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Concept of hydropower potential of the Bednja River at the location Lovrentovec, Croatia

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Abstract: The purpose of the paper is to assess the hydropower potential of the Bednja River for the construction of hydroelectric power plants using turbines that use the potential energy of water and those that exploit the kinetic energy of the watercourse. The location near Lovrentovec, specifically at the bridge over the Bednja River, is analyzed. Small hydropower plants can greatly contribute to the development of rural areas and thus improve the quality of life in such regions. Based on known data at the observed location and field measurements, the output power of hydroelectric power plants is calculated, depending on whether it is potential energy or kinetic energy of the watercourse. The Bednja River is one of the rivers on which it is possible to build a plant that could use the power of water to produce electricity for nearby settlements in Varaždin County. In addition to the measured data obtained through field research and the use of appropriate measuring devices, this paper also contains data related to the neighboring hydrological measuring stations Ključ and Tuhovec. With all the data obtained and the output power calculated, the results can be compared and thus the real potential of the Bednja River can be estimated.

Key words: turbines, potential energy, kinetic energy, environment, small hydropower plants

Koncept hidroenergetskog potencijala rijeke Bednje na lokaciji Lovrentovec, Hrvatska

Sažetak: Svrha rada je procjena hidroenergetskog potencijala rijeke Bednje za izgradnju hidroelektrana koristeći turbine koje koriste potencijalnu energiju vode i one koje iskorištavaju kinetičku energiju vodotoka. Analizira se lokacija u blizini Lovrentovca, tj. konkretno kod mosta preko rijeke Bednje. Male hidroelektrane mogu uvelike doprinijeti razvoju ruralnih područja i time poboljšati kvalitetu života u takvim regijama. Na temelju poznatih podataka na promatranoj lokaciji i terenskih mjerenja, proračunava se izlazna snaga hidroelektrana, ovisno o tome radi li se o potencijalnoj energiji ili kinetičkoj energiji vodotoka. Rijeka Bednja je jedna od rijeka na kojoj je moguće izgraditi postrojenje koje bi moglo koristiti snagu vode za proizvodnju električne energije za obližnja naselja u Varaždinskoj županiji. Uz izmjerene podatke dobivene terenskim istraživanjem i korištenjem odgovarajućih mjernih uređaja, ovaj rad također sadrži podatke vezane uz susjedne hidrološke mjerne postaje Ključ i Tuhovec. Sa svim dobivenim podacima i izračunatim izlaznim snagama mogu se usporediti rezultati i na taj način može se procijeniti stvarni potencijal rijeke Bednje.

Key words: turbine, potencijalna energija, kinetička energija, okoliš, male hidroelektrane

1. INTRODUCTION

Nowadays as humanity fights climate change that affects the entire living world, it is imperative to use renewable energy sources (RES) such as solar energy, wind energy, watercourse energy, geothermal energy, biomass energy, wave energy and tidal energy. All energy comes mainly from the Sun, and it is an inexhaustible energy source. This paper will consider water energy, or the use of river hydropower. The benefits of hydroelectric power plants are numerous. The advantages include clean energy with the least amount of waste generated (compared to other renewable energy sources) during and after construction, as well as during operation. The water used is free of charge and there are no fuel costs. Still, hydroelectric power plants have some disadvantages, including dependence on precipitation and a possible threat to ecosystems at the power plant site and along the river course [1]. Also, the legal legislation and regulations related to the design and construction of all hydroelectric power plants are complex and require a time-consuming process of obtaining them. First, after the study documentation containing the hydrological and energy potential of the analyzed documentation and after the public presentation, it is necessary to obtain approvals for the design and construction of the hydroelectric power plant from public, state and local legal and administrative institutions, then statements from the competent ministries and enter the process of preparing project documentation, which are procedures that may take time.

