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Design and Construction of Mini Hydropower Plant with Propeller Turbine

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Abstract

Nowadays, the hydropower plant is considered as one of the more desirable sources of producing electrical energy due to its environmentally-friendly nature and extensive potential available throughout the world. On the other hand the hydropower plant allows the autonomous production of quantities of electrical energy capable of meeting the requirements of individual users starting from water resources which would otherwise be wasted.

Based on the continuous requirement for renewable energy, a mini hydropower plant by using a propeller turbine is discussed due to its simple structure and easy production. The key parameters are studied for designing a hydropower plant, like water head, water flow-rate and turbine speed.

The propeller turbine is considered for working under the best working conditions. During the detailed design of a hydropower plant some parameters are known and give us some indication about the geometry of the turbine and this is the starting point. The indication parameters are: turbine power, runner diameter, turbine speed, turbine housing design, draft tube, etc.

A detailed design and construction of a mini hydropower plant was done for a recreational center in the village Sllakovc, Vushtria, Republic of Kosovo, financed by European Union. The hydropower plant consists of water intake, penstock, hydro turbine, control system, and a hydropower house. A synchronous generator is connected directly to the turbine which converts the hydraulic energy into electrical energy.

Keywords:	Design; Hydropower plant; Propeller turbine; Design parameters; Efficiency

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1. Introduction

Energy is one of the more fundamental elements in our universe. It is based for survival and inevitably for the development of activities for promoting education, health, transportation and infrastructure for attaining a reasonable standard of living and is also a critical factor for economic development and employment [1, 2, and 3].

Over the past decade, as well as now, problems with energy supply are present everywhere in the world. Problems coming from different sources like the oil crisis, climate change, technical capacity limits, continuously growing demands and restrictions on the whole sale. These difficulties are continuously growing, which represent an urgent need for using alternative sources which would enable assurances of their solutions. One of these alternative sources is to generate electricity as close as possible to consumption demands by using renewable sources that do not cause environmental pollution. The renewable sources are considered to be energies produced by wind, solar, geothermal, hydropower, etc., [2].

Hydropower energy is part of a renewable energy resource which comes from the motion of water through hydropower device in order to generate electricity. When the water is flowing by the force of gravity, its potential energy converts into kinetic energy. This kinetic energy of the flowing water turns blades or vanes in hydro turbines, and then energy is changed to mechanical energy. The turbine turns the generator rotor which converts this mechanical energy into electrical energy [4]. Many other components may be used in a hydropower system to produce energy. It is perhaps the oldest renewable energy technique.

Depending on the capacity of water sources and flow of water by the force of gravity, hydropower plants may be large, small, mini, and micro. The larger hydropower plants would supply many consumers with electricity, while small mini and micro hydropower plants operate individually for their own energy needs or to sell power to utilities. These hydropower plants can provide effective cost of energy to remote rural communities, recreational centers and restaurants which have suitable water sources.

Actually, several schemes for small, mini and micro hydropower plant have been proposed, designed and successfully implemented, including Pelton, Turgo, Francis, Kaplan, propeller and cross flow hydro turbines. The Pelton, Turgo and Francis turbines work with high and medium water heads with less water flow, while Kaplan, propeller and cross flow turbines works with lower heads and larger flow rates.

Nowadays, the propeller turbine is gaining in popularity because it works with very low heads and larger water flow-rates. Many places have good potential with low water heads from 2 to 10 [m] but only a few have been developed because there has been a lack of appropriate turbine design. Typically components of a propeller hydro turbine are shown in Figure 1.

In Kosovo, electricity is generated mainly by coal power plants and only around 5% of consumption comes from hydropower plants. There are some summer houses, recreation centers, restaurants, etc., in the mountains and hills where public electrification is not yet available but water sources exist. Therefore the availabilities of water sources are a main factor in electricity generation from hydro sources.

This paper describes a design and process of construction of a mini hydropower plant. The design of the mini hydropower plant was done by taking into account a lot of requirements during study, like the designing of the turbine and hydropower plant. This hydropower plant was installed at a recreational center in the village of Sllakovc, Vushtria, Republic of Kosovo and financed by the European Union. The hydropower plant consists of a water intake, penstock, hydro turbine, control system, and hydropower house.

2. Design process of hydropower plant

The design process of the hydropower plant, especially for a mini power system with propeller turbine, involves the following steps.

2.1. Measuring of the site data

For determining power generation, there are two major parameters: water flow- rate and water fall head. If these parameters are available then it involves calculations and measuring the net head of the hydropower plant. If the actual flow-rate is lower than the turbine design flow, the turbine will generate very little power. In view of this, it is very important to determine as precisely as possible the water flow-rate and water fall head.

