstorovina SHPP. The study outlines the technical, environmental and economic aspects of SHPP development, including site selection, design optimization and integration into local energy grids. It also examines the socio-economic benefits of SHPPs, such as improving the living conditions of the local population and promoting local economic growth. The Bistrica Majstorovina SHPP case study demonstrates the practical implementation of sustainable energy solutions and highlights best practices and lessons learned from project implementation. This paper provides a comprehensive framework for future SHPP projects, contributing to the wider adoption of sustainable energy practices.

Index Terms – Small hydropower plant, Design flow, Methodology, Case study

I Introduction

As global energy demand rises and environmental concerns become more pressing, the development of renewable energy sources has become a key priority [1]. Among these, small hydropower plants (SHPPs) stand out as a sustainable and efficient solution for electricity generation. According to the internationally accepted convention, small hydropower in continental waters includes plants up to 10 MW. The convention is not binding, so each country, depending on its natural (climatic, hydrometeorological, topographic and other) specifics, level of technological development and economic standard, defines the limit values for SHPPs, but also changes them as necessary [2]. SHPPs minimize their ecological footprint while offering reliable power supply and economic benefits to local communities [3]. The successful implementation of SHPPs requires a well-structured methodology that accounts for technical, economic, and environmental factors [4-9]. Key considerations include site selection, design flow optimization, and financial feasibility, all of which influence the overall efficiency and sustainability of a project [10]. This paper explores the significance of SHPPs in advancing sustainable energy solutions, with a particular focus on the Bistrica Majstorovina SHPP as a case study. It provides an in-depth analysis of the planning and implementation process, highlighting best practices and challenges encountered. By examining the methodology used to determine optimal design parameters, this study aims to contribute valuable insights for future SHPP projects, ensuring their viability and long-term success in the global shift toward renewable energy. In addition to the scientifically based methodology, which takes into account all the energy-economic and ecological conditions of the design, construction and exploitation of the SHPP in question, special attention is devoted to the improvement of the living conditions of the local community.

II Methodology for SHPP Development

The successful development of SHPPs involves several critical stages, including site selection, feasibility studies, design optimization, environmental impact assessment, and project implementation. Each phase ensures that the project is technically, economically, and environmentally viable. Since the design flow rate is one of the most important parameters in the planning of SHPP, a methodology was developed to determine it as accurately as possible [9,11]. The methodology is based on technical and economic parameters. Technical parameters are the installed capacity and the annual electricity production, and economic parameters are the annual revenue, the net present value (NPV), the internal rate of return (IRR) and the payback period (PB). The term SHPP installed parameter (Ki) is also introduced, which represents the ratio between the design flow and the average perennial flow obtained from the flow duration curve at the location of the planned water intake. The methodology varies the value of Ki in the range from 1.0 to 2.5. with the step $\Delta Ki = 0.1$. For any given value of the design flow rate, the developed in-house software performs an optimization procedure, the results of which is the design flow rate that gives the highest electricity production, the highest gross income and the best economic parameters. In some cases, a unique solution is obtained, and in some cases, several solutions for the SHPP installed parameter are obtained. A detailed analysis of the built and planned small hydro power plants in Montenegro showed that the economic parameters NPV and IRR are the most influential parameters when choosing a SHPP installed parameter, and that for designing you should choose a SHPP installed parameter that is optimal from the aspect of NPV and IRR [12]. For all considered SHPPs, there were hydrological data obtained from the Registry of Small Rivers and Potential Locations of SHPPs in Montenegro [13,14] and Institute of

Hydrometeorology and Seismology of Montenegro [15]. The annual electricity production is calculated based on the hydrological data and the annual revenue is determined with the help of the incentive tariff, Table 1.

Table 1. Electricity prices depending on the capacity of the power plant [16]

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

In the previous decade, 31 (thirty-one) small hydropower plants have been built and commissioned in Montenegro. A comparison was made between the built state of each of them and the results of the methodology. The following diagrams show some examples, one with equal methodology and constructed solution (Šeremet SHPP - Figures 1 and 2), one with different methodology and constructed solution (Temnjačka SHPP - Figures 3 and 4) and so-called No Name SHPP (Figures 5 and 6) with negative NPV value.

