Science Literature

Turkish Journal of Electromechanics and Energy
ISSN: 2547-975X
Vol:6, No:3, Page 108-122 (2021)
https://www.scienceliterature.com

Turkish Journal of Electromechanics & Energy
an international open access journal

Conceptual design of a regulator-type hydropower plant

A. Cüce[1], H. Küçük[2, *], A. Midilli[3]

[1]22nd Regional Directorate of State Hydraulic Works, 61220, Trabzon, Turkey

[2] Department of Mechanical Engineering, Faculty of Engineering and Architecture, Recep Tayyip Erdoğan University, 53100, Rize, Turkey

[3]Department of Mechanical Engineering, Faculty of Mechanical Engineering, Yıldız Technical University, 34349, İstanbul, Turkey

ARTICLE INFO

***Article Type*:**
Research Article

Article History:
Received: 14 September 2021
Revised: 22 November 2021
Accepted: 14 December 2021
Published: 30 December 2021

Editor of the Article:
M. E. Şahin

Keywords:
Regulator type HPP, Optimisation, Design of HPP, Optimum tunnel diameter, Optimum penstock diameter

ABSTRACT

In this study, the design of a regulator-type hydropower plant was first performed in detail for the flow rates in the stream bed in the Eastern Black Sea region in Turkey. The water transmission tunnel has a free surface flow, and penstocks are externally reinforced. According to the value of project volumetric flow rate, sedimentation pond, optimum tunnel diameter, optimum penstock diameter, installed power capacity, turbine type selection, several turbines and generator capacity analysis have been conducted. Annual firm energy, annual secondary energy, and annual total energy have been calculated to be 55.399, 90.500 and 145.899 GWh. Also, optimum tunnel diameter and penstock diameter are obtained as 3.30 m and 2.75 m, respectively, using the maximum net income method for 35 m^3/s of maximum flow rate. Three turbines are used for 28.129 MW of installed power, and 9.973 MW of turbine is selected for 11.20 m^3/s of flow rate and 98.71 m of the net head. Voith brand Francis Turbine with 518 rpm, 166 m-kW of specific speed and 0.92 efficiencies is selected. Generators with 500 rpm of synchronous speed, 50 Hz, 14 double pole numbers, close to the turbine speed of 518 rpm are preferred.

Cite this article: A. Cüce, H. Küçük, A. Midilli, "Conceptual design of a regulator-type hydropower plant," *Turkish Journal of Electromechanics & Energy*, 6(3), pp.108-122, 2021.

1. INTRODUCTION

Water is one of the most important renewable energy sources because of its high energy potential. Shortly, it does not seem possible to give up fossil fuels to supply increasing electricity demand worldwide. However, hydropower maintains its place and importance among energy sources to satisfy this energy demand [1]. For efficient and on-site use of the resources in the evaluation studies of hydroelectric potential, the calculations should be carried out using highly detailed and different methods to design the regulator type hydropower plants (HPPs). Regulator-type HPPs have an effective rate in the hydroelectric potential [1]. In the design of regulator type hydropower plants, determination of hydroelectric production potential in the stream bad, where the power plant will be established, is possible with detailed analysis of the flow data. If there is a flow monitoring station in the accessible basins, the hydroelectric production potential of the basin can be determined by using long-term flow data. Otherwise, the size and type of the system can be decided after extrapolating the approximate result by using different calculation methods. Hydropower plants' sizing is a complex process that needs to be concluded with cost-benefit analysis after obtaining hydrological data [2].

For energy production in regulator type hydropower plants, the water taken into the duct or pipes is passed over the turbine blades. The turbines are rotated, and generators connected directly to turbines are also converted from mechanical energy into electrical energy. Regulator-type hydropower plant construction can be economical where hydropower plant with reservoir is not possible to build technically or economically. Still, stream flows are relatively uniform, and land conditions or geographical structures are suitable for energy production [3, 4]. Regulator-type hydropower plants can be built where the stream bed provides appropriate head values. They have a high slope or short water transmission line (channel or tunnel) constructed in the curves of the stream and sometimes by using diversions from one branch to another branch or from the basin to another basin [5]. Since energy is produced in the regulator type hydropower plants without storage [6], a detailed feasibility study is required to economically use the flow discharge of the stream in energy production. The amount of produced energy depends on long-term values of water flow rate in water diversion axes, the variation of the water flow rate depending on time, the amount of head and installed power capacity of the hydropower plant [5, 6]

The flow duration curves can estimate the firm and secondary energy amounts in a regulator-type hydropower plant. The unit benefit of firm energy is assumed as the unit cost of energy production per kWh. This cost is the direct production cost of the committed energy, but it doesn't include the investment costs of the facility [2]. Investment costs of the facility and annual fixed expenses should only be considered in calculating reliable

*Corresponding author e-mail: haydar.kucuk@erdogan.edu.tr

capacity benefits [2]. In Turkey, each institution takes a different approach and uses various unit benefits to calculate the annual benefits of hydropower plants. In addition, the power value, which should typically be referred to as firm power, is called peak power and its benefit is considered the benefit of peak power [2].

Under these considerations, some critical studies have been performed in the literature. Anagnostopoulos and Papantonis [6] conducted a numerical analysis for optimal sizing of a run-of-river type small hydropower plant. They found that when two turbines of different sizes are used, the plant's energy production is enhanced, decreasing its investment cost. Also, optimisation studies relating to the run-of-river type small hydropower plant are performed by researchers in the literature [7-12] and presented a techno-economic model for the capacity sizing of a small hydropower plant by considering some parameters such as; turbine type, turbine dimensions, annual energy production, maximum installation height, machine cost, net present value and internal rate of return. Also, some studies were performed relating to the capacity sizing of a hydropower plant to maximize the investment profitability from the economic point of view [13-16]. Also, Barelli et al. [17] presented a different design approach for mini and micro-hydro plants to maximise the economic benefits by considering the hydrogeological characteristics of the river. Yildiz and Vrugt [4] developed a numerical method that uses a daily time step to simulate technical performance, energy production, maintenance and operational outgoings and economic profit of the run-of-river. Cavazzini et al. [18] suggest a new approach for calculating the electromechanical equipment outgoings. However, Yüksek et al. [19] studied problems and possible solutions to the environmental impacts of small hydropower plants in Turkey. They categorised the environmental impacts as short-termed problems arising from construction and long-termed problems resulting from operational activities.

Constructing a regulator-type hydropower plant aims to obtain maximum energy from the potential energy [20] of the water in the drainage area. For this, the water transported to the turbines through the transmission structures must be transferred to the turbine to minimize cost and minimum head loss. Also, hydraulic calculation errors should be reduced to the minimum design for the power plant to work uninterrupted.