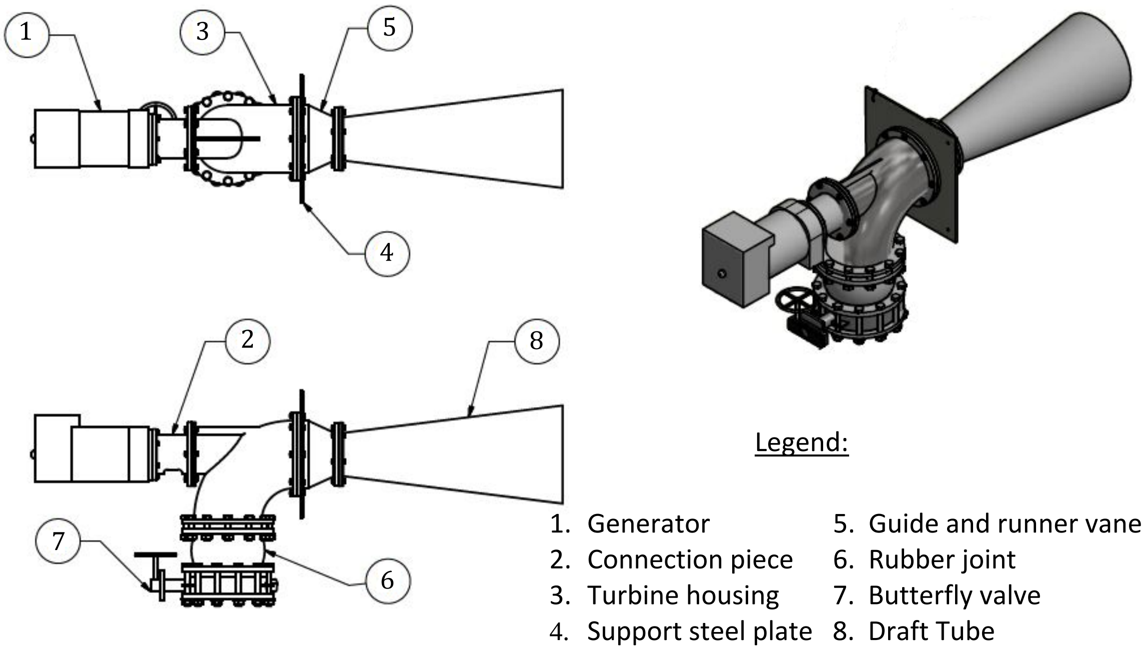

Figure 1: Design of a propeller hydro turbine with generator

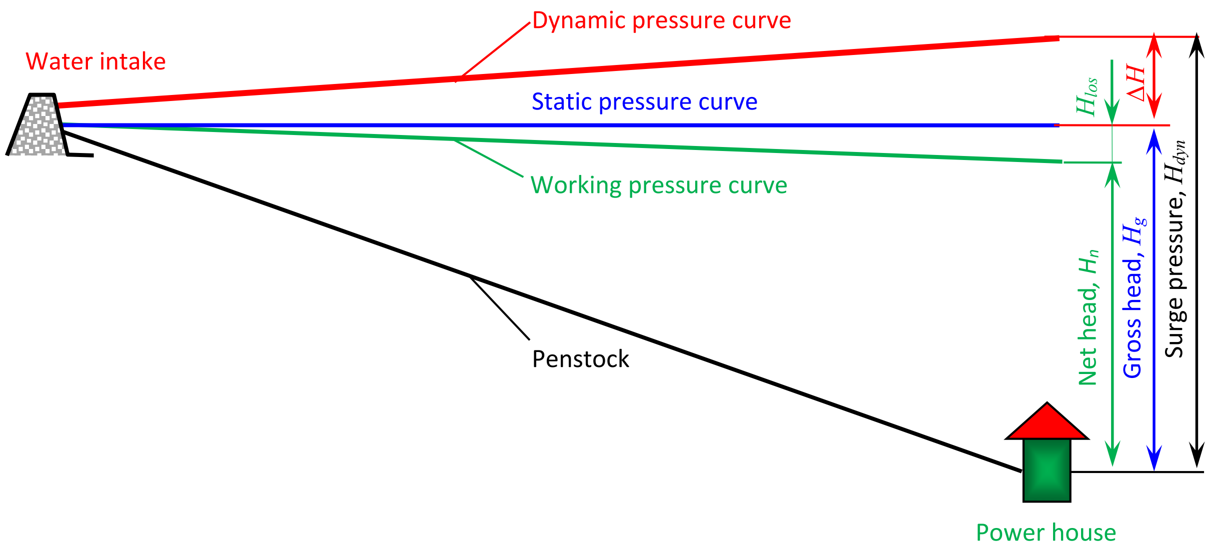

Figure 2: Principal scheme of hydro-electric power system

a. Estimation of the water flow- rate

The water flow rate (Q) can be estimated in different ways but a more suitable method could be measuring the river water flow velocity and river cross-section areas at the same measuring place by employing the following expression:

$$Q = A_r \cdot v_r \text{ [m}^3\text{/s]} \tag{1}$$

where:

A_r [m^2] – river cross-section,

v_r [m/s] – river water-flow velocity.

As is known, the river levels change throughout the seasons, so it is important to measure water flow-rates at various intervals of the year. The best estimation is considered when available data for many years observation are at your disposal. If this is not possible, attempts can be made to determine various annual river flow-rates by discussing with a neighbor, or finding hydrological flow data for your river or a nearby larger river. In most cases these data should be provided from the National Hydrological Institute which is responsible for calculating water flow-rate, quality of water, rainfall, etc.

Using of the all river's water for a hydropower plant is not allowed because certain amounts of water need to flow across the river bed as fish, birds, plants, and other living things rely on your river for survival.