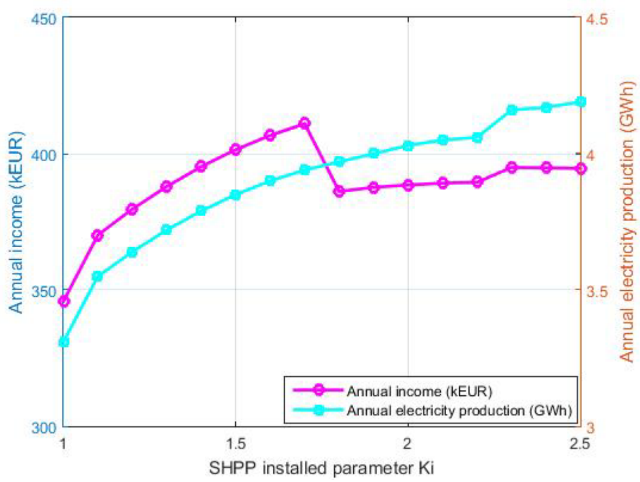

Figure 1. Annual electricity production and income – Šeremet SHPP

The maximum electricity production of 4.19 GWh is achieved at Ki = 2.5. Annual revenue increases up to Ki = 1.7, where it reaches its peak value of 411 kEUR, before declining at Ki = 1.8 due to the installed capacity exceeding 1 MW, which leads to a reduction in the incentive tariff. On the other hand, the maximum values for NPV (2605.95 kEUR) and IRR (22.54%) are obtained at Ki = 1.7 and Ki = 1.5, respectively. The total investment required for achieving the maximum NPV is 1458.2 kEUR, while for the maximum IRR, it stands at 1415.83 kEUR, with corresponding payback periods of 4.21 years and 4.19 years, respectively. The difference in revenue compared to the maximum NPV scenario is 9.52 kEUR, whereas the investment gap between the highest revenue scenario and the maximum IRR scenario is 42.37 kEUR. The optimal solution for the Šeremet SHPP is determined to be Ki = 1.7. The designed Ki value for the constructed Šeremet SHPP is 1.7. A comparison of the results obtained through the developed methodology with the designed parameters confirms that the same parameter values are achieved. From an economic perspective, this designed solution appears to be well-chosen.