Hydropower is one of the most important and widespread sources of electricity in general. Many developed countries in the world use the energy of watercourses to generate electricity on a massive scale, while undeveloped countries are still lagging behind in the use of this type of energy. First of all, rural and scattered areas face major problems in terms of development due to the lack of electricity, and this is precisely one of the most important problems that needs to be solved today. Today, the construction of hydroelectric power plants is based on locations outside large cities and the areas in smaller settlements, where the ultimate goal is to improve the lives of residents, are mostly acceptable. Certainly, the process of building any type of hydroelectric power plant is a painstaking and time-consuming process that involves substantial financial needs, but mainly related to capital investment, as well as project documentation.

The Bednja River is one of the watercourses where the potential of the watercourse is not sufficiently exploited. Large hydroelectric power plants will not be constructed on this river, but the construction of small hydroelectric power plants is quite possible. Small hydropower plants are the solution with the lowest environmental impact compared to other renewable energy sources, since they do not drastically usurp watercourses and thereby their environmental impact is negligible. Several such small hydroelectric power plants are planned on the Bednja River, but it is known that this procedure has become demanding for every investor with all the legal regulations and today the goal is to facilitate this procedure. The presence of such a type of energy source would help create numerous opportunities in the wider area, from sports activities onwards, certainly with appropriate environmental protection. Flood protection and flow regulation would be an indispensable segment in such a project. The Bednja River has not yet been fully hydrologically investigated, so the objective of this paper is to contribute to the investigation of the river itself. Measurements were conducted for the location near Lovrentovec (Figure 1) and are presented and analyzed below.

Figure 1. Bridge on the Bednja River in Lovrentovec [2]

The purpose of the paper is to calculate the power of the turbines, which is the basis for estimating electricity production, thus defining the hydropower potential of the Bednja River at the analyzed location. The power calculation is carried out according to certain expressions, which are specified in the paper below. It should be noted that this paper is from the topic of the defended graduation thesis of co-author Anja Kutnjak.

2. POTENTIAL AND KINETIC HYDROELECTRIC POWER PLANTS

Turbines that use the potential energy of water are one of the options used in the construction of hydroelectric power plants. Potential energy is related to position in space, that is, it depends on the head and flow. On the other hand, kinetic hydroelectric power plants use the kinetic energy of water, the energy of water movement. The movement of water includes the velocity and the surface area through which the water moves. When using potential energy, the output (effective) power at the exit from the hydroelectric power plant according to the expression is:

$$P_{out} = \rho \cdot g \cdot Q \cdot H \cdot \eta_{tot} \quad (1)$$

where:
P_{out} is the output power from the hydroelectric power plant [W], ρ is water density [kg/m^3], g acceleration of gravity [m/s^2], Q flow [m^3/s], H is the achieved head (net head) [m], η_{tot} total efficiency of the hydroelectric power plant.

If kinetic energy is used, the expression for the output (effective) power from the hydroelectric power plant is as follows:

$$P_{out} = \frac{\rho}{2} \cdot A \cdot v^3 \cdot \eta_{tot} \quad (2)$$

where: A – is input area [m^2], v velocity [m/s].

Small hydropower plants (SHPP) can be designed for a low head with a low gradient or for a high head with a high gradient. Every SHPP harnesses the power of river flow with the possibility of presence of a small reservoir, or without a reservoir. The operation of a SHPP is possible only when there is a sufficient amount of water, or when there is a certain flow in the riverbed, otherwise the operation stops. There is a shortage of non-renewable (fossil) energy sources in the Republic of Croatia, which directly indicates the importance of requiring the use of natural energy sources, or the necessary investment in the development and construction of hydroelectric power plants. Every investor in such a type of investment must consider all aspects, primarily the technical and economic analysis of the project's cost-effectiveness.

3. SITE ANALYSIS

3.1. The Bednja River

Measurements for the purposes of this paper were carried out in the settlement of Lovrentovec near the town of Varaždinske Toplice in Varaždin County, on the Bednja River. The Bednja River rises in the village of Bednjica, near Trakošćan in Maceljsko Gorje as part of Hrvatsko Zagorje. This river is considered the longest river that has both its spring and confluence in the Republic of Croatia (Figure 2). The river course extends for 133 km and is a right tributary of the Drava River. Of the four rivers of Hrvatsko Zagorje, only the Bednja River flows into Drava. The Bednja River flows through the settlements of Bednja, Lepoglava, Ivanec, Beletinec, Novi Marof, Varaždinske Toplice, Ludbreg and flows into Drava near Mali Bukovac [3].

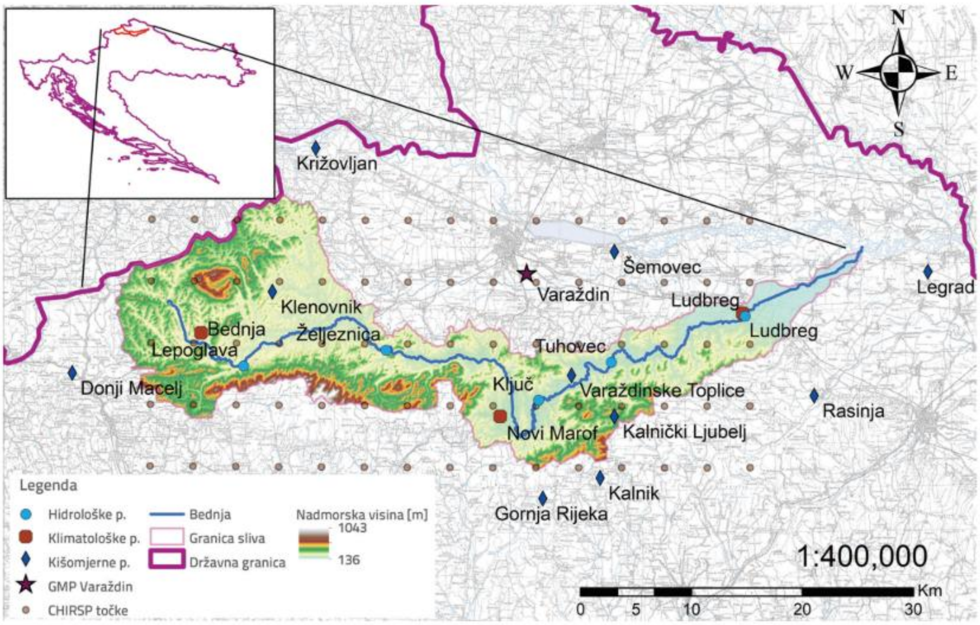

Figure 2. The Bednja River basin [4]

The area of the Bednja River basin is 596 km^2, and the direction of the river is from west to east, and its basin is elongated in the same direction. Three relief units are distinguished in the Bednja basin: the alluvial plain, the Tertiary mountain system, and the Paleozoic mountains. The initial course of the Bednja River covers the hilly part along Ivanšćica and Kalnik, and in the settlement of Slanje it enters the Podravina plain [5]. It is a matter of course that the Bednja River was narrower before the regulation than it is today, and much deeper in some locations where this is no longer the case. Floods were known to have occurred often in the past, precisely because of this river in that area [3].

Today, there are a total of five hydrological measuring stations in the Bednja basin, namely Lepoglava, Ključ, Željeznica, Ludbreg, and Tuhovec. The basic statistical indicators of daily flows at gauging stations on the Bednja River in the period from 2000 to 2018 are presented in Table 1.

Table 1. Overview of statistical indicators of average flows at gauging stations on the Bednja River in the period from 2000 to 2018 [4]

Gauging stations/ Indicators	Number of data	Arithm. Means	Std. Deviation	Min.	25%	50%	75%	Max.
Lepoglava	6940	1.21	2.70	0.03	0.24	0.50	1.07	44.7
Željeznica	6940	3.30	6.38	0.21	0.80	1.44	2.91	123.0
Ključ	6435	4.91	8.86	0.33	1.33	2.21	4.20	90.2
Tuhovec	6549	5.08	9.19	0.55	1.51	2.31	4.35	103.0
Ludbreg	6940	6.10	10.09	0.43	1.90	2.95	5.68	116.0

According to hydrological research that has been conducted, the Bednja River is a very torrential watercourse, and thereby its flow directly depends on precipitation, but also on snowmelt in the source area in the winter periods [6]. The highest flows occur in spring (March and April) when snow melts along with precipitation in the form of rain [7]. Stormy showers are also common, most often occurring in August and September. Stormy showers cause an exceptionally sudden increase in flow, and so do long-lasting and heavy rains in the autumn part of the year, September and October. Analysis of flows at hydrological stations on the Bednja River for the period 2000-2018 determined that the lowest flow of 0.032 m^3/s was measured on 8 August 2000, at the most upstream station Lepoglava, and the highest flow of 123 m^3/s was measured on 20 September 2017, at the Željeznica station [4]. The hydrograph of the Bednja River from 2007 to 2018 is in Figure 3.

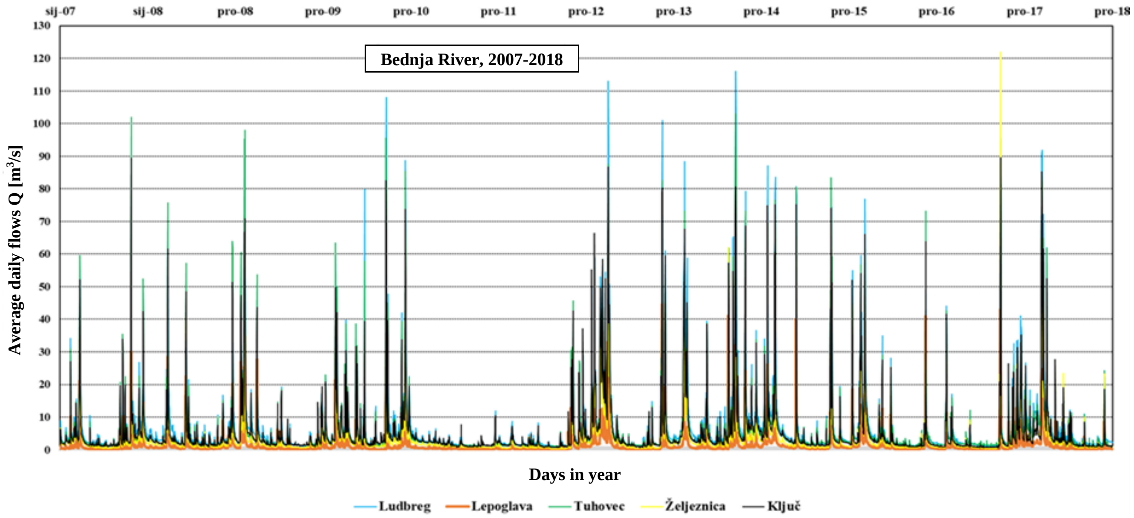

Figure 3. Hydrograph of the Bednja River from 2007 to 2018 [8]

Figure 4 shows the exact location of the measurements made with a red circle.

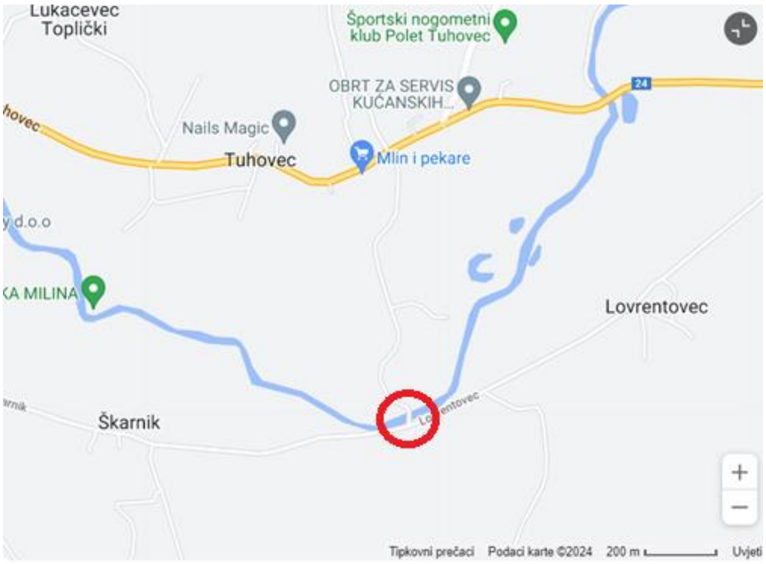

Figure 4. Lovrentovec [9]

Figures 5 and 6 show the measurement profiles on which measurements were made on 6 June 2024 and 20 June 2024.

Figure 5. Measurement location - Profile 1 [10]

Figure 6. Measurement location - Profile 2 [10]

4. RESULTS

Measurements were made on two different profiles numbered 1 and 2 on 6 June 2024, while on 20 June 2024 measurements were also made at the same locations again. Figure 7 shows the position of the measured profiles (marked in red). Profile 1 is located upstream, and profile number 2 is located immediately next to the bridge.

Figure 7. View of the positions of measurement profiles 1 and 2 [9]

Tables 2-5 show the results obtained using expression (2). An insight into the complete (detailed) calculation procedure is in the works of author Kutnjak [10,11].

Table 2. Input data and obtained powers of kinetic turbines for Profile 1, date 6 June 2024.

PROFILE 1 – 6 June 2024.							
Widths (m)	**0.5m**	**1m**	**1.5m**	**2m**	**2.5m**	**3m**	**4m**
Velocities (m/s)	0.470	0.457	0.452	0.451	0.438	0.418	0.389
Areas (m^2)	0.68	1.41	2.04	2.99	4.18	5.41	7.74
Power (W)	11	20	28	41	53	59	68

Table 3. Input data and obtained powers of kinetic turbines for Profile 2, date 6 June 2024.

PROFILE 2 – 6 June 2024.					
Widths (m)	**0.5m**	**1m**	**1.5m**	**2m**	**2.5m**
Velocities (m/s)	0.548	0.534	0.524	0.485	0.442
Areas (m^2)	0.74	1.38	2.04	2.68	3.76
Power (W)	18	31	44	46	49

Table 4. Input data and obtained powers of kinetic turbines for Profile 1, date 6 June 2024.

PROFILE 1 – 20 June 2024.									
Widths (m)	**0.5m**	**1m**	**1.5m**	**2m**	**2.5m**	**3m**	**4m**	**5m**	**5.5m**
Velocities (m/s)	0.349	0.339	0.341	0.342	0.341	0.336	0.315	0.305	0.282
Areas (m^2)	0.51	1.03	1.56	2.08	3.08	4.43	6.28	7.18	8.8
Power (W)	3	6	9	13	18	25	29	31	29

Table 5. Input data and obtained powers of kinetic turbines for Profile 2, date 20 June 2024.

PROFILE 2 – 20 June 2024.							
Widths (m)	**0.5m**	**1m**	**1.5m**	**2m**	**2.5m**	**3m**	**3.5m**
Velocities (m/s)	0.377	0.364	0.351	0.333	0.317	0.298	0.276
Areas (m^2)	0.8	1.56	2.26	2.88	4	4.44	5.48
Power (W)	6	11	15	16	19	18	17

When calculating the power of a hydroelectric power plant, where potential water energy is used, the calculation requires data according to formula (1). Unlike turbines that use kinetic water energy, where the turbine efficiency is assumed as 30%, for turbines that use potential water energy, the turbine efficiency is assumed as 80% [12].

All the data needed for the power calculation are shown in Table 6. For each of the profiles, the flow values are different. For Profile 1, the flow value is 3.18 m^3/s on 6 June 2024, for Profile 2 the flow value is 3 m^3/s on the same day, and on 20 June 2024, the flow value for Profile 1 is 1.75 m^3/s, while for Profile 2 a flow of 1.77 m^3/s was measured on that day, 20 June 2024. Taking into account that Profile 1 was measured upstream, and Profile 2 was measured at the bridge, some differences in the measured flow values are observed. The profiles were measured at the beginning of June and at the end of June 2024. The differences observed in the flow values indicate that the water inflow was increased at the beginning of June, which was actually to be expected because a higher precipitation was recorded in a wider area in the previous period. The power was calculated depending on the achieved head, which is a variable value subject to change.

Table 6. Calculated powers of potential hydroelectric power plants for Profiles 1 and 2

Profile	Flow (m^3/s)	Density (kg/m^3)	Gravity acceleration (m/s^2)	Net head (m)	Efficiency (%)	P(W)
1 - 6 June 2024	3.18	1000	9.81	0.5	0.8	12470
				0.75		18706
				1		24941
				1.25		31176
				1.5		37411
				1.75		43647
				2		49882
2 - 6 June 2024	3.00	1000	9.81	0.5	0.8	11760
				0.75		17640
				1		23520
				1.25		29401
				1.5		35281
				1.75		41161
				2		47041
1 – 20 June 2024	1.75	1000	9.81	0.5	0.8	6875
				0.75		10312
				1		13750
				1.25		17187
				1.5		20625
				1.75		24062
				2		27499
2 - 20 June 2024	1.77	1000	9.81	0.5	0.8	6934
				0.75		10401
				1		13867
				1.25		17334
				1.5		20801
				1.75		24268
				2		27735

The location where the measurements were made in Lovrentovec is between the hydrological stations Ključ and Tuhovec. Lovrentovec is located downstream of the hydrological station Ključ and upstream of the station Tuhovec (Figure 8).

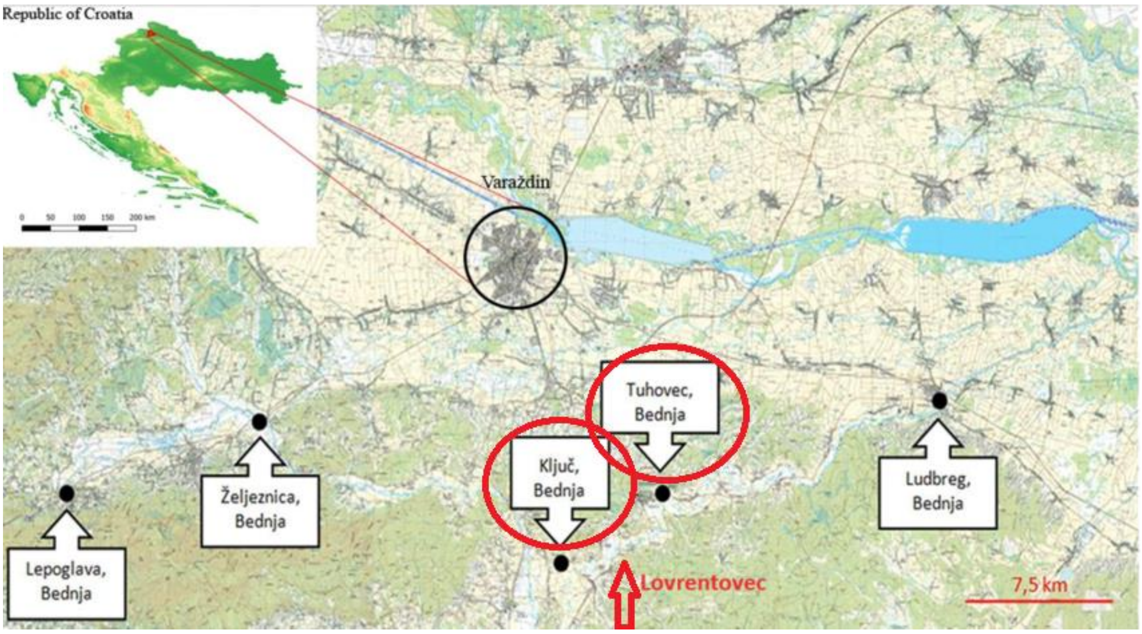

Figure 8. View of the hydrological stations Ključ and Tuhovec [3]

According to the data on the website of the Croatian Meteorological and Hydrological Service (*DHMZ - Državni hidrometeorološki zavod*), for the period from 2014 to 2023, the values of maximum and minimum flows at the hydrological stations Ključ and Tuhovec measured for each year in the observed period were read, as shown in Table 7.

Table 7. Values of maximum and minimum average daily flows at the stations Ključ and Tuhovec for the period from 2014 to 2023 [8]

Year	KLJUČ		TUHOVEC	
	Qmax (m^3/s)	Qmin (m^3/s)	Qmax (m^3/s)	Qmin (m^3/s)
2014	80.62	1.40	123.6	1.70
2015	77.75	1.14	84.38	1.63
2016	71.88	0.81	75.69	0.92
2017	95.87	0.88	101.5	1.23
2018	81.98	0.78	86.77	0.92
2019	78.15	1.11	85.63	0.97
2020	46.23	1.56	43.89	1.84
2021	63.82	0.91	66.55	1.16
2022	43.97	0.50	50.64	0.16
2023	85.65	1.11	112.5	1.09
Average:	72.59	1.02	83.12	1.16

Furthermore, with the obtained average value for the maximum flow over a certain period and the average value for the minimum flow for a certain period, it is possible to start calculating the power depending on the maximum and minimum flow of the Bednja River through the hydrological stations Ključ and Tuhovec. For the hydrological station Ključ, the value of the average maximum daily flow over a certain period is 72.59 m^3/s, while the value of the average minimum daily flow is 1.02 m^3/s. On the other hand, for the hydrological station Tuhovec, the value of the average maximum daily flow is 83.12 m^3/s, and for the average minimum daily flow, the flow value is 1.16 m^3/s. The values of the maximum and minimum daily flow at the Ključ station are lower than the values of the same flows for the Tuhovec station. The power was calculated according to expression (1) for each station separately, and the obtained results are shown in Table 8.

Table 8. Calculated powers of potential hydroelectric power plants for the stations Ključ and Tuhovec.

Station	Flow (m^3/s)	Density (kg/m^3)	Gravity acceleration (m/s^2)	Net head (m)	Efficiency (%)	P(W)
Station Ključ/Qmax	72.59	1000	9.81	0.5	0.8	284851
				0.75		427277
				1		569702
				1.25		712128
				1.5		854553
				1.75		996979
				2		1139404
Station Ključ/Qmin	1.02	1000	9.81	0.5	0.8	4000
				0.75		6000
				1		8000
				1.25		10000
				1.5		12000
				1.75		14000
				2		16001
Station Tuhovec/Qmax	83.12	1000	9.81	0.5	0.8	326143
				0.75		489215
				1		652287
				1.25		815358
				1.5		978430
				1.75		1141501
				2		1304573
Station Tuhovec/Qmin	1.16	1000	9.81	0.5	0.8	4556
				0.75		6834
				1		9112
				1.25		11389
				1.5		13667
				1.75		15945
				2		18223

For each individual turbine, or the turbine that uses the kinetic energy of water and the one that uses the potential energy of water, the powers were determined for the observed location. It was established that the powers for the turbine that uses the potential energy of water are much higher compared to the turbines that would use the kinetic energy of water. The values obtained for the power of the SHPP that uses the potential energy of water are more than 100% higher than the values obtained for the turbines that use the kinetic energy of water.
Likewise, if the results are compared, it is obvious that, for turbines that use the kinetic energy of water, the speeds decrease as the width between the blades increases, and as a result the inlet surfaces constantly increase and the power of the kinetic turbine itself increases.
According to the results, for turbines that use the potential energy of water, or with the obtained power values, it is evident that with an increase in the achieved head, the power value itself

increases. Namely, the greater the flow is, the greater the power will be. The highest power values were obtained for Profile 1 because Profile 1 also had the highest measured flow on 6 June 2024. Then, the highest power values based on the average daily maximum and minimum flows (values taken from the *DHMZ* website) were obtained at the Tuhovec hydrological station for the maximum flow at that location. Likewise, if the results are compared, it is evident that the power values for the minimum flow are also higher at the Tuhovec location than at Ključ. The power range for potential turbines lies in the value of the selected head, or the height of the dam, which ranges from 0.5 m to 2 m, which is actually a variable value that can be regulated, depending on the available capacity of the watercourse, or the available height, so as to avoid water overflows. The value of flow also plays a role in the power values for turbines that use potential water energy. It should also be considered that increasing the height of the dam also increases the load on the sluice gate, due to the hydrostatic and hydrodynamic pressure of the water.
For turbines that use the kinetic energy of water, logically, the values depend on the water velocity itself in different parts of the watercourse. For the calculation of power for kinetic turbines, average water velocities were used, which directly affects the results. It is also evident that the velocities are highest in the middle of the cross-section of the watercourse bed, while the velocities decrease moving towards the edge of the bed on either side of the bank. For kinetic turbines, or the calculation of power, it can be seen that increasing the inlet surface also increases the power of the turbine. The calculated powers of hydroelectric power plants that use the kinetic energy of water were obtained for low water levels, or low flows in relation to the entire year, since the measurements were made in the dry period of the year. With an increase in flow, the average water flow velocities are expected to increase, which, with an increase in the inlet velocity, increases the power of such turbines. This calculation also requires measurements of flows and velocities during the period of the year with higher flows (rainy periods), while determining the complex relationships between flow and velocity, as well as the cross-sectional area, which is beyond the scope and purpose of this paper.

5. CONCLUSION

The objective of this paper was to establish the hydropower potential of the Bednja River in the settlement of Lovrentovec for the construction of turbines that use kinetic or potential water energy. The results show that the presence of a small hydroelectric power plant in this area would be feasible. Although the values are on the side of turbines that use potential water energy, it is known that these same turbines are more expensive to build, that is, initial investments in such a plant are expected to be higher. Turbines that use potential water energy, although with large investment resources, do not require much maintenance and additional costs later. On the other hand, the power calculated for turbines that use kinetic water energy is lower, but the advantage of such construction lies in lower initial investments with constant maintenance. However, such plants are much easier to put into operation and constantly monitor their operation.

The results obtained for turbines that use kinetic water energy show that the velocity of the watercourse is variable and depends on the flow or precipitation in the wider area around the Bednja River, and therefore the results, which were obtained on two occasions, one in early June, the other in late June 2024, are different. The average values of the maximum and minimum average daily flow, which is required to calculate the power of turbines that use potential water energy, were obtained at the hydrological stations in Tuhovec and Ključ. Since the location in Lovrentovec is halfway between Ključ and Tuhovec, the results are consistent with the thesis that in Lovrentovec the power values for turbines that use potential water energy should be higher than in Ključ and lower than the power values at the Tuhovec hydrological station.

In any case, at a time when the consequences of climate change are evident in all aspects of life, investing in renewable energy sources is becoming one of the most important topics today. Although there is a decline in the construction of larger hydroelectric power plants, there is a place for small hydroelectric power plants, which can be constructed in different locations and can certainly serve as a better and less harmful solution compared to larger hydroelectric power plants. Due to their numerous advantages, small hydroelectric power plants provide the opportunity for a cleaner environment and cheaper energy. Every small hydroelectric power plant can help in flood protection and there is no requirement for a large area. The possibilities for finding a location for the construction of small hydroelectric power plants are increasing, but humanity needs to be much more involved in such projects, and the key lies primarily in education about such types of plants, their possibilities, advantages, disadvantages and the improvement with which they can contribute to the environment.

Hydroelectric power plants that use the kinetic energy of water generally have a smaller impact on the watercourse and ecosystem compared to hydroelectric power plants that use the potential energy of water. The fact that kinetic turbines do not require raising the water level with dams, as well as the simpler construction of the facility and the smaller watercourse area occupied compared to potential hydroelectric power plants, imply a lower environmental impact.

One of the approaches to exploiting the hydropower potential of the Bednja River involves a combination of small hydroelectric power plants and solar photovoltaic systems, which can ensure stable energy production over a longer period of time, while reducing dependence on hydrological conditions and increasing energy efficiency. For this location, it is planned to continue this kind of research on the complementarity of hydro energy and the energy of solar photovoltaic panels, which has also already been initiated on the Bednja River [13].

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