There are more known methods for measuring water flow-rate like: measuring by flow—container, float, and weir [5].

b. Estimation of the net head

Water fall head is also called water pressure which is created by the difference in elevation between the intake of the level of water and the hydro turbine power house, Figure 2.

Water head can be measured as vertical distance or as pressure. Regardless of the size of your stream, a higher head will produce greater pressure, and therefore higher power output at the hydro turbine.

An altimeter can be useful in estimating the head for preliminary site evaluation but should not be used for the final measurement. GPS altimeters are often used even though they provide less accurate measuring. Topographic maps can also be used for providing a very rough idea of the vertical drop along a section of a river's sources. The best way when measuring water head can be done by employing modern electronic digital levels.

Net head (H_n) is calculated by employing the following expression:

$$H_n = H_g - H_{los} \text{ [m]} \tag{2}$$

where:

H_g [m] – The gross head; the vertical distance between water surface level at the intake of water and at the turbine site,

H_{los} [m] – head losses due to the open channel, trash rack, intake, penstock and gate or value. These losses were approximately in some cases around 6% of gross head [2], *ΔH, H_{dyn}* [m] – surge pressure, dynamic pressure appeared during emergency stop of hydro turbine.

2.2. Calculation of output power generation from hydro turbine

The output power generation from the hydro turbine (P_{gen}), can be estimated by the following expression:

$$P_{gen} = \rho \cdot g \cdot H_n \cdot Q \cdot \eta_t \cdot \eta_{gen} \text{ [W]} \quad (3)$$

where:

$\rho = 1000$ [kg/m^3] – water density,

$g = 9.81$ [m/s^2] – gravity acceleration,

η_t [%] – turbine efficiency,

η_{gen} [%] – generator efficiency.

2.3. Calculation of the hydro turbine specific speed

The specific speed gives an indication of the geometry of the turbine and it is the starting point for detailed design. There are many different ways for determining the specific speed (N_s) of a hydro turbine. For our case, the following expression was used:

$$N_s = \frac{N \cdot \sqrt{Q}}{H_n^{3/4}} \quad (4)$$

where:

N [rpm] – turbine's rotation speed.

The choices of the turbine rotation speed depend on the speed of the generator and the type of drive used. Often it is possible to use a direct drive, with the turbine runner attached to the end of an extended generator shaft. On the other hand, using a single stage belt drive allows for the possibility of changing the turbine operating speed. This gives more flexibility in the turbine design and when matching to site conditions.

According to Simpson and Williams the expected range of specific speed for propeller turbine values is $70 < N_s < 300$ [6, 7]. If the specific speed is $N_s < 70$, then you should look at other alternative type of turbine – e.g. cross-flow (Mitchell-Banki), pump as turbine or turgo turbine. Other criteria during designing of turbine should avoid specific speed $N_s > 300$ because of this will tend to have a turbine with low efficiency. Where the head is low and the flow high, it might be a good idea to design for parallel turbines, each operating on part of the total flow. Otherwise it is necessary to choose a lower speed for the turbine, which will result in a larger physical size. Two smaller turbines running at higher speed are LESS costly than one large turbine.

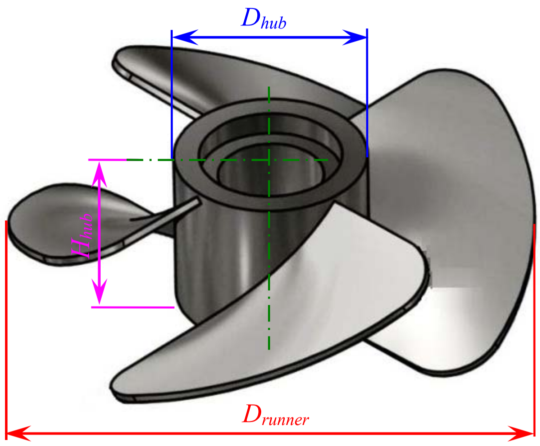

Figure 3: Design of propeller runner performed in Autodesk Inventor 3D

2.4. Calculation of the diameter of the turbine runner and hub

Determining of diameter of the runner (D_{runner}) can be done in different ways. One of the more popular expressions for calculating of the diameter of a propeller turbine runner is:

$$D_{runner} = 84.5 \cdot (0.79 + 1.602 \cdot N_s) \cdot \frac{\sqrt{H_n}}{60 \cdot N} \text{ [m]} \quad (5)$$

The hub diameter of runner (D_{hub}) can be estimated by the following expression:

$$D_{hub} = \left(0.25 + \frac{0.0951}{N_s}\right) \cdot D_{runner} \text{ [m]} \quad (6)$$

Figure 3 shows the design of a propeller runner by introducing the diameter of runner & hub and hub height.