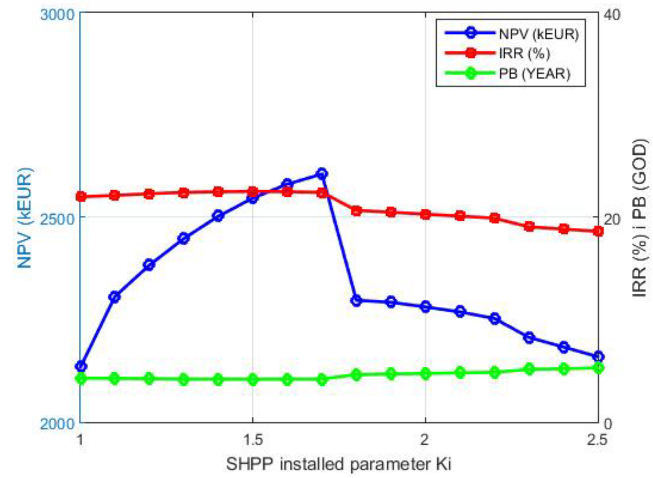

Figure 2. Annual electricity production and income – Šeremet SHPP

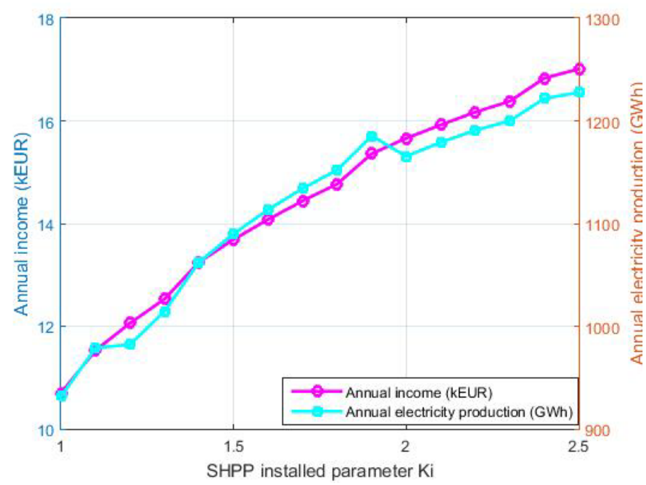

Figure 3. Annual electricity production and income – Temnjačka SHPP

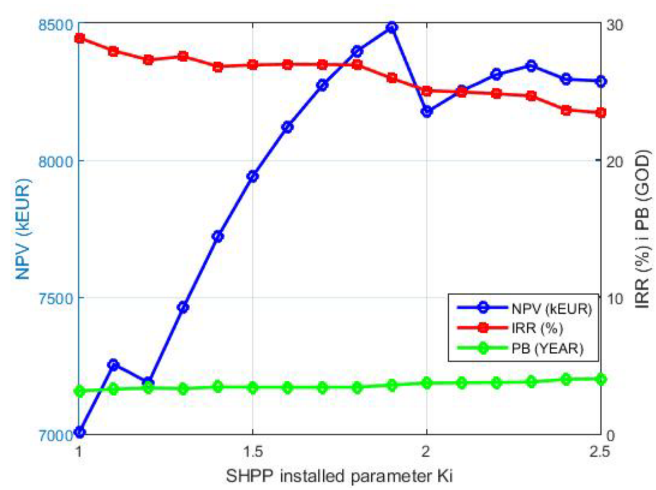

Figure 4. NPV, IRR and PB – Temnjačka SHPP

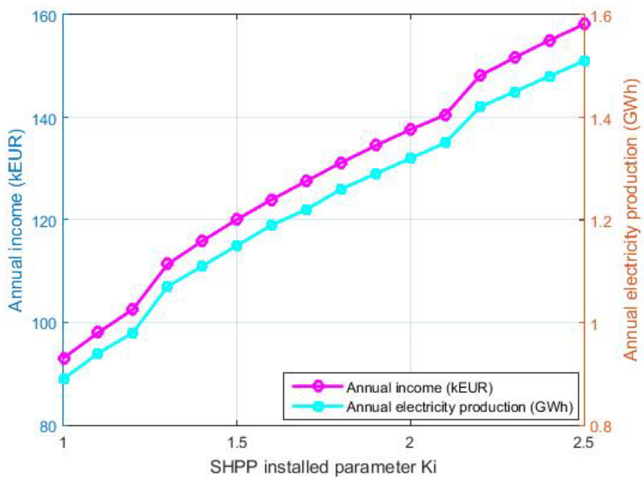

Figure 5. Annual electricity production and income - No Name SHPP

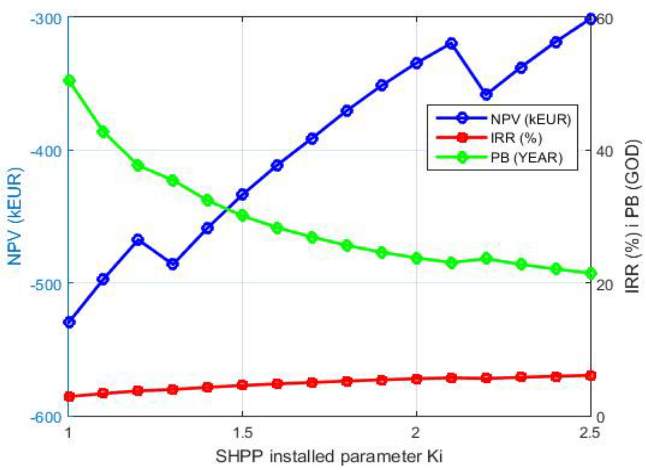

Figure 6. NPV, IRR and PB - No Name SHPP

The maximum electricity production and revenue is achieved at Ki = 2.5. On the other hand, the highest values for NPV (8,484.88 kEUR) and IRR (28.94%) are obtained at Ki = 1.9 and Ki = 1.0, respectively. As the pipeline diameter increases from DN800 to DN900, the NPV value experiences a slight decline up to Ki = 1.1, after which it steadily rises until Ki = 1.9. Beyond this point, due to exceeding the 5 MW threshold, NPV shows a slight decrease and remains nearly constant throughout the remaining range. The total investment required for achieving the maximum NPV is 3,784.95 kEUR, while for the maximum IRR, it stands at 2,651.96 kEUR, with corresponding payback periods of 3.14 years and 4.03 years, respectively. The revenue difference compared to the maximum NPV scenario is 42.32 kEUR, while the difference in revenue relative to the maximum IRR scenario amounts to 296 kEUR. Additionally, the investment gap between the highest revenue scenario and the maximum IRR scenario is 1,691.3 kEUR, whereas the difference compared to the maximum NPV scenario is 558.31 kEUR. Based on this findings the optimal solution for the Temnjačka SHPP is determined to be Ki = 1.9. The actual installed parameter for Temnjačka SHPP is Ki = 1.3. At this installed parameter, the total production is 12.53 GWh, annual revenue is 1,014.57 kEUR, NPV is 7,461.46 kEUR, IRR stands at 27.57%, and the payback period (PB) is 3.32 years. By comparing these two installed parameters, it can be observed that the optimal solution yields slightly better results in terms of higher annual revenue, total production, and NPV.