Determination of installed power capacity of hydropower plants is the most critical problem in power plant design [6]. The best solution is providing the highest net income [4]. The installed power optimization is used to determine many parameters that will make the net income maximum [2]. For optimization, the installed power, water diversion structure, diameter, slope and length of the tunnel, penstock diameter, time and construction method are the essential parameters [2]. Since the optimum installed power depends on many parameters, it is impossible to write an equation that provides direct optimization. Therefore, trial and error or iterative optimization should be made [21].

This study aims to present firstly the design of a typical regulator type hydropower plant in which water transmission tunnel has a free surface flow, and penstocks are externally reinforced have been performed for the flow rates in the stream bed as detailed in the Eastern Black Sea region of Turkey. In this scope, using Excel program annual average volumetric flow rate, annual effective volumetric flow rate, the yearly amount of water that will be processed for each water intake rate, friction losses, local losses, net head, and amounts of the firm and secondary energy has been estimated. Also, the value of project volumetric flow rate, sedimentation pond, optimum tunnel diameter, optimum penstock diameter, installed power capacity, turbine type selection, number of turbines and generator capacity analysis have been conducted. Since this study contains a comprehensive calculation relating to the design of a regulator-type hydropower plant in Turkey's Eastern Black Sea region, it is considered that it will contribute to researchers, scientists, and the private sector.

2. SYSTEM DESCRIPTION AND ANALYSIS

The system details and analysis of regulator-type hydropower plants are presented in this section.

2.1. System Description

In this section, the main aspects of the system considered for the analysis have been introduced. This research has been performed in Turkey's Eastern Black Sea region, which has mountainous terrain, and water is only transferred through the tunnel. The tunnel passes through intact rock, seasonal rainfalls are relatively uniform, and a short diversion conduit where high head values can be achieved. A general view of a regulator-type hydropower plant is given in Figure 1. The units and elements of a regulator-type hydropower plant generally consist of the structures such as; a regulator, sedimentation pond, channel or tunnel, forebay, penstock, station including electromechanical equipment and permanent equipment tailwater channel, energy transmission line, transportation roads, etc. In regulator type HPPs, the water is taken from the stream bed by a regulator and transferred to the sedimentation pond. A sedimentation pond is used to precipitate the drifted material, which is suspended in the water taken to the transmission line by the regulator not to damage the water transmission line and turbine blades. After, the water is transferred by the channels or pipes over the turbine blades, and the turbines are rotated. The mechanical energy is converted into electrical energy in the generators directly connected to the turbines. Then, the electrical power in the generators is brought to appropriate values by using various electrical equipment, and it is given to the transmission line.

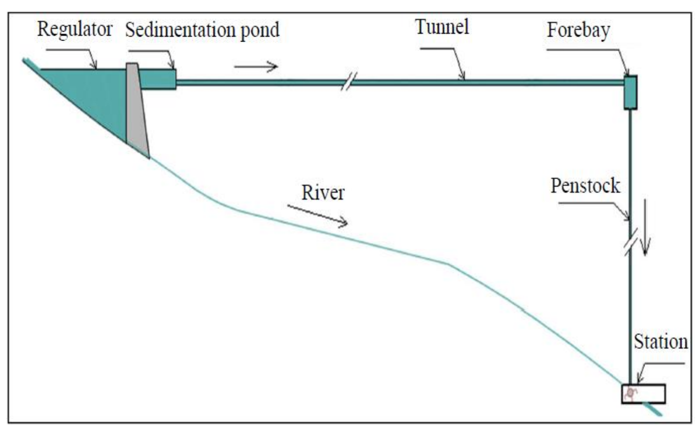

Fig. 1. A general view of a regulator-type hydropower plant.

Graph of flow duration curves is created for flow rate and % time flow exceeded. Annual average volumetric flow rate, annual effective volumetric flow rate, annual water quantity that will be processed for each flow rate, friction losses, local losses, total head losses, net head, the amounts of the firm and secondary energy were estimated by using Excel program. Total energy incomes are estimated by using unit energy benefits of State Hydraulic Works according to calculated energy amounts. The total outgoings of the facility are obtained by assessing depreciation, maintenance and renovation outgoings. Net incomes for each flow rate are calculated, and the maximum flow rate, which makes net income maximum, is determined as project flow rate. Sedimentation pond, optimum tunnel diameter, optimum penstock diameter, installed power capacity, turbine type selection, number of turbines and generator capacity are calculated by considering the estimated project flow rate value.

2.2. Analysis of HPP

A regulator-type hydropower plant analysis is performed by using the following assumptions and calculation procedures.

2.2.1. Assumptions

The following assumptions have been taken into consideration for the analysis:

- The flow data used in the calculations are available in the stream bed as the flow rate values after the lifeline water are subtracted.
- Gross head: 100 m
- Length of the tunnel: 2500 m
- Tunnel is excavated in the intact rock formation; it has a horseshoe-shaped cross-section, and inside of the tunnel is coated with concrete.
- Manning's friction coefficient for tunnel: 0.014
- Manning's friction coefficient for penstock: 0.012
- Length of penstock: 250 m
- Material of penstock: St 37
- Diameter of penstock: Constant
- Wall thickness of penstock: Constant.
- Unit cost of penstock: 4.34 USD/kg [2]
- Cost of penstock reinforcing rings and support elements: 10% of penstock's cost [2, 22]
- Efficiency of turbine: 0.92 [2, 23]
- Efficiency of generator: 0.96 [2]
- Efficiency of transformer: 0.98 [2, 24]
- Cost of the regulator: 18% of CPE.
- Cost of forebay: 6% of CPE [2]
- Cost of building construction: 20% of CPE
- Cost of turbine-generator group: 55% of CPE [2, 25]
- Cost of auxiliary equipment: 25% of CPE [2]
- Occupancy rate of the tunnel: 82% [2, 22]
- Critical velocity limit in WTT: 3 m/s [5, 2]
- Local losses: 30% of friction losses in tunnel and penstock [5, 2]
- Width of sedimentation pond: 20 m
- Average water height in the sedimentation pond: 3.6 m
- Base slope of sedimentation pond: 0.01 [2]
- Predicted AO: 0.108 times of the total IC [2, 22]
- Cost of unit installed power price for predicted total investment cost: 900 USD/kW [2]
- UFEC of power plant and switchyard: 338 USD/kW [2]
- 1 kWh = 0.073 USD [2]
- Social discount rate (i)= 9.5%
- MC for electromechanical equipment: 0.0216 [5, 2]
- MC for regulator, tunnel and forebay: 0.005 [2, 22]
- MC for energy transmission line: 0.01 [5, 2]
- MC for transportation roads: 0.02 [5, 2]
- MC for fixed installations: 0.01 [5, 2]
- MF for penstock: 0.01 [26]
- Density of precipitated particle: 1650 kg/m^3
- Density of steel material: 7.85 g/cm^3
- Water impact effect: 40% [2, 22]
- Rust share: 2 mm [23]