3. Design of a mini hydropower plant in Kosovo

The of a mini hydropower plant was made by several visits during 2013 to the recreational center "Trofta e

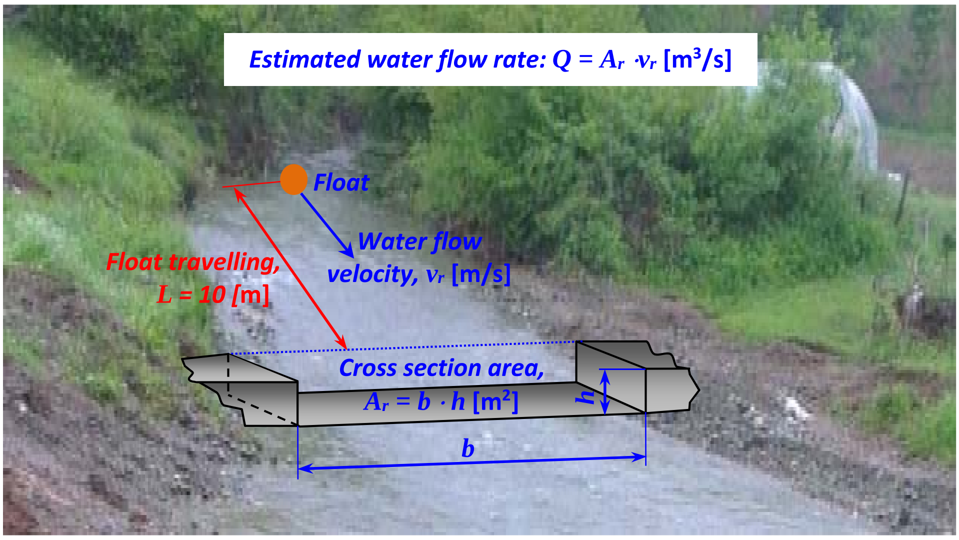

Figure 4: Measuring of water flow-rate by the floating approach

Lumit", Village Sllakoc, Vushtria, Republic of Kosovo to gather important information regarding water flow-rate, water fall height, owner of property, form of investment, etc. The following presented the approach for determining water flow-rate and water head.

3.1. Determining of water flow-rate and gross water head

The water flow-rate is estimated by measuring the river's water flow velocity and river cross-section areas in the place where it is planned building of the water intake, Figure 4.

The river flow changes throughout the seasons, so it is important to measure water flow-rate at various intervals of the year. In most of the cases this data are provided from The National Hydrological Institute. Unfortunately, this kind of data was not available; therefore it was necessary to develop the measuring approach by floating.

The best estimation of water flow-rate is considered when measuring was done covering many years observations of river but this requires a long time to do. In our case, measuring was done once per month during 2013. The critical flow was during three months, like July, August and September 2015 where the levels of water flow were very low and water was used only for ecology and irrigation purposes.

Figure 5 presents the water balance of the Sllakoc River as well as the availability of water for the generation of electricity from water. From the graphs can be seen the available water for generation of energy is $Q_{available}$ = 0.165 [m^3/s] for nine months of the other months the hydropower plant should be stopped. From the graph can be seen, the river water for generation of energy is available only for nine months ($Q_{vailable}$ = 0.165 [m^3/s]), while for other months (July, August and September) is used for irrigation of agriculture's land, therefore the hydropower plant should be stopped.

For determining the sustainability curve of the annual production of electricity by water, by employing data present in Figure 5 and considering ecological flow and the irrigation period, it can be concluded that the mini hydropower plant will be stopped for around 90 days therefore water will flow to its bed and could be used by the community for agricultural irrigation.

Despite the use of water for power generation and other needs for communities, determined ecological flow must be respected. There are different approaches for determining the minimum ecological approach which can be used.

Figure 6 shows how much water is available for generating energy and the sustainability of the River Sllakoc vs days of 2013 year.

3.2. Determining of penstock diameter for the hydropower plant

The penstock (pipeline) diameter depends on these factors:

- Losses in the penstock as a result of friction between the water flow in the penstock and the inside walls of the penstock,
- The thickness of the walls to cover static and dynamic pressure, and
- The cost and installation of the penstock.

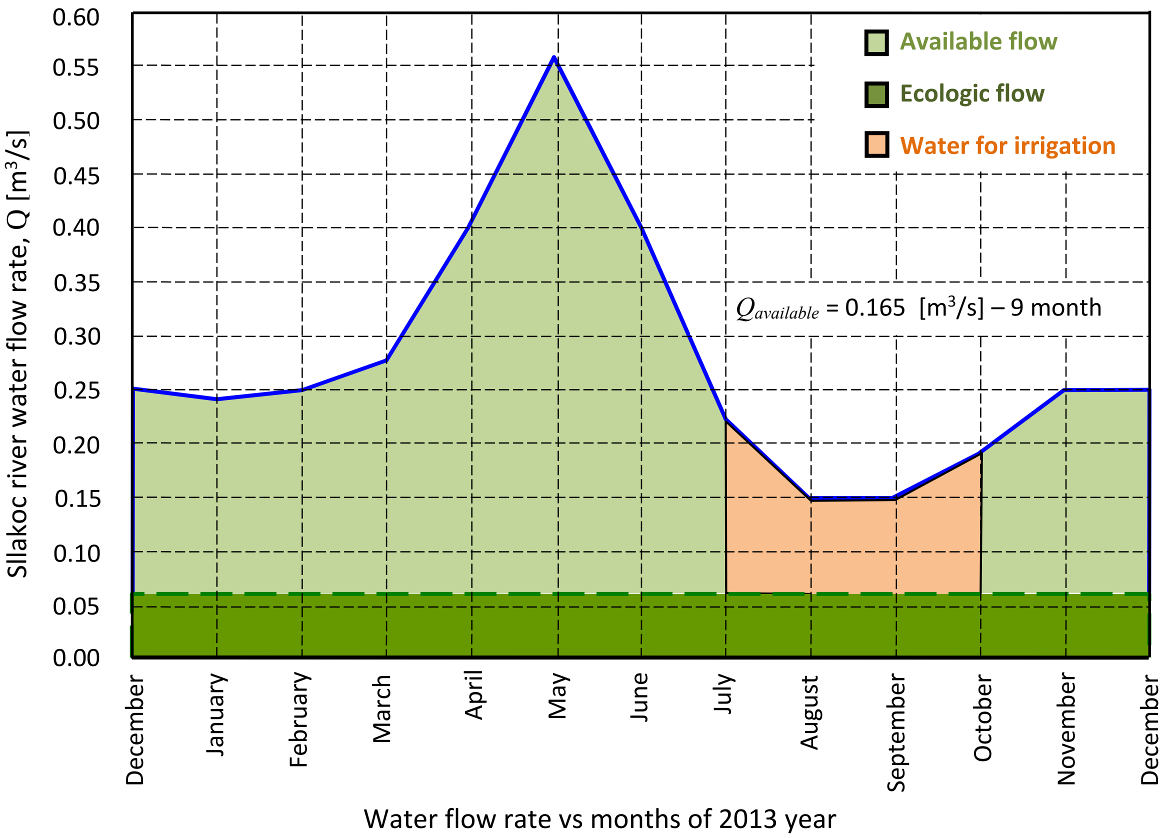

Figure 5: Water balance of Sllakoc River during 2013

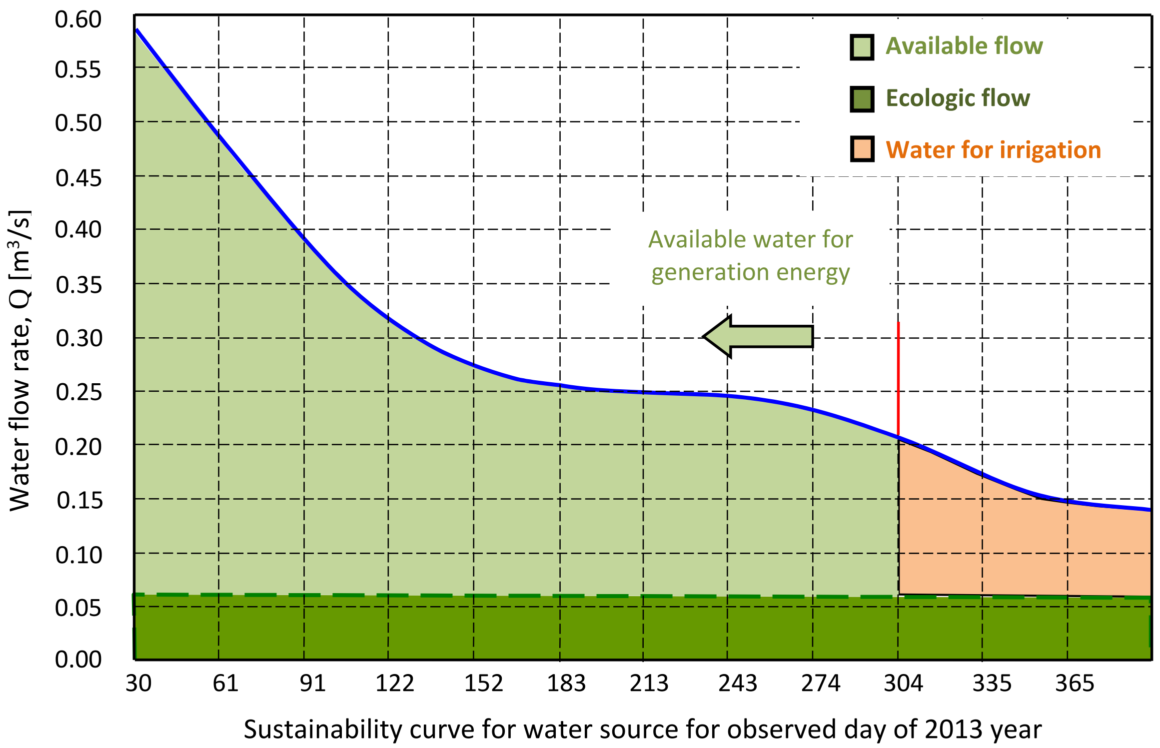

Figure 6: Sustainability of Sllakoc River observed during 2013 year

Table 1: Water flow velocities for different penstock diameters and water flow-rate Q = 0.165 [m^3/s]

Internal penstock diameter, D [mm]	200	250	300	350	400	450
Water flow velocity, v [m/s]	5.25	3.36	2.33	1.71	1.31	1.04

Table 2: Coefficient of friction depending on the Reynolds Number

If $R_e \leq 2000$ flow is Laminar	If $2000 < R_e < 4000$ flow is transition zone	If $R_e \geq 4000$ flow is turbulent
$\lambda = \frac{64}{R_e}$	-	$\lambda = \left(1.8 \cdot Log\left(\frac{R_e}{7}\right)\right)^{-2}$

As a result of reducing of penstock diameter for a certain amount of water flow, velocity of water in the penstock increases, and consequently the energy losses increase. The greater the energy losses mean the smaller the energy generation. On the other hand, by increasing the penstock diameter, the energy losses will decrease then the energy generated is greater.