For No Name SHPP, the maximum value of annual production 1.51 GWh and the maximum value of annual income 158.15 kEUR is obtained for K_i = 2.5. The maximum values for NPV (-301.11 kEUR) and IRR (6.08%) i.e. the corresponding PB (21.48 years) were obtained also for K_i = 2.5. Designed value of K_i on constructed No Name SHPP is 1.8. For this value, annual electricity production is 1.26 GWh, annual income is 131.16 kEUR, NPV is -370.25 kEUR, IRR is 5.22% and PB is 25.65 years. Based on the obtained results, it can be noted that the NPV has a negative value for the entire K_i range, which indicates that this SHPP was not designed properly or was designed with wrong input data. Also, the maximum IRR value of 6.08% is lower than the adopted discount rate of 8%, which means that the project is not feasible.

The normalized values of NPV and IRR are used for a precise comparison of the results obtained by the methodology and the constructed SHPP solution. Normalized values were obtained by dividing calculated values with optimal ones given with chosen K_i for every plant. 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 or IRR lines give constructed NPVs or IRRs. Figure 7 shows the criteria for evaluating the validity of the constructed solution.

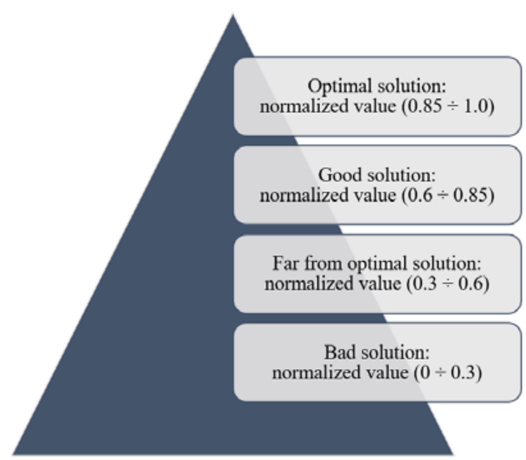

Figure 7. Criteria for evaluating the validity of the constructed solution (normalized values of NPV i IRR)

For Šeremet SHPP (Figure 8), the solution obtained by the methodology is the same as the constructed solution. Considering the above, the constructed SHPP installed parameter (NPV=1) is the optimal solution.

Figure 9 shows normalized values of NPV for Temnjačka SHPP. Comparing the constructed, SHPP installed parameter and the SHPP installed parameter obtained by the methodology; it can be observed that better results of all considered parameters are provided by the optimal solution. Based on this comparison, the normalized value accounts for 88% (NPV = 0.88) of the optimal solution, indicating that the constructed SHPP installed parameter represents a well-balanced alternative in the range of the optimal solution near the lower limit of 0.85.

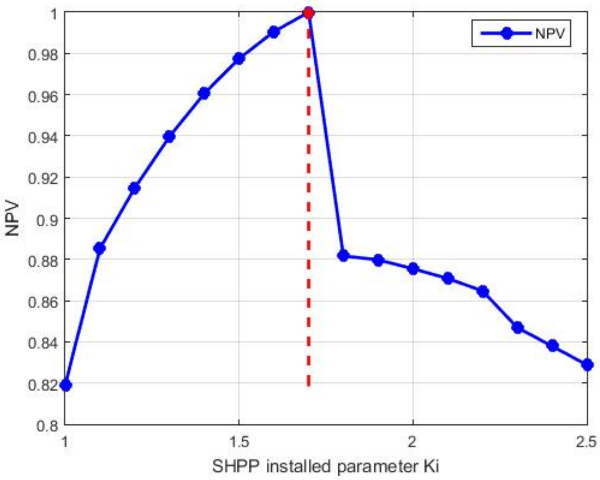

Figure 8. Normalized values of NPV –Šeremet SHPP

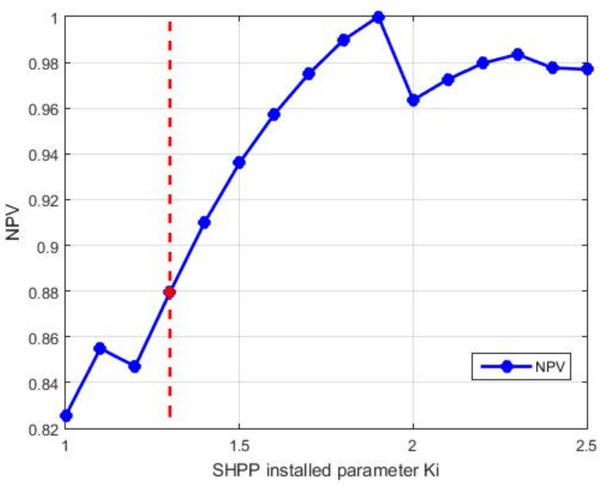

Figure 9. Normalized values of NPV –Temnjačka SHPP

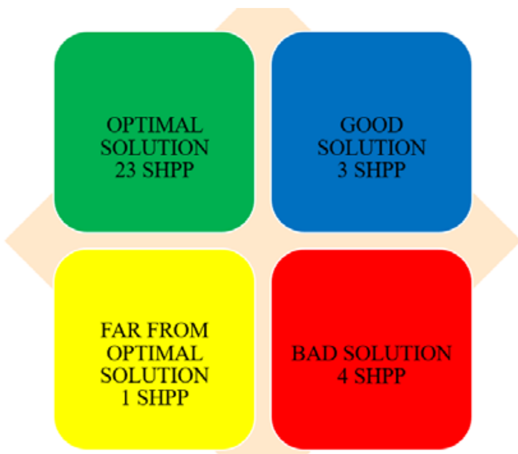

Figure 10. Evaluation of the validity of the implemented solutions

Considering that the net present value (NPV) for the No Name SHPP, has a negative value and the maximum IRR value is below the assumed discount rate, one can conclude that this power plant was built as a bad solution. Fig.10 shows results for all 31 newly-built SHPPs in Montenegro.

It can be concluded that out of 31 newly built SHPP in Montenegro, even 23 were made as an optimal solution, which is a very high 74%. Three can be considered as a good solution, one as far from optimal and four SHPPs were built as a bad solution.

III Case Study: Bistrica Majstorovina SHPP

The Bistrica Majstorovina SHPP, located in Bijelo Polje, Montenegro, serves as an exemplary model for small-scale hydropower development. This section provides an overview of its development process and outcomes. In November 2011, a limnigraph for measuring the water level was installed on the watercourse at the position of the planned water intake, Figure 11, and continuous measurements were carried out for two full years. The flow was measured several times every month using a flow-tracer, a device that measures the change in the concentration of the solution in the watercourse, Figure12. A hydrological study was performed and a flow duration curve (FDC) was obtained, Figure 13, which during design was used to estimate annual electricity production and determine ecological flow.