2.2.2. Calculation Procedure

The value of project flow rate determined by calculating from the different flow rates values available in the stream bed during the year should make maximum the annual net income. The flow rate, which is available 95-97% of the time in the flow duration curve, is used to calculate the firm power generation of the regulator-type hydropower plant without storage. If the hydropower plant is not to be operated as a base plant, to use secondary energies, the installed power must be selected greater than reliable power. The flow rate value of the regulator-type hydropower plants is generally determined in 80-100 days of the year or according to the water flow rate with 20-30 % time flow exceeded [23]. All flow rates are more excellent than reliable flow rates are used for secondary energy production.

Average and effective flow rates are given in Equation (1) and Equation (2), respectively [25].

$$Q_{ave} = \frac{\sum Q_i \ \Delta t_i}{\sum \Delta t_i} \tag{1}$$

$$Q_{eff} = \left(\frac{\sum {Q_i}^3 \ \Delta t_i}{\sum \Delta t_i}\right)^{\frac{1}{3}} \tag{2}$$

Installed power is obtained using gross head or a certain percentage of the gross for each flow rate as given in Equation (3) [18, 27-30].

$$P = \rho g \ Q \ H_n \ \eta_{tot} \tag{3}$$

Total loss head is assumed to be 3% of gross head, and the net head is calculated from Equation (4).

$$H_n = \left(H_{gross} - \Delta H_{tot}\right) \tag{4}$$

Total efficiency is obtained by using Equation (5).

$$\eta_{tot} = \eta_t \ \eta_g \ \eta_{tr} \tag{5}$$

The amount of firm energy corresponding to the reliable flow rate, which exists at 95% of all time, is calculated using Equation (6) [2].

$$E_{firm} = \rho g \ H_n \ \eta_{tot} \ Q_{rel}/3600 \tag{6}$$

Tunnel diameter is found from Equation (7) by considering the maximum flow rate.

$$Q = A \ V_T \tag{7}$$

The optimum diameter of the penstock is as below [21].

$$V_{opt,P} = 0.125 \sqrt{2 \ g \ H_{gross}} \tag{8}$$

The radius of a tunnel with a horseshoe-shaped cross-section is estimated from Equation (9) [21].

$$V_T = \frac{1}{n} R_T^{2/3} \ S_T{}^{1/2} \tag{9}$$

Head losses in the tunnel resulting from frictions are obtained from Equation (10) [23]. Effective flow rate is used in the head loss calculations.

$$\Delta H_T = n_T^2 \frac{V_T^2}{R_T^{4/3}} L_T \tag{10}$$

Head losses in the penstock resulting from frictions are found in Equation (11) given in Table 2 [23].

$$\Delta H_P = n_P^2 \frac{V_P^2}{R_P^{4/3}} L_P \tag{11}$$

Estimated costs for electromechanical equipment and fixed installations are calculated by using Equation (12) for 5-1000 MW installed power and Equation (13) for 0.5-5 MW installed power [5, 18, 31-33].

$$EC_{EME} = 3.3x10^6 P^{0.92} H_n^{-0.32P^{0.058}} \tag{12}$$

$$EC_{EME} = 4.61x10^6 P^{0.7} H_n^{-0.35} \tag{13}$$

Unit estimated cost of the tunnel are found from Equation (14) for intact rock formation [5].

$$EC_T = 287 D_T^{1.676} L_T^{0.168} \tag{14}$$

Unit estimated cost of exposed penstock is obtained from Equation (15) and Equation (16) for H<120 and H≥120, respectively. The unit cost of penstock is taken as 4.34 USD/ kg.

$$EC_P = 8.635\pi D_P (6D_P + 2)(UC)_P \tag{15}$$

$$EC_P = 0.4663\pi H D_P^2 (UC)_P \tag{16}$$

Annual outgoings of the facility are estimated from Equation (19) depending on the depreciation, maintenance and renovation outgoings. The depreciation factor used in calculating depreciation outgoing obtained by multiplying the depreciation factor with the investment cost of the facility is given in Equation (17) [26]. Maintenance outgoings for electromechanical equipment, regulator, tunnel, forebay, energy transmission line, transportation roads and fixed installations are found by multiplying the maintenance coefficient with the investment cost of each part. The renovation factor used in estimating renovation outgoing is presented in Equation (18) [5].

$$DF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{17}$$

$$RF = \frac{iC}{(1+i)^n - 1} \tag{18}$$

$$AO = ADO + AMO + ARO \tag{19}$$

In the sizing of the sedimentation pond, the water flow rate entering the pond, the diameter of the precipitated particle and the depth, length and width of the pond are important parameters. The type of turbine and turbine blade structure are effective parameters in calculating precipitated particle diameter [2]. Particles larger than 0.1 mm, 0.3-0.5 mm and 0.5-0.7 mm must be precipitated for Pelton, Francis and Kaplan turbines, respectively [22]. The diameter of the precipitated particle is estimated from Equation (20) [34].

$$\phi = \frac{1000\, R\, J}{0.06\, \rho} \tag{20}$$

Length of sedimentation pond is calculated from Equation (21) [34] by using the width of sedimentation pond and precipitating velocity obtained from the literature [35] depending on the particle diameter.

$$L_{SP} = \frac{3600\, Q_{max}}{V_p\, B} \tag{21}$$

The optimum diameter of the water transmission tunnel is the diameter at which the outgoings are minimum [2]. Investment cost, annual depreciation, maintenance, renovation and yearly outgoings of the tunnel are given in Equation (22) to (26), respectively.

$$IC_T = 380.26 D_T^{1.676} L_T^{0.168} \tag{22}$$

$$ADO_T = 36.52 D_T^{1.676} L_T^{0.168} \tag{23}$$

$$AMO_T = 1.58 D_T^{1.676} L_T^{0.168} \tag{24}$$

$$ARO_T = 0.01 D_T^{1.676} L_T^{0.168} \tag{25}$$

$$AO_T = 38.11 D_T^{1.676} L_T^{0.168} \tag{26}$$

Energy loss due to friction in a tunnel for unit length is obtained from Equation (27) for $Q_{eff}/Q_{max} = \alpha \text{ and } S_T = 1.77x10^{-3} Q_{max}^2 D_T^{-16/3}$.