The cost of the penstock drastically increases when increasing the penstock diameter. So we are pushed to have balance between energy loss, pipe diameter, and material and wall thickness of the pipe.

For the initial design, the water flow speed can be obtained from v = 1 ... 2 [m/s]. The internal diameter of the penstock (D) can be determined by the following expression:

$$D = \sqrt{\frac{4 \cdot Q}{\pi \cdot v}} \text{ [m]} \quad (7)$$

Table 1 shows the estimated water speeds through the penstock for different tube diameters and average flow rate Q = 0.165 [m^3/s]. According to the calculations it attempted to select the optimal diameter.

Based on the recommendations of the experts, the water flow velocity can be obtained from v = 1 ... 2 [m/s], the diameters of the penstock 400 or 450 will be eligible for further calculations.

3.3. Determining of energy losses in penstock

The total energy losses that arise in the pipeline can be: longitudinal (H_{long}) and local losses (H_{loc}) and is written as follow:

$$H_{los} = H_{long} + H_{loc} \text{ [m]} \quad (8)$$

Longitudinal losses

Several authors have developed different expressions for determining the longitudinal losses in penstock but as a universal expression which is valid for different penstock diameter is the Darcy-Weisbach expression with Colebrook coefficient for friction. The longitudinal losses are determined by the following expression:

$$H_{long} = \frac{\lambda}{2} \cdot \frac{L}{D} \cdot \frac{v^2}{g} \text{ [m]} \quad (9)$$

where:

λ – friction coefficient of water with penstock (Colebrook coefficient),

L [m] – length of penstock.

The coefficient of friction (λ) depends on the value of the Reynolds Number (R_e), and the type of flow. The coefficient of friction is determined by the expression shown in Table 2.

Local losses

Expression for determining local losses is as follow:

$$H_{loc} = \frac{k}{2} \cdot \frac{v^2}{g} \text{ [m]} \quad (10)$$

where:

k – coefficient of local losses through bends, fittings, etc.

3.4. Determining of net head and output bends, fittings, etc.

Finally, the net head of water is determination by the following expression:

$$H_n = H_g - \left(H_{long} + H_{loc}\right) = H_g - \left(\frac{\lambda}{2}\cdot\frac{L}{D} + \frac{k}{2}\right)\frac{v^2}{g} \text{ [m]} \quad (11)$$

For water flow rate Q = 0.165 [m^3/s] and gross head H_g = 10 [m], total energy losses (H_{los}) in penstock and net head for different diameter of pipe is presented in Figure 7.

From curves presented in Figure 7 is shown that, with increasing diameter of penstock, the energy losses in penstock decrease while net head increase too.

In order for the energy losses to be as small as possible, by decision the penstock diameter should be Ø 450 [mm] and then provide 3.88% energy losses as well as create net head by H_n = 9.61 [m].

By assuming the efficiency of the propeller, the hydro turbine should be η_t = 80% and efficiency of generator η_{gen} = 85%, then the expectation output generation power as function of penstock diameter is shown in Figure 8.

From diagram shown in Figure 7 it is observed that, output power from generator will increase by increasing penstock diameter.

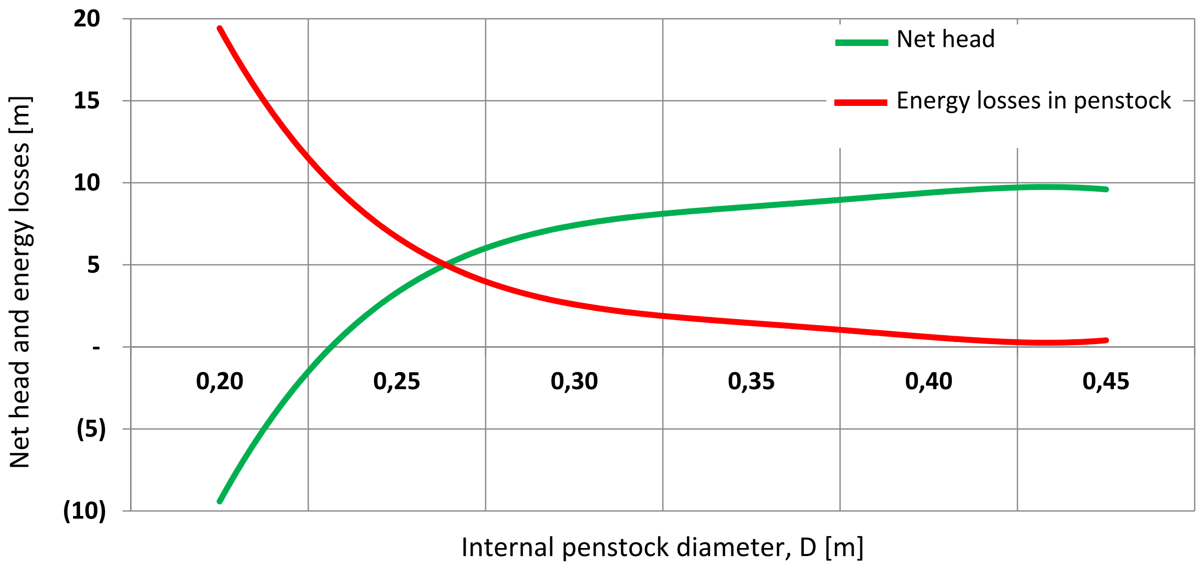

Figure 7: Net head and energy losses vs internal penstock diameter

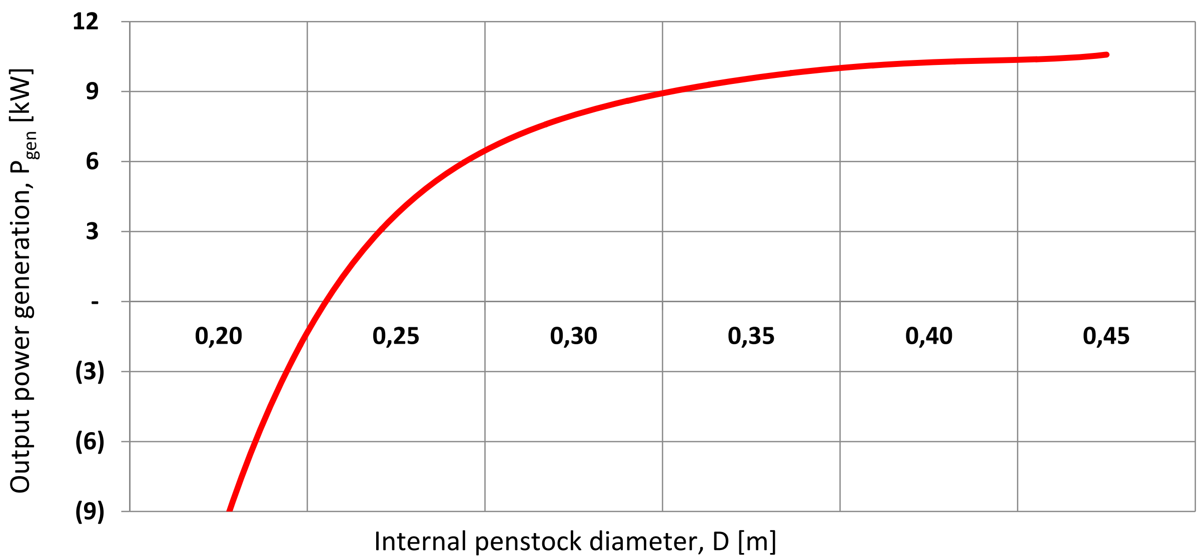

Figure 8: Output power generation vs internal penstock diameter

Table 3: Indication parameters for propeller turbine

Description of indication parameter	**Symbol**	**values**	**Unit**
Water flow rate	Q	0.165	[m^3/s]
Gross head	H_g	10	[m]
Net head	H_{net}	9.61	[m]
Power generation	P_{gen}	10.58	[kW]
Generator speed	N	1500	[rpm]
Specific speed	N_s	116.63	[-]
Turbine runner diameter	D_{runner}	232.00	[mm]
Hub Diameter	D_{hub}	124.00	[mm]

Figure 9: Design of propeller hydro turbine with 12.5 [kVA] synchronous generator performed in Autodesk Inventor 3D

4. Design of mini hydro turbine

By taking in consideration the availability of water flow-rate: Q = 0.165 [m^3/s] and net head H_n = 9.61 [m], the suitable turbine for working under such conditions is foreseen as the propeller hydro turbine. Some indication parameter for determining geometry of the turbine should be determined.

4.1. Design of propeller turbine

The indication parameters for a propeller turbine are: specific speed, turbine runner diameter, hub diameter, turbine housing design, draft tube, etc. In order to determine such indicative parameters some input data is required. The generator rotation speed is selected to be with four poles and rotation speed is: N = 1500 [rpm]. By employing know values elaborated on previously and substations in expressions (4), (5) and (6), then the output results will be as shown in Table 3.

Figure 9 presents the propeller hydro-generator performed in Autodesk Inventor 3D. An synchronous generator is connected to the turbine shaft which converts the hydraulic energy into electric energy.

4.1. Design of hydro turbine power house

In order for the hydro turbine power house to be useful and suitable as much as possible, there is selected such a design where the mini hydro turbine, control box and discharge of water are in the same place, Figure 10.

Figure 11 present front view of the hydro turbine power house for the recreational centre, in the village Sllakovc, Vushtrri.

5. Construction works

Performing of the civil works was not difficult due suitable terrain with a minor slope. Work started by removing the old water wheel turbine which had never fulfilled the demand for energy and had a lot of problems regarding maintenance, Figure 12. Reason for removing the old water turbine wheel was done in order to build a power house in the same place.

Figure 13 presents the excavation work and discharge place by removing the old water wheel turbine in order to build a hydro turbine power house in the same place.

Figure 10: Design of the hydro turbine power house in 3D view for recreational center, in the village Sllakovc, Vushtrri

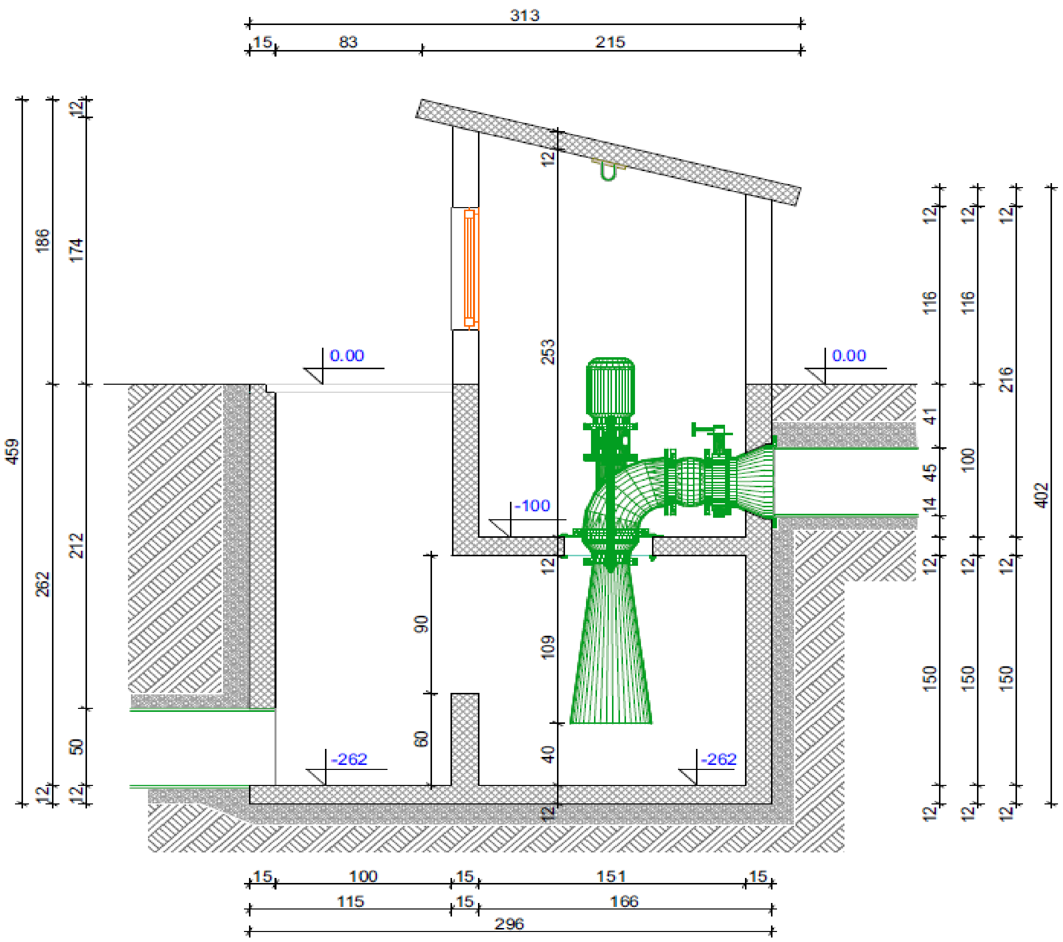

Figure 11: Front view of the hydro turbine power house in the village Sllakovc, Vushtrri

Figure 12: Old water wheel turbine for generating energy from water

Figure 13: Excavation works and construction works for hydro turbine power house in the village of Sllakovc, Vushtrri

Figure 14: Open channels with excavators and connecting penstock with hydropower house

Figure 14 present activity for open channels for installing penstock and connection penstock with hydro turbine power house.

6. Discussion of results

Due to limitation of budget, there has not been possible installing water flow meter and output power meter for measuring generated energy from generator. Therefore, to determine the hydro turbine efficiency was difficult to do it. But, according to some measuring instruments that are installed in mini hydropower plant such as ampere meter, voltage meter and consumption energy meter is determined that the maximum generated energy from this plant when river flow is maximal has reached the value of 9.0 kW.

The investment cost for building of this mini hydropower plant has value from 25 thousand Euros. According to existing feeding tariffs in Kosovo, investment payback period for this plant is about 6 years. The investing cost for producing of the one kW energy is ~ 2,800 €.

Due to the limitation of water resources, the mini hydropower plant works only 9 months and planning for remount is foreseen to perform only during the period when the turbine is stopped, therefore installing of other turbine in order to increase readiness of plant is not reasonable.

7. Conclusion

Nowadays requirements for energy continue growing more and more as a result of population growth and the rapid development of technology. Many countries have serious problems with supply regarding energy, especially for green energy. There are still many countries in the world that don’t have electrification.

In order to reduce as much as possible the problem with generating energy and to improve peoples’ lives as well as environmental protection, we can draw the following conclusions:

- Many places in World have good potential for developing mini hydropower plants,
- In locations where public grids do not exist, mini hydropower plants are crucial,
- The only requirements for mini hydropower plants are water sources, turbines, generators, penstock and power houses, which not only helps each individual person but also helps the world and environment as a whole,
- The choice of turbine will depend mainly on the available water head and the water flow rate,
- Mini hydropower plants usually are run-of-river systems, which do not require a dam, and are installed on the water flow available on a year round basis,
- Construction work and production of mini hydro turbines can be done without higher qualified personnel,
- Investment in a mini hydropower plant is not that high and period of turnover is shorter when compared with other alternative sources,
- The investment costs increase drastically by increasing penstock diameter but energy losses decrease too.

Therefore, studying the potential of water for installing mini hydropower plants creates opportunity for employing new workers and enables the developing of new business and will be a good source for financial support in order to improve the lives of the population.

Developed project performed in this paper has achieved the predicted result in power generation and has been working from May 2014.

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