Figure 11. Limnigraph at the location of the water intake

Figure 12. Flow measurement using a flow-tracer

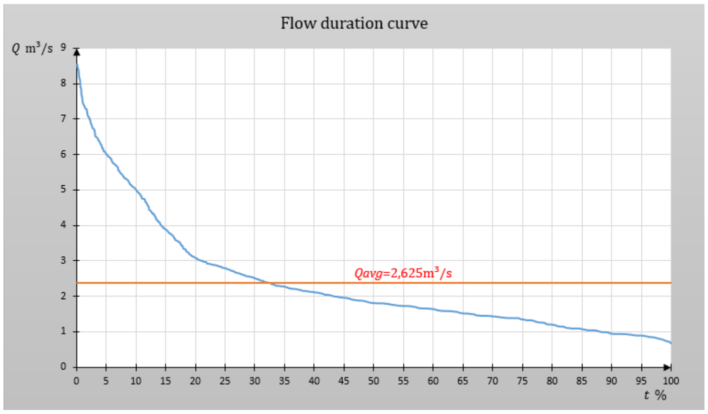

Figure 13. Flow measurement using a flow-tracer

Bistrica Majstorovina SHPP was commissioned at the end of 2017 and has been in commercial operation since January 2018. Its basic characteristics are given in Table 2.

Table 2. Main technical characteristics of the Bistrica Majstorovina SHPP

Gross head:	H_b = 102.00 m
Average perennial flow at the water intake:	Q_{avg} = 2.625 m^3/s
Ecological flow	Q_{DEF} = 0.260 m^3/s
Design discharge:	Q_D = 4.20 m^3/s
SHPP installed parameter	K_i = 1.6
Net head:	H_n = 95.5 m
Pipeline diameter:	D = 1600 mm
Pipeline length:	L = 3723 m
Two equal Francis turbines:	P_F = 1800 kW
Total capacity	P = 3600 kW
Designed annual electricity production:	E_{DEP} = 11.7 GWh

The anticipated investment in the Bistrica Majstorovina SHPP project was about 7260 kEUR with a specific investment of 2016 EUR/kW and 0.62 cEUR/kWh. After the project completion, the total costs were exceeded by about 7% and amounted to about 7785 kEUR with a specific investment of 2162 EUR/kW and 0.66 cEUR/kWh. Figure 14 shows the cost structure.

The most, 50%, was the cost of civil works which is construction of a power house, water intake and procurement and installation of pipeline. Electro-mechanical and hydro-mechanical equipment cost is 22%, while design and infrastructure cost 5% each. The infrastructure costs include the installation of an underground energy cable to connect the power plant to the grid on 10 kV level and the construction and asphalting of the access road to the power house. Other costs, which account for 18%, include management and supervision of the project, settlement of property-legal relations, preparatory works and implementation of multi-purpose solutions for the needs of the local community. It should be emphasized that only electro-mechanical and hydro-mechanical equipment was purchased abroad, and that the rest of the invested money remained in Montenegro and partly in Serbia, where the pipeline was purchased. The following pictures show the main parts of the Bistrica Majstorovina SHPP.

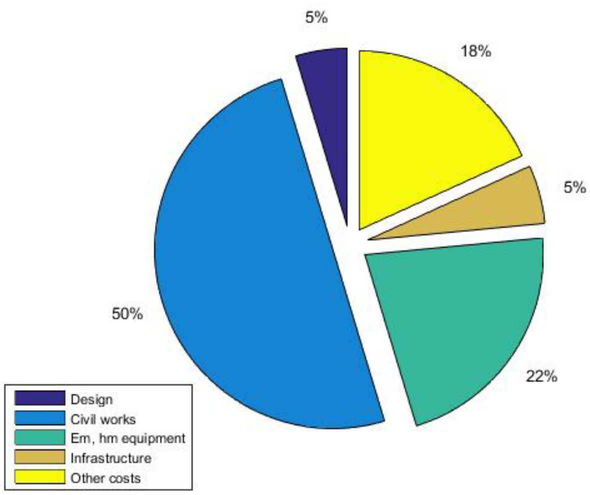

Figure 14. Cost structure of the Bistrica Majstorovina SHPP

Figure 15. Water intake of the Bistrica Majstorovina SHPP

Bistrica Majstorovina SHPP (Figures 15-17) has been in operation for seven years. Table 3 shows the costs of its work in this period as well as the amount of energy produced. Table 4 shows the difference between the foreseen and actually produced amount of electricity, from which it can be seen that in seven years of operation, the Bistrica Majstorovina SHPP produced 648 MWh less electricity than was designed.

Figure 16. Bistrica Majstorovina SHPP pipeline

Figure 17. Bistrica Majstorovina SHPP power house

Table 3. Energy production, income and costs of the Bistrica Majstorovina SHPP

Year	Electricity production MWh	Income EUR	Loan EUR	OM costs EUR	Concession fee EUR	Operator fee EUR
2018	9.525	852.451,59	675.963,37	103.124,92	51.688,28	6.667,18
2019	10.236,32	875.102,95	474.518,97	117.102,72	56.881,69	7.165,42
2020	10.352,05	888.516,59	476.783,40	175.888,39	57.753,58	7.297,28
2021	12.336,98	1.055.675,71	481.030,87	134.837,02	68.618,92	9.400,78
2022	12.854,80	1.126.337,26	485.074,17	140.280,48	73.211,92	9.024,07
2023	17.170,64	1.700.065,08	551.990,85	142.184,26	110.504,23	11.160,92
2024	8.777,80	943.788,64	1.920.755,41	252.110,38	61.346,26	6.755,39
SUM:	**81.253,13**	**7.441.937,83**	**5.066.117,04**	**1.065.528,17**	**480.004,88**	**57.471,04**

Table 4. Difference between designed and actual energy production

Year	2018	2019	2020	2021	2022	2023	2024	SUM
$E_{DEP} – E_{AEP}$ MWh	- 2175	-1464	-1348	637	1154	5470	-2922	-648

Table 5. Difference between designed and average ecological flow

Year	2018	2019	2020	2021	2022	2023	2024
Average ecological flow (Q_{AEF}) l/s	840	770	1650	1050	744	1650	550
Q_{AEF} / Q_{DEF}	3.2	3.0	6.3	4.0	2.9	6.3	2.1

Designed ecological flow (DEF) for Bistrica Majstorovina is $Q_{DEF} = 0.1Q_{AVG} = 0.260$ m^3/s according to the law valid in 2015. In order to monitor the ecological flow downstream of the water intake, a limnigraph was installed, Figure 18.

Every year, a hydrological study of the watercourse downstream of the water intake was carried out and a FDC as well as a value of the average ecological flow was determined, Figure 19. Table 5 shows that the average ecological flow is always higher than the designed ecological flow, at least 2.1 times in 2024 and at most 6.3 times in 2020 and 2023.

Figure 18. Limnigraph downstream of the intake

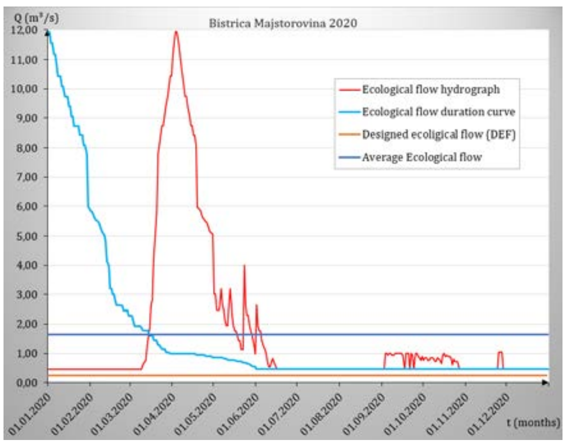

Figure 19. Ecological flow, example from 2020 year

The local community also had and has numerous benefits from the construction of a SHPP. A significant amount of money was set aside for the settlement of property-legal relations. For several households, drinking water was brought from the water intake. Several kilometres of the local road and the plateau in front of the elementary school were paved. Although the power plant works in automatic mode, eight young people got permanent employment, formed families and stayed to live in their native hearths. In cooperation with the local community, the most socially vulnerable families are provided with firewood and assisted in various ways. Downstream from the water intake of the SHPP and the limnigraph for measuring ecological flow, and for the needs of Ravna Rijeka monastery, three large-scale fishponds are constructed, which are producing trouts for commercial use. Off-grid solar systems have been installed on 15 katuns, which significantly improved the living conditions of people who go up to the mountain with their cattle during the summer.

Applying the developed methodology to the case of Bistrica Majstorovina SHPP gives the result shown in Figure 20. The normalized value of IRR = 0.82 means that constructed solution with K_i = 1.6 belong to group of good solution close to upper limit of 0.85. It is also can be seen that decreasing SHPP installed parameter to K_i = 1.4 will bring solution to the group of optimal and the best results will be obtained for K_i = 1.0.

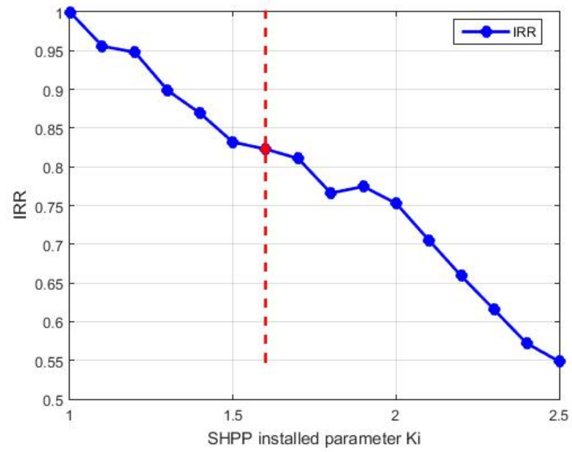

Figure 20. Normalized values of IRR –Bistrica Majstorovina SHPP

IV CONCLUSION

The development of small hydropower plants (SHPPs) plays a crucial role in advancing sustainable energy solutions by providing clean, renewable, and reliable electricity with minimal environmental impact. This study has explored the methodology for SHPP planning and design, emphasizing the importance of technical, economic, and environmental parameters in optimizing performance. Through an in-depth analysis of various SHPPs in Montenegro and a detailed case study of the Bistrica Majstorovina SHPP, the practical application of the proposed methodology has been validated. In the case of Bistrica Majstorovina SHPP, the selected parameter (Ki = 1.6) resulted in a well-balanced solution, as confirmed by the normalized value of IRR. This demonstrates that the developed methodology provides a robust framework for selecting optimal design parameters, ensuring maximum efficiency and economic return. Furthermore, the evaluation of 31 newly constructed SHPPs in Montenegro revealed that 74% were designed optimally, with an additional 10% classified as good solutions. However, the study also identified cases where suboptimal design choices led to reduced financial feasibility, highlighting the importance of rigorous methodological application. Beyond economic and technical aspects, SHPP development has contributed to local socio-economic growth and infrastructure improvements. The Bistrica Majstorovina SHPP, in particular, has provided employment opportunities, enhanced local infrastructure, and supported ecological initiatives, such as off-grid solar systems and fish farming projects. Overall, the research underscores the significance of a systematic approach to SHPP development, ensuring that future projects are both economically viable and environmentally sustainable. The proposed methodology serves as a valuable tool for decision makers, engineers, and investors aiming to implement small hydropower solutions that align with global energy sustainability goals. At the same time, the presented SHPP is an example of good practice showing that goals can only be achieved with respect and constant verification of all standards-defined, legally prescribed, socially and environmentally acceptable, technically feasible and economically rational conditions for the construction and operation of a conteprorary SHPP.

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Značaj razvoja malih hidroelektrana u unapređenju održivih energetskih rešenja: metodologija i studija slučaja MHE Bistrica Majstorovina

***Rezime** - Male hidroelektrane (MHE) su se razvijale na održiv način, obezbeđujući čistu, obnovljivu i pouzdanu električnu energiju sa minimalnim uticajem na životnu sredinu. Ovaj rad razmatra metodologiju za planiranje MHE, sa detaljnom studijom slučaja MHE Bistrica Majstorovina. Studija opisuje tehničke, ekološke i ekonomske aspekte razvoja MHE, uključujući izbor lokacije, optimizaciju projektovanja i integraciju u lokalne energetske mreže. Takođe, ispituje društveno-ekonomske koristi MHE, kao što su poboljšanje životnih uslova lokalnog stanovništva i podsticanje lokalnog ekonomskog rasta. Studija slučaja MHE Bistrica Majstorovina demonstrira praktičnu primenu rešenja za održivu energiju i ističe najbolje prakse i lekcije naučene iz implementacije projekta. Ovaj rad pruža sveobuhvatan okvir za buduće projekte MHE, doprinoseći širem usvajanju praksi korišćenja održive energije.*

***Ključne reči** - mala hidroelektrana, projektni protok, metodologija, studija slučaja*