$$E_{loss,T} = 131.608 Q_{max}^3 \alpha^3 D_T^{-16/3} \tag{27}$$

Loss of head affects permanent equipment, which should be included in the calculations. In this case, the installed power loss is as fallow.

$$P_{loss} = 0.015 Q_{max}^3 D_T^{-16/3} \tag{28}$$

Facility, project and investment costs of permanent equipment are estimated from Equation (29) to (31), respectively.

$$FC_{pe} = 5.57 Q_{max}^3 D_T^{-16/3} \tag{29}$$

$$PC_{pe} = 5.85 Q_{max}^3 D_T^{-16/3} \tag{30}$$

$$IC_{pe} = 6.41 Q_{max}^3 D_T^{-16/3} \tag{31}$$

Annual outgoings of decreasing permanent equipment are found in Equation (32).

$$AO_{dpe} = 0.76Q_{max}^3 D_T^{-16/3} \quad (32)$$

The total annual outgoing of the tunnel is given in Equation (33).

$$TAO_T = 38.11D_T^{1.676}L_T^{0.168} + (9.607\alpha^3 - 0.76)Q_{max}^3 D_T^{-16/3} \quad (33)$$

The optimum diameter of the tunnel is obtained from Equation (34).

$$D_{opt,T} = \frac{\partial(TAO_T)}{\partial D_T} = 0 = (0.802\alpha^3 - 0.063)^{0.143}Q_{max}^{0.429}L_T^{-0.024} \quad (34)$$

The optimum slope of the tunnel is found from Equation (35).

$$S_{opt,T} = 1.77x10^{-3}Q_{max}^2 D_{opt,T}^{-16/3} \quad (35)$$

In calculating optimum penstock diameter, load losses occurred at the maximum flow rate, minimum wall thickness required for safe operation, and detailed cost calculations for penstock outgoings are performed. The optimum diameter of penstock is calculated for the maximum flow rate that maximizes net income [2]. The optimal diameter of penstock is calculated when single, two and three penstocks are used. Using two and three penstocks, extra energy structures and cost increases are estimated [2]. Wall thicknesses of penstock for H<120 and H≥120 are found from Equation (36) and Equation (37), respectively [2, 22].

$$t = 6D_P + 2 \quad (36)$$

$$t = 0.05H_{gross}D_P + 2 \quad (37)$$

The value that minimises the total annual outgoings in the penstock should be selected as the optimum diameter of the penstock. Annual depreciation, maintenance, renovation and total outgoings of penstock is obtained from Equation (38) to (41), respectively.

$$ADO_P = (DF)_P(IC)_P \quad (38)$$

$$AMO_P = (MF)_P(FC)_P \quad (39)$$

$$ARO_P = (RF)_P(FC)_P \quad (40)$$

$$AO_P = ADO_P + AMO_P + ARO_P \quad (41)$$

Estimated and investment costs of penstock is given in Equation (42) and Equation (43), respectively.

$$EC_P = 180.385\pi D_P t \quad (42)$$

$$IC_P = 1.21(EC)_P \quad (43)$$

Annual outgoing of penstock is obtained from Equation (44).

$$AO_P = 90.54D_P^2 + 30.18D_P \quad (44)$$

The slope of penstock is estimated from Equation (45).

$$S_P = 1.482x10^{-3}Q_{eff}^2 D_P^{-16/3} \quad (45)$$

Energy loss resulting from friction in penstock is calculated from Equation (46).

$$E_{loss,P} = 110.19Q_{max}^3\alpha^3 D_P^{-16/3} \quad (46)$$

The energy cost because of energy losses in penstock is given as follows.

$$CE_{E-loss,P} = 8.04Q_{max}^3\alpha^3 D_P^{-16/3} \quad (47)$$

Effect of head loss on permanent equipment at a maximum flow rate in one-meter length penstock is found from Equation (48).

$$E_{loss,pe} = 0.01Q_{max}^3 D_P^{-16/3} \quad (48)$$

Facility and investment costs of decreasing permanent equipment are obtained from Equations (49) and (50), respectively.

$$FC_{dpe} = 3.38Q_{max}^3 D_P^{-16/3} \quad (49)$$

$$IC_{dpe} = 3.73Q_{max}^3 D_P^{-16/3} \quad (50)$$

Annual outgoings of decreasing permanent equipment are found from Equation (51).

$$AO_{dpe} = 0.39Q_{max}^3 D_P^{-16/3} \quad (51)$$

Total annual outgoings of penstock are estimated from Equation (52).

$$TAO_P = 90.54D_P^2 + 30.18D_P + 8.04Q_{max}^3\alpha^3 D_P^{-16/3} - 0.39Q_{max}^3 D_P^{-16/3} \quad (52)$$

The optimum diameter of penstock is obtained from Equation (53) for H<120 and α>45.

$$D_{opt,P} = \frac{\partial(TAO_P)}{\partial D_P} = 0 = (0.236\alpha^3 - 0.01)^{0.136}Q_{max}^{0.408} \quad (53)$$

The optimum diameter of penstock is calculated from Equation (54) if n penstock is used.

$$D_{opt,Pn} = n^{-0.408}D_{opt,P} \quad (54)$$

Friction losses if single and n penstock are used in Equation (55) and Equation (56), respectively.

$$\Delta H_P = 1.482x10^{-3}Q_{eff}^2 D_{opt,P}^{-16/3} L_P \quad (55)$$

$$\Delta H_{Pn} = 1.482x10^{-3}\left(Q_{eff}/n\right)^2\left(n^{-0.408}D_{opt,P}\right)^{-16/3} L_P \quad (56)$$

The turbine selection considers the design head, design flow rate and current conditions. Total installed capacity is constructed with three equal capacity turbines. Turbine speeds (rpm) are calculated from the characteristic specific speeds given by different turbine manufacturers, and the speed closest to the synchronous generator speed is selected as the turbine speed.

3. RESULTS

To perform the economic feasibility of a regulator-type hydropower plant planned and compare the various operating options, the energy potential of the hydropower plant should be first determined.

For this purpose, the flow duration curve of the regulator-type hydropower plant is used. To prepare the flow duration curve seen in Figure 2, different hydrological methods should calculate the previous flow values at the water intake point. While the flow duration curve is prepared, the other flow rate values during the year are arranged in ascending order. To estimate % time flow exceeded, the flow rate values are divided by the total flow rate value. In this calculation, the probability of exceeding the largest flow rate value will be close to zero, and the likelihood of exceeding the minimum flow rate value will be 100%. The flow duration curve should be prepared based on daily flow rates. The results obtained from the flow duration curve prepared by using daily flow rates are approximately 93-95% of the result of the flow duration curve prepared by using monthly average flow rates.

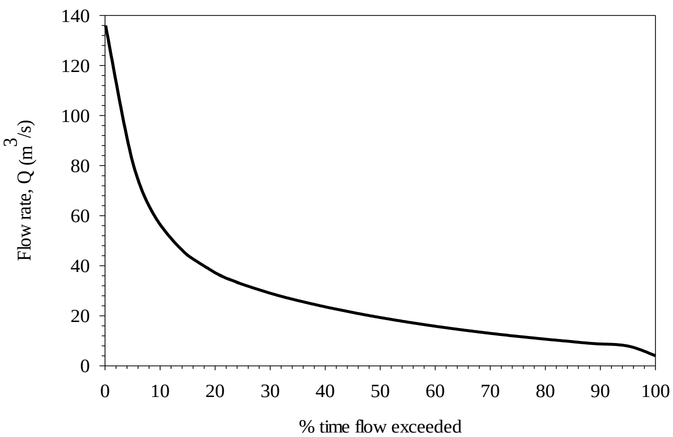

Fig. 2. Flow duration curve.

Because the annual flow rate corresponding to the different % time flow exceeded flow rates is calculated from the area under the flow duration curve. The curve equation is obtained as given in Equation (57).

$$y = 85.4775e^{-0.1816x} + 51.8516e^{-0.0198x} \quad (57)$$

Variations of maximum, effective and average flow rates are given in Figure 3 depending on the flow rate and % time flow exceeded. Average and effective flow rates between 30% and 100%-time flow exceeded are very close to each other. The power plant is not operated as a base plant, namely the different flow rates during the year are used, and the incomes and outgoings are taken into consideration in detail.

Since the flow rate of the project generally corresponds to the range of 20-30%-time flow exceeded, which the effective flow rate is higher than the average flow rate, in the regulator-type hydropower plant, loss calculations are performed according to the effective flow rate. Because of the effective flow rate jumping, the use of the regulator-type hydropower plant is not economically suitable when the flow rates are under 20%-time flow exceeded.

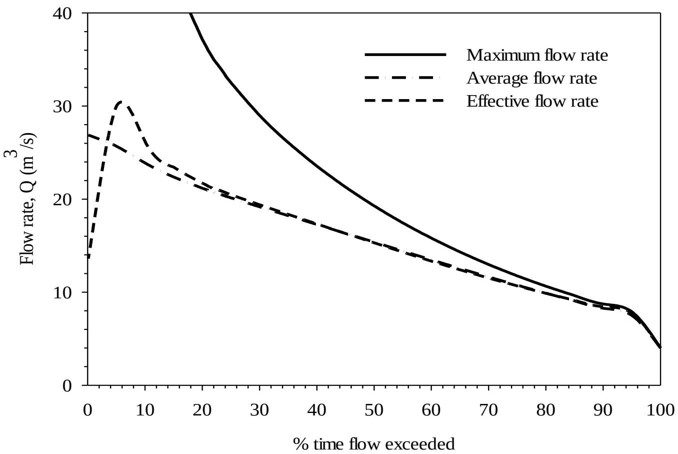

Fig. 3. Maximum, effective and average flow rates for various flow rates and % time flow exceeded.

As observed in Figure 4, the slope of the flow rate is maximum when the flow rates are between 0 and 40 m^3/s, decreases between 40 and 80 m^3/s and is almost constant after 80 m^3/s. Regulator-type hydropower plants are economically more suitable when the flow rate is under 40 m^3/s. The flow rate of 40 m^3/s exists 19-20% time flow exceeded during the year. In other words, the project flow rate should be selected under 40 m^3/s. Annual flow rates for energy production are estimated from Equation (57) and given in Figure 4.

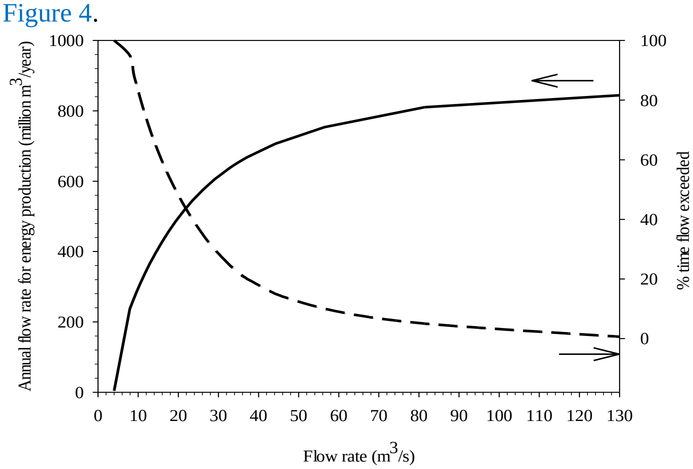

Fig. 4. Annual flow rates for energy production and % time flow exceeded for different flow rates.

All flow rates above the reliable flow rate are used for secondary energy. Annual secondary energy is calculated by subtracting reliable energy from total energy calculated using Equation (57). Annual predicted income is calculated by taking the unit price of firm energy as 0.06 USD/kWh and secondary energy as 0.033 USD/kWh. Predicted annual outgoings are estimated by taking 0.108 times the cost calculated for each installed power. Predicted yearly net income is obtained by subtracting predicted annual outgoings from expected annual incomes and given in Table 1. The flow rate maximizing net income is selected as the project flow rate. Net income is maximum as 3,715,642 USD/year at 26.08 m^3/s of maximum flow rate when the unit cost of installed power is selected as 900 USD/kW.

Table 1. Predicted maximum net incomes for flow rates.

Flow rate (m^3/s)	*Predicted capacity (MW)*	*Predicted cost (USD)*	*Predicted energy income (USD)*	*Predicted energy outgoing (USD)*	*Predicted net income (USD)*
7.90	6.504	5,853,919	3,430,410	632,223	2,798,187
8.73	7.188	6,468,951	3,619,787	698,647	2,921,140
9.64	7.937	7,143,263	3,816,001	771,472	3,044,528
10.64	8.760	7,884,266	3,971,990	851,501	3,120,489
11.75	9.674	8,706,778	4,020,594	940,332	3,080,262
12.97	10.679	9,610,801	4,230,942	1,037,967	3,192,976
14.32	11.790	10,611,154	4,447,660	1,146,005	3,301,655
15.81	13.017	11,715,248	4,669,126	1,265,247	3,403,879
17.46	14.375	12,937,902	4,894,728	1,397,293	3,497,435
19.28	15.874	14,286,526	5,121,911	1,542,945	3,578,967
21.30	17.537	15,783,351	5,350,027	1,704,602	3,645,425
23.55	19.390	17,450,607	5,577,324	1,884,666	3,692,659
26.08	**21.473**	**19,325,343**	**5,802,779**	**2,087,137**	**3,715,642**
29.00	23.877	21,489,070	6,028,163	2,320,820	3,707,343
32.52	26.775	24,097,398	6,257,747	2,602,519	3,655,228
33.33	27.442	24,697,610	6,304,969	2,667,342	3,637,627
34.20	28.158	25,342,282	6,353,618	2,736,966	3,616,651
35.00	28.817	25,935,084	6,396,579	2,800,989	3,595,589
36.00	29.640	26,676,086	6,447,989	2,881,017	3,566,971
37.16	30.595	27,535,649	6,504,706	2,973,850	3,530,856
44.14	36.342	32,707,846	6,792,056	3,532,447	3,259,609
56.45	46.477	41,829,585	7,150,475	4,517,595	2,632,880
81.44	67.052	60,347,235	7,577,798	6,517,501	1,060,297

Table 2. Losses of head occurred at critical velocities for effective flow rates.

Effective flow rate (m^3/s)	*Loss head in the tunnel (m)*	*Loss head in the penstock (m)*	*Local losses (m)*	*Total head loss (m)*	*Net head (m)*
4.00	0.10	0.05	0.04	0.19	99.81
7.77	0.36	0.19	0.16	0.71	99.29
8.43	0.42	0.22	0.19	0.84	99.16
9.13	0.50	0.26	0.23	0.98	99.02
9.88	0.58	0.30	0.27	1.15	98.85
10.68	0.68	0.35	0.31	1.35	98.65
11.52	0.79	0.41	0.36	1.57	98.43
12.40	0.92	0.48	0.42	1.82	98.18
13.33	1.06	0.55	0.48	2.10	97.90
14.31	1.22	0.64	0.56	2.42	97.58
15.30	1.40	0.73	0.64	2.77	97.23
16.32	1.59	0.83	0.73	3.15	96.85
17.35	1.80	0.94	0.82	3.56	96.44
18.38	2.02	1.05	0.92	3.99	96.01
19.41	2.25	1.17	1.03	4.45	95.55
20.49	2.51	1.31	1.14	4.96	95.04
20.71	2.56	1.34	1.17	5.07	94.93
20.95	2.62	1.37	1.20	5.18	94.82
21.13	**2.67**	**1.39**	**1.22**	**5.27**	**94.73**
21.40	2.73	1.43	1.25	5.41	94.59
21.73	2.82	1.47	1.29	5.58	94.42
23.45	3.28	1.71	1.50	6.50	93.50
26.20	4.10	2.14	1.87	8.11	91.89
30.00	5.37	2.80	2.45	10.63	89.37

30% of the total friction losses in the water transmission tunnel and penstock are assumed to be total local losses. Total head loss is calculated by adding losses of the water transmission tunnel, penstock, and total friction losses and net head loss are estimated using Equation (4), as seen in Table 2. Firm and secondary energies are calculated for each flow rate depending on the critical velocities, and the results are given in Table 3. Using optimum diameter values at a project flow rate of 35 m^3/s and by determining the amount of primary and secondary water to be turbined from Equation (57), the annual firm, secondary and total energies are estimated 55,398,685 kWh, 90,499,460 kWh and 145,898,145 kWh, respectively.

Table 3. Firm and secondary energies for each flow rate depend on the critical velocities.

Flow rate (m^3/s)	*Annual total energy (kWh)*	*Annual firm energy (kWh)*	*Annual secondary energy (kWh)*
7.90	55,405,899	55,405,899	0
8.73	60,993,535	55,405,899	5,587,635
9.64	66,761,774	55,405,899	11,355,875
10.64	72,708,072	55,405,899	17,302,173
11.75	78,871,087	55,405,899	23,465,188
12.97	85,163,412	55,405,899	29,757,512
14.32	91,593,575	55,405,899	36,187,676
15.81	98,103,209	55,405,899	42,697,310
17.46	104,663,285	55,405,899	49,257,385
19.28	111,190,326	55,405,899	55,784,427
21.30	117,656,990	55,405,899	62,251,090
23.55	124,008,076	55,405,899	68,602,177
26.08	130,212,897	55,405,899	74,806,998
29.00	136,314,594	55,405,899	80,908,695
32.52	142,410,307	55,405,899	87,004,408
33.33	143,645,662	55,405,899	88,239,762
34.20	144,907,044	55,405,899	89,501,145
35.00	146,045,674	55,405,899	90,639,774
36.00	147,356,408	55,405,899	91,950,509
37.16	148,765,128	55,405,899	93,359,229
44.14	155,711,680	55,405,899	100,305,781
56.45	163,316,836	55,405,899	107,910,937
81.44	170,763,900	55,405,899	115,358,001

Installed power corresponding to different maximum flow rates is obtained using Equation (3) depending on the net head given in Table 2 and are presented in Table 5. Renovation factors for penstock, building, construction, permanent equipment; regulator, tunnel, forebay, energy transmission line and site facilities are calculated via Equation (18) depending on renovation ratio and renovation period and given in Table 4. The renovation outgoings are calculated by multiplying the renovation factor of each section by the facility cost of the same section, and the annual total renovation outgoing of the facility is obtained.

As a result of the income and outgoing calculations, it is seen that the maximum flow rate maximizing net income is 35 m^3/s which exist in 22%-time flow exceeded as seen in Table 5. This flow rate is 35 m^3/s and is selected as the project flow rate. In the predicted capacity calculations, this value is 26.08 m^3/s, as seen in Table 1. It is seen that the expected maximum net income cannot be obtained even for higher maximum flow rates according to detailed outgoing calculations.

Table 4. Renovation factor for parts of the hydropower plant.

Parts of hydropower plant	*Renovation ratio, c (%)*	*Renovation period (year)*	*Renovation factor*
Penstock	50	45	0.000814
Building, construction	10	20	0.00185
Permanent equipment	100	35	0.00414
Energy transmission line	100	45	0.00163
Site facilities	10	20	0.00185
Regulator, tunnel, forebay	30	100	0.000033

Table 5. Net income and unit installed power costs for critical velocities at different flow rates.

Flow rate (m^3/s)	*Installed power (MW)*	*Cost (USD)*	*Annual income (USD)*	*Annual outgoing (USD)*	*Net income (USD)*	*Unit cost (USD/kW)*
7.90	6.666	15,887,199	3,324,354	1,662,943	1,661,411	2,383
8.73	7.358	16,361,407	3,508,746	1,715,782	1,792,964	2,224
9.64	8.114	16,870,254	3,699,098	1,772,480	1,926,618	2,079
10.64	8.942	17,417,692	3,895,326	1,833,478	2,061,848	1,948
11.75	9.857	18,011,923	4,098,705	1,899,690	3,909,015	1,827
12.97	10.858	18,650,468	4,306,352	1,970,840	2,335,512	1,718
14.32	11.961	19,341,594	4,518,547	2,047,849	2,470,698	1,617
15.81	13.171	20,086,293	4,733,365	2,130,827	2,602,538	1,525
17.46	14.503	20,891,496	4,949,848	2,220,547	2,729,301	1,440
19.28	15.963	21,758,364	5,165,240	2,317,137	2,848,103	1,363
21.30	17.573	22,697,242	5,378,640	2,421,752	2,956,888	1,292
23.55	19.355	23,717,760	5,588,226	2,535,463	3,052,763	1,225
26.08	21.347	24,837,790	5,792,985	2,660,262	3,132,723	1,164
29.00	23.634	26,099,588	5,994,341	2,800,858	3,193,483	1,104
32.52	26.377	27,582,823	6,195,499	2,966,127	3,229,372	1,046
33.33	27.005	27,918,174	6,236,266	3,003,493	3,232,773	1,034
34.20	27.679	28,276,439	6,277,892	3,043,413	3,234,479	1,022
35.00	**28.303**	**28,606,642**	**6,315,467**	**3,080,206**	**3,235,261**	**1,011**
36.00	29.074	29,012,721	6,358,721	3,125,453	3,233,268	998
37.16	29.962	29,477,879	6,405,209	3,177,283	3,227,926	984
44.14	35.278	32,210,349	6,634,445	3,481,748	3,152,697	913
56.45	44.416	36,730,774	6,885,415	3,985,436	2,899,979	827
81.44	62.496	45,183,284	7,131,168	4,927,256	2,203,912	723

While predicted annual net income is 3,723,471 USD/year when the project flow rate is selected as 26.08 m^3/s, this value is estimated as 3,235,261 USD/year when the project flow rate is 35 m^3/s. Installed power, total costs, the unit cost of installed capacity, total annual income and total annual outgoing are 28.303 MW, 28,606,642 USD, 1,011 USD/kW, 6,315,467 USD/year, 3,080,206 USD/year, respectively when the project flow rate is 35 m^3/s. These values are recalculated after determining the optimum diameters of the tunnel and penstock.

The length of the sedimentation pond is calculated as 93 m when the width of the sedimentation pond is 20 m, the height of the sedimentation pond is 3.6 m, and the maximum flow rate is 35 m^3/s. The variation of sedimentation pond length and particle diameter depending on the hydraulic diameter are presented in Figure 5. As seen in Figure 5, when the hydraulic radius increases, sedimentation pond length decreases and the diameter of the particle increases.

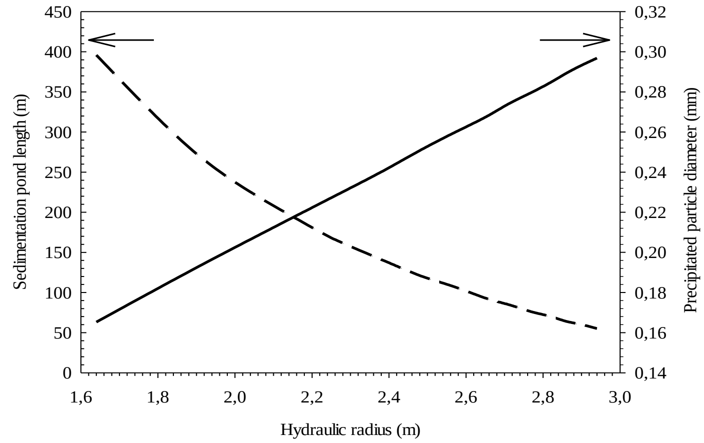

Fig. 5. Sedimentation pond length and particle diameter depend on the hydraulic radius for project flow rate.

Figure 6 shows the sedimentation length and water velocity variations in the sedimentation pond depending on flow rate and sedimentation pond width. It is seen that when the flow rate and sedimentation pond width rise, sedimentation length and water velocity in the sedimentation pond are also increased.

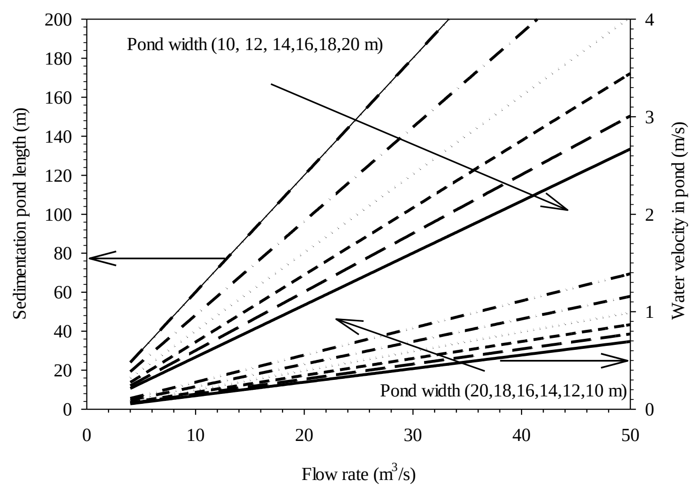

Fig. 6. Sedimentation pond length and water velocity in pond depending on the flow rate for different sedimentation pond widths.

Optimum tunnel diameter is obtained from Equation (38) for different tunnel slope and flow rates and presented in Table 6. If the tunnel's slope is below, the suspended material in the water precipitates and accumulates at the bottom of the tunnel. So, the slope of the tunnel base is not taken below 0.001. The optimum tunnel slope is calculated as 0.0037 according to the optimum tunnel diameter, given in Figure 7. As seen in Figure 7, the tunnel slope rises when the flow rate increases. Although the tunnel slope increases, the tunnel diameter grows slightly below the optimum slope value. When the tunnel slope increases, the tunnel diameter slightly rises for undervalues of the optimum pitch, and it highly rises for upper values of the optimum slope.

Table 6. Diameter values depending on flow rate and slope in the water transmission tunnel for 0.82 of the occupancy rate of the tunnel.

Manning (0.014)	*Horseshoe-Cross Section Air-Shared Wet Area ($0.7332D^2$) Tunnel Slope*										
Flow rate	*0.001*	*0.002*	*0.003*	***0.0037***	*0.004*	*0.005*	*0.006*	*0.007*	*0.008*	*0.009*	*0.01*
4.00	1.87	1.64	1.52	1.46	1.44	1.38	1.34	1.30	1.27	1.24	1.22
7.90	2.42	2.12	1.97	1.89	1.86	1.79	1.73	1.68	1.64	1.60	1.57
8.73	2.51	2.20	2.04	1.96	1.93	1.85	1.79	1.74	1.70	1.66	1.63
9.64	2.60	2.29	2.12	2.04	2.01	1.93	1.86	1.81	1.76	1.72	1.69
10.64	2.70	2.37	2.20	2.11	2.08	2.00	1.93	1.88	1.83	1.79	1.75
11.75	2.80	2.46	2.28	2.19	2.16	2.07	2.00	1.95	1.90	1.86	1.82
12.97	2.91	2.56	2.37	2.28	2.24	2.15	2.08	2.02	1.97	1.93	1.89
14.32	3.02	2.65	2.46	2.36	2.33	2.23	2.16	2.10	2.04	2.00	1.96
15.81	3.13	2.75	2.55	2.45	2.42	2.32	2.24	2.18	2.12	2.08	2.04
17.46	3.25	2.86	2.65	2.55	2.51	2.41	2.32	2.26	2.20	2.15	2.11
19.28	3.38	2.96	2.75	2.64	2.60	2.50	2.41	2.34	2.29	2.24	2.19
21.30	3.50	3.08	2.85	2.74	2.70	2.59	2.50	2.43	2.37	2.32	2.28
23.55	3.64	3.20	2.96	2.85	2.81	2.69	2.60	2.53	2.46	2.41	2.36
26.08	3.78	3.32	3.08	2.96	2.92	2.80	2.70	2.63	2.56	2.50	2.46
29.00	3.93	3.46	3.20	3.08	3.03	2.91	2.81	2.73	2.66	2.61	2.56
32.52	4.11	3.61	3.34	3.21	3.17	3.04	2.94	2.85	2.78	2.72	2.67
33.33	4.15	3.64	3.37	3.24	3.20	3.07	2.96	2.88	2.81	2.75	2.69
34.20	4.19	3.68	3.41	3.28	3.23	3.10	2.99	2.91	2.83	2.77	2.72
35.00	4.22	3.71	3.44	**3.30**	3.26	3.12	3.02	2.93	2.86	2.80	2.74
36.00	4.27	3.75	3.47	3.34	3.29	3.16	3.05	2.96	2.89	2.83	2.77
37.16	4.32	3.79	3.51	3.38	3.33	3.19	3.09	3.00	2.92	2.86	2.80
44.14	4.61	4.04	3.75	3.60	3.55	3.41	3.29	3.20	3.12	3.05	2.99
56.45	5.05	4.44	4.11	3.95	3.89	3.74	3.61	3.51	3.42	3.35	3.28
81.44	5.80	5.09	4.72	4.53	4.47	4.29	4.14	4.02	3.92	3.84	3.76

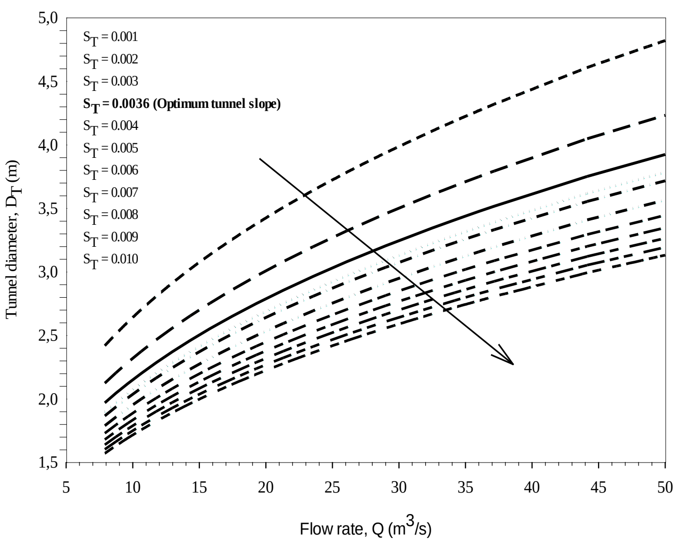

Fig. 7. Variation of tunnel diameter depending on tunnel slope and flow rate.

Selecting the tunnel slope more minor than the optimum slope reduces friction loss; hence facility income increases. However, as the diameter of the tunnel increases, outgoings also increase. Therefore, the slope calculation should be considered an essential parameter in the tunnel. As shown in Figure 8, the maximum optimum diameter value is 3.30 m when the maximum and average flow rates are 35 m^3/s and 20.73 m^3/s, respectively.

Head losses in the tunnel are presented in Figure 9 depending on effective flow rates and tunnel diameter for 0.014 of Manning's friction coefficient. It is seen that when the effective flow rate increases and tunnel diameter decreases, the head losses in the tunnel rise. The most friction losses in the regulator-type hydropower plant occur in the water transmission tunnel. The tunnel's diameter, in other words, the water velocity in the tunnel and tunnel coating, are essential parameters in calculating friction loss. The thickness of the tunnel coating and the coating quality is highly effective on cost and head loss, respectively.

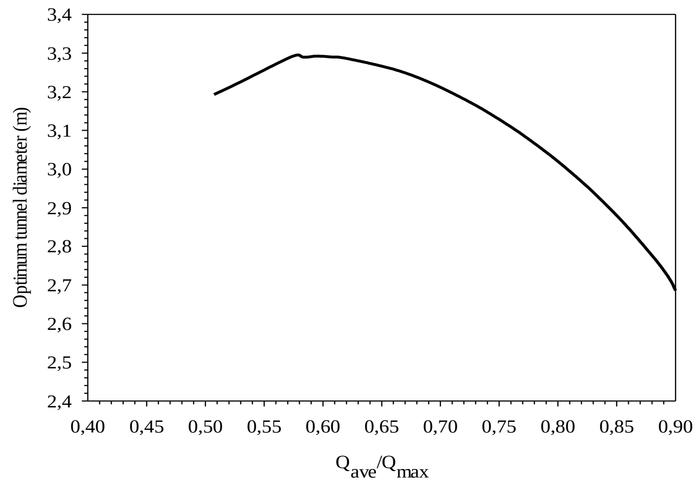

Fig. 8. Optimum tunnel diameