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THE SELECTION OF A SMALL HYDRO POWER PLANT (SHPP) SOLUTION IN LINE WITH THE ECOSYSTEM

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Abstract. *Population growth and new forms of energy use have the effect that the energy demand grows year after year. The harmful influence of the use of fossil and nuclear fuels has influenced the intensive development of renewable energy sources (solar energy, small hydro power plants, wind energy, bio-renewable sources - biomass, geothermal energy). This paper gives an overview of the choice of design solution, technical parameters and the efficiency of small hydro power plants (SHPP) on small watercourses. Special attention in these considerations is dedicated to harmonization of selected solutions with natural resources and protection of ecosystems. In order to define the technical solution of one small HPP on a small watercourse, the following analyzes and studies need to be done: Hydrological study; Analysis of the available hydro potential; Pre-feasibility study of the chosen technical solution; Study on Environmental Impact Assessment; Analysis of the investment value of the elements of the system and the system as a whole; Analysis of annual fees and expenses. In analyzing the available hydro potential, it is necessary to examine in detail the influence of the minimum sustainable flow rate in the watercourse (biological minimum) both from the aspect of environmental protection and from the aspect of the techno-economic justification for SHPP construction. On the basis of the "cross-cutting" of the results of these analyzes, one can see the techno-economically justified solution for the construction of SHPP in line with the ecosystem. The goal of all previous analyzes is to select a technical solution that maximizes the use of hydro power potential and ensures optimum use of renewable energy sources, while paying special attention to ecology, environmental protection and sustainable development.*

Key words: *small hydro power plant, design solution, ecosystem protection*

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1. INTRODUCTION

Hydroelectric power is a renewable energy source, since the water on Earth is continuously replenished by precipitation. As long as the water cycle continues, we won't run out of this energy source. Hydroelectric energy is the most widely used form of renewable energy, accounting for 16% of global electricity consumption [1]. In 2015, hydropower was Europe's largest renewable energy resource accounting for more than 14% of total primary energy production of renewable energy in the EU-28 (380 TWh electricity generation in EU-28 and 600 TWh in Europe).

Production of electricity from renewable energy sources (RES) has become a major issue in meeting the ambitious European renewable energy targets set in the European Commission (EC) legislations [2] and confirmed in the action plans of the Member States (EU27) [3–5]. From 1990 to 2016, the total growth of electricity production in EU due to hydro power is around 20%.

Modern environmental standards that fall under designated areas such as Natura 2000 and the Water Framework Directive significantly affects small hydro power (SHP) potential. For some countries, the SHP economically feasible potential was reduced by more than a half. According to ESHA [6] research, there is still a large potential for SHP development in the EU-27. Less than half of the potential has already been used - some 44 TWh/ year, and more than 50 TWh/year can be brought in the future. In order to achieve this task and to take advantage of the remaining potential SHP must be designed site by site in order to comply with all the environmental requirements. The most promising countries for SHP further expansion in the EU are Italy, France, Spain, Austria, Portugal, Romania, Greece, Poland and Sweden. Bodies et al. [7] introduce a transparent methodology to assess new suitable locations for mini and small hydro power plants in Europe. The proposed analysis of the technical potential points out the exact geographical locations and their corresponding capacities instead of only a theoretical potential; therefore it can serve as a reference for the policy debate over the sustainable management of water resources. Table 1 shows average GTC, TEP and EFP in mentioned European countries according to World Energy Council, Hydropower & Dams, World Atlas and ESHA.

Table 1 Average GTC, TEP and EFP in European countries

	GTC	TEP	EFP
Austria	88333	61667	56000
France	223333	110000	86533
Germany	120000	28567	17013
Greece	80000	18333	14667
Italy	243333	108333	65000
Poland	24333	13250	7500
Portugal	32050	26190	20528
Romania	70000	38170	26235
Spain	154000	66500	40667
Sweden	192000	130000	91333

GTC – Gross Theoretical Capability [GWh/year]
TEP – Technically Exploitable Potential [GWh/year]
EFP – Economically Feasible Potential [GWh/year]

In many Member States, stakeholders complained about environmental requirements, in particular the Environmental Impact Assessments (EIA) and the Water Framework Directive

(WFD). The criticism refers also to the fact that the environmental benefits of the renewable energy systems are not taken into account properly.

The environmental requirements for SHP are too restrictive and do not apply criteria that consider its benefits; an incoherent implementation of the WFD has also become a strong impediment for the SHP sector, by assuming hydropower as a menace for the water bodies and their ecological status, and by imposing restrictive administrative and environmental requirements, that lead to a decreasing number of hours of production and therefore to a lower profitability. The Western Balkans still represent a significant portion of untapped European hydropower potential (table 2). Efforts are being made to strengthen regional cooperation between the European Union and Albania, Bosnia and Herzegovina, Kosovo, Macedonia, Montenegro and Serbia. In 2016 the European Union commissioned a regional hydropower master-plan for the Western Balkans, which will aim to define how to develop the region's hydropower potential in a way that balances energy generation, flood protection and ecological concerns.

As stated before, the development of hydropower projects in the last decade has been accompanied by controversy and concern for the ecological aspect. The challenge for the investors is to align financial feasibility of such projects with social and economic aspects. Accordingly, the advantages and disadvantages of the three groups of aspects are considered: economic, social and environmental aspects [8].

Economic aspects are: long life and low operation and maintenance cost, load flexibility (hydropower plant with reservoirs primarily), integration and fostering regional development, providing new employment opportunities, best energy efficiency and independent source of energy, etc. Disadvantages of the economic aspects are: high investments, long term planning, precipitation dependency, reliance on foreign contractors and funding.

Table 2 The Western Balkans hydropower potential

Country	Net generation (GWh/year)	Technical potential (GWh/year)	Unused technical potential (GWh/year)	Utilization rate
Bosnia and Herzegovina	4552	24000	19448	19%
Albania	3657	15000	11343	24%
Serbia	10011	19000	8989	53%
Macedonia	881	5000	4119	18%
Montenegro	1536	4269	2733	36%
Kosovo	76	800	724	10%

The advantages of social aspects are: providing flood protection, enhancing recreational facilities, enhancing accessibility of the territory and its resources (access roads and ramps, bridges), providing opportunities for construction and operation with a high percentage of local manpower and improving living conditions. On the other hand, hydropower plant can cause resettlement, local landscape and land use can be modified and there is certain impact on the life of the population and their cultural heritage.

Last but not least are great environmental advantages of SHP since it produces no atmospheric pollutants, nor pollutes the water, produces no waste, and avoids depleting non-renewable fuel resources. Finally there are some environmental disadvantages related to the use of water resources: inundation of terrestrial habitat, modification of hydrological regimes and aquatic habitants, barriers to fish passage.

2. HYDROPOWER FACILITIES

Generally speaking there are three types of hydropower facilities: impoundment, pumped storage and diversion. A fourth possible solution is in-stream hydropower scheme within the small dam in the riverbed, where the river flow is not diverted, but this type of hydropower scheme can be used only for low head locations.

The most common type of hydroelectric power plant is an impoundment facility [9]. An impoundment facility, typically a large hydropower system, uses a dam to store river water in a reservoir. Hydropower plants that are permitted to regulate flows in the river can store and utilize water as needed to meet variations in electrical demand. However, there are environmental concerns associated with water storage or "peaking" operations, since they alter natural water level and flow cycles in the river. Damming interrupts the flow of rivers and can harm local ecosystems, and building large dams and reservoirs often involves displacing people and wildlife and requires significant amounts of carbon-intensive cement.

Pumped storage [10] is the process of storing energy by using two vertically separated water reservoirs. Pumped storage facilities store excess energy as gravitational potential energy of water. Although pumped storage is able to store large amounts of energy and despite the fact that it has the largest capacity of any other storage types, it is limited because the facilities can only exist in areas with a very specific topography.

Third type is a diversion [11], sometimes called run-of-river (ROR), facility channels a portion of a river through a canal or penstock. Water is not stored for run-of-river schemes and thus European Small Hydropower Association (ESHA) states they "do not have the same kinds of adverse effects on the local environment as large-scale hydro", when properly and lawfully built. ROR developments often incorporate a dam and a reservoir, but generally at a much smaller scale. ROR do not alter the natural flow patterns downstream of the hydroelectric facility, but even a small dam and long diversion length can have significant influence on local ecosystems, especially in the case of low river residual flow.

Some European and also Balkan countries are using fixed thresholds for river residual flow; others are more pragmatics and give more importance to the case by case study (hydro biological study). WFD is in course of implementation and in general its implementation causes higher residual flow for SHP and an increase in their operating costs. There is a need for analysis and discussion of the imposition of minimum ecological flows and compensatory measures for the implementation of SHP involving a joint force between national authorities and the promoters.

2.1 Analysis of potential hydropower location

In order to define the technical solution of one SHPP on a small watercourse, the following analyzes and studies need to be done:

- Hydrological study
- Analysis of the available hydro potential
- Pre-feasibility study of the chosen technical solution
- Study on Environmental Impact Assessment
- Analysis of the investment value of the elements of the system and the system as a whole
- Analysis of annual fees and expenses

Available hydro potential is usually calculated according to the location hydrology (flow duration curve-FDC) and available gross head obtained from geodetic measurements. The flow duration curve (FDC) is a graphical representation of the observed historical variation of stream flows with different time resolutions such as daily (1-day), weekly (7-day) monthly (30-day), and seasonal at the sampling site that show the percent of time specified discharges will be equaled or exceeded over different time scales of interest [12]. Environmental flow (EF) is usually estimated using flow duration curve (FDC) and derived using two approaches: (a) period of record and (b) stochastic approaches for daily, 7-, 30-, 60-day moving averages.

An environmental flow management decision is difficult due to the uncertainty regarding how to quantify the ecological base flow. At present, the relevant calculation methods are relatively matched and there are about more than 200 kinds of methods in the world that can be divided into the hydrological, hydraulic, physical habitat and comprehensive methods. The hydrological method is the most commonly used method to calculate river ecological base flow in the world, which uses simple hydrological indicators to set the flow. The result is usually a single flow, and a commonly used method is the Tennant method [13]. The hydraulic method uses the Manning equation to establish the relationship between environmental flow and hydraulic factors, and the commonly used method is the R2Cross method [14]. The physical habitat method is an improved vision of the hydraulic method, and determines the ecological base flow by establishing the relationship between the environmental factors of protected species habitat, the hydraulic and flow conditions, whereas the commonly used method is the environmental hydrodynamic method [15]. This comprehensive method emphasizes the river is an integrated ecosystem. However, this method requires a lot of ecological data, and the evaluation takes a long time, which limits its application [16].

In analyzing the available hydro potential, it is necessary to examine in detail the influence of the minimum sustainable flow rate in the watercourse (biological minimum or environmental flow) both from the aspect of environmental protection and from the aspect of the techno-economic justification of the construction of the SHPP.

On the basis of these analyzes, one can see the techno-economically justified solution for the construction of SHPP in line with the ecosystem. The goal of all previous analyzes is to select a technical solution that maximizes the use of hydro power potential and ensures optimum use of renewable energy sources, while paying special attention to ecology, environmental protection and sustainable development.

These analyzes are prepared by varying the installed flow from the minimum possible to the maximum possible (or the diameter of the diversion pipeline in the ROR hydroelectric power plants) as well as the values of the environmental river flow. On the basis of the "cross-cutting" of the results of these analyzes, where water potentials are considered (Daily Flow Duration curve - FDC), system geometry, investments, operating costs, revenues, etc., one can see the techno-economically justified solution to the system of the considered small hydroelectric power plant. In principle, a technical solution should be sought between the criterion of the fastest recovery period, i.e. the number of years of simple payback (SPB) investments and twelve-year net inflows (guaranteed feed-in tariff) less investment. If the concession is obtained over a longer period of time, a technical solution is usually requested to the right of the maximum value of the function of a 12-year inflow minus the value of the investment.

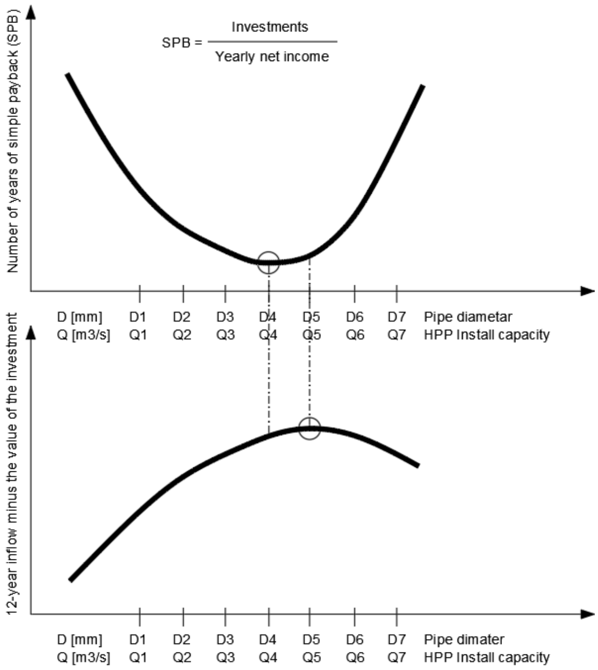

Fig. 1 Optimal technical solution for SHPP

The basic requirement for investing in one hydro-energy facility is the techno-economic consideration of the justification of the investment. The aim is to define a hydro power facility with maximum income for the smallest investment, with the criteria for its compliance with the ecosystem. As a basis for possible production, hydro potential is usually calculated according to the location hydrology (flow duration curve-FDC) and available gross/net head. The calculation of possible production over the year is reduced essentially to the integration or calculation of the area under the flow duration curve (FDC), which is proportional to the production of energy. The figure 2 shows the usual curve of average daily flow (FDC - Flow Duration Curve).

Starting from the need for a more realistic determination of the production and power of the SHPP, the following must be considered in detail:

- Disposition of main facilities and equipment at the SHPP
- The existence of a guaranteed environmental flow that must be provided on the water catchment
- The existence of a technical minimum of the turbine (QTmin) under which work is unacceptable
- Existence of hydraulic flow losses
- The existence of a change in the efficiency of the turbine in function of discharge
- Change in the generator efficiency depending on the load
- Transformer efficiency and SHPP own consumption.

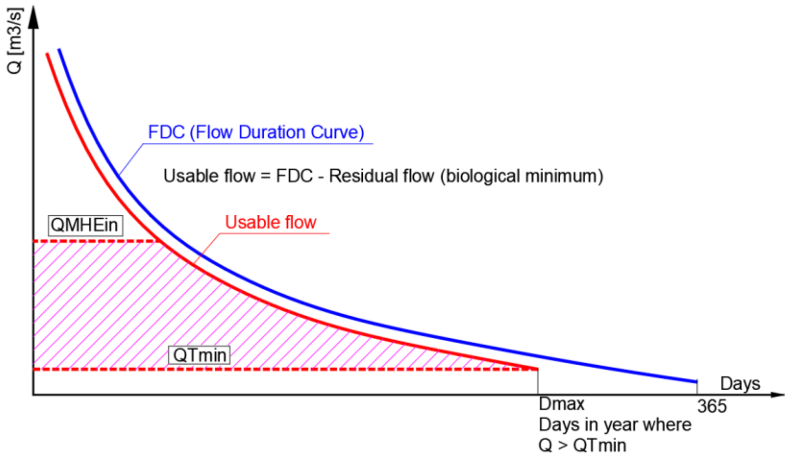

Fig. 2 Flow Duration Curve-FDC

The area under the FDC represents the amount of water flowing through the considered profile. Since it is a diversion facility with a Tyrolean weir, a channel and a pipeline, the environmental flow (biological minimum) must be deducted from the available quantity, which must be released into the river.

On the other hand, the available turbine capacity limits the use of flows to values less than the installed flow rate of the SHPP (QMHEin) even though there is more water on the watercourse. Since, for economic reasons, SHPP are not designed with more turbine aggregates (usually one or two), the technical minimum of turbine (QTmin) also appears as a limiting factor in the use of potential at minimum inflows.

A small, or non-existent, useful volume (Tyrolean weir with sand trap) as well as downstream variations in level or flow, prevents concentration or storage of small flows and their use in a shorter time interval during the day. All of this points to the reality of the need that flow less than the technical minimum of an aggregate (QTmin) bypassing the turbine in a certain period, i.e. available energy is not used.

Based on the aforementioned, it can be concluded that the use of water on one side at maximum inflows is limited to the value of the installed capacity of SHPP (QMHEin), and on the other hand under the conditions of minimum inflows by the criteria of the environmental flow and the characteristics of the turbine aggregate (QTmin). These boundary conditions show how much of the available hydro potential can be used by SHHP and which is the maximum number of working days (Dmax) during the year.

When calculating the SHPP production, it is important to note that the entire production is based on data from the hydrological study (FDC) and how accurate these data are, the same is also the analysis of energy production. The energy produced on the facility of one SHHP, besides the inflow (FDC), depends on many other conditions. The most important conditions are: available geodetic height (gross head); efficiency of turbine; efficiency of electrical equipment (generator, transformer); the time of operation of the hydro power plant; characteristics of inlet installations (pipe diameter, pipeline length, etc.); functionality of equipment and natural conditions.

One of the most important factors affecting the production of SHPP is the value of the environmental flow (biological minimum) that should be left in the watercourse. These are two opposite criteria, for higher value of environmental flow, SHPP have lower production and vice versa. For each Investor, the starting point for making a better capital investment is in the decision-making phase. The main goal in the development of a hydro-energy facility on a selected location is to minimize the cost of exploration works. In other words, prior to entering into the procedure for obtaining the design conditions and construction permits, the goal is to minimize preliminary investigations and to evaluate the cost-effectiveness of SHPP location. Minimally, the investigation involves the development of a hydrological study of the considered area and the minimum required geodetic measurements. At this stage, the value of the environmental flow is usually not known, and it significantly influences the techno-economic justification of the construction of a small hydro power plant. The required minimum value is obtained after the development of an environmental impact study and obtaining conditions from water management authority. Practice has shown that the value of environmental flow at some watercourse ranges from about 10% to 30% of the mean annual flow. In accordance with the aforementioned, a techno-economic and ROI (return of investment) analysis should be made in order to find best solution that meets both requirements: protection of the environment and the viability of investments with respect of good technical practice. This implies that all technical solutions should be calculated with the variation of environmental flow in the range from 10% to 30% of the mean annual flow.

2.2 Example results of one SHPP location

In order to analyse the available hydropower potential of certain locations, in the previous period, the authors of this paper have performed an analysis of a large number of locations in the Serbia. ROR small hydroelectric power plants locations were primarily analysed. In order to show an example of the analysis with technical solution that maximizes the use of hydro power potential and ensures optimum use of renewable energy sources, while paying special attention to ecology and environmental protection, following data were prepared:

- Flow duration curve based on minimum period of 20 years
- Available gross head at location
- Turbine efficiency in function of installed flow rate percentage
- Generator efficiency in function of load
- Calculated annual energy production for chosen solution
- Calculated investment cost for considered solution

Input data for location:

- Upstream water level: app 1025 m.a.s.l.
- Downstream water level: app 927 m.a.s.l.
- Pipe length: app 2145 m
- Average flow: Q_sr = 0.50 m^3/s

Obtained results are presented on following figures:

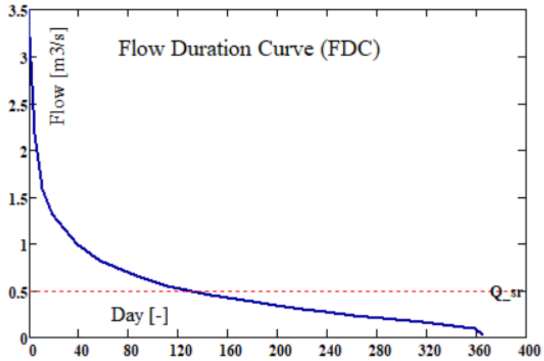

Fig. 3 Location flow duration curve

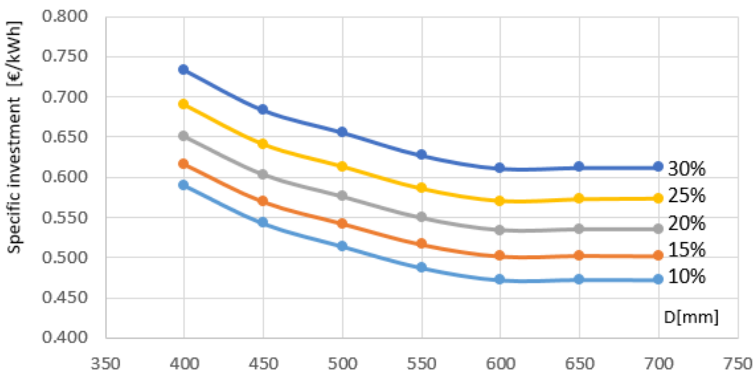

Fig. 4 Specific investment in function of pipe diameter, installed and environmental flow

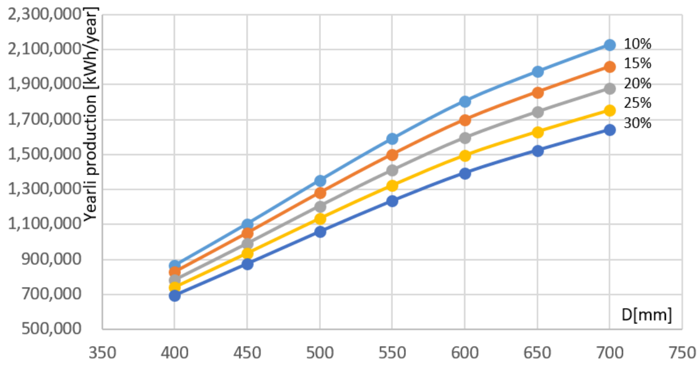

Fig. 5 Annual production (kWh) in function of pipe diameter, installed and environmental flow

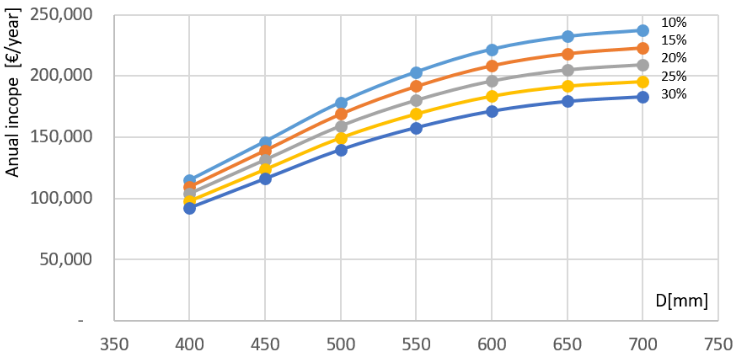

Fig. 6 Annual income in function of pipe diameter, installed and environmental flow [percent of average flow]

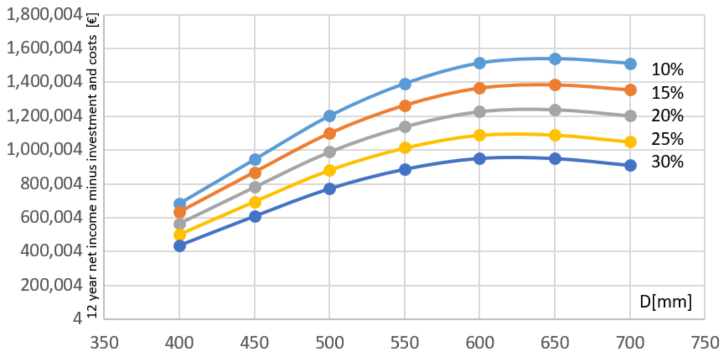

Fig. 7 A 12-year net income minus investment and costs in function of pipe diameter, installed and environmental flow [percent of average flow]

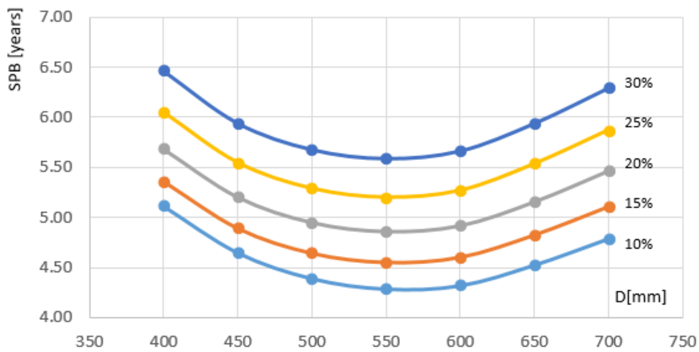

Fig. 8 ROI (SPB) in function of pipe diameter, installed and environmental flow [percent of average flow]

3. Conclusion

In analyzing the available hydro potential, it is necessary to examine in detail the influence of the minimum sustainable flow rate both from the aspect of environmental protection and from the aspect of the techno-economic justification of the construction of the SHPP. On the basis of the "cross-cutting" of the results of these analyzes, one can see the techno-economically justified solution for the construction of SHPP in line with the ecosystem. SHPP ROR scheme is in line with European regulations (EIA and WFD) and from the proper analysis a technical solution that maximizes the use of hydro power potential and ensures optimum use of renewable energy sources can be found, while paying special attention to ecology, environmental protection and sustainable development.

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IZBOR TEHNIČKOG REŠENJA MALE HIDROELEKTRANE (MHE) U SKLADU SA EKOSISTEMOM

Ključne reči: *male hidroelektraRast populacije kao i novi načini korišćenja energije značajno utiču na rast potrošnje energije iz godine u godinu. Štetni uticaji korišćenja nuklearnih i fosilnih goriva uticali su na intenzivni razvoj obnovljivih izvora energije (solarne, malih hidroelektrana, biomase, geotermalne energije). Ovaj rad daje pregled izbora projektnog rešenja, tehničkih parametara i efikasnosti malih hidroelektrana (MHE) na malim vodotocima. Posebna pažnja u ovim razmatranjima posvećena je usklađivanju odabranih rješenja sa prirodnim resursima i zaštitom ekosistema. Da bi se na malom vodotoku definisalo tehničko rešenje jedne MHE, potrebno je uraditi sledeće analize i studije: Hidrološka ispitivanja; Analiza raspoloživog hidro potencijala; Prethodna studija izvodljivosti izabranog tehničkog rešenja; Studija o proceni uticaja na životnu sredinu; Analiza vrednosti investicije elemenata sistema i sistema u celini; Analiza godišnjih naknada i troškova. Prilikom analize raspoloživog hidro potencijala neophodno je detaljno ispitati uticaj minimalnog održivog proticaja u vodotoku (biološki minimum) kako sa aspekta zaštite životne sredine, tako i sa aspekta tehnološko-ekonomske opravdanosti izgradnje MHE. Na osnovu "ukrštanja" rezultata ovih analiza, vidljivo je tehnološko-ekonomski opravdano rješenje za izgradnju MHE u skladu sa ekosistemom. Cilj svih prethodnih analiza je odabrati tehničko rješenje koje maksimizira korištenje hidroenergetskog potencijala i osigurava optimalno korištenje obnovljivih izvora energije, a posebnu pažnju posvećuje ekologiji, zaštiti životne sredine i održivom razvoju.*

ne (MHE), projektno rešenje, zaštita životne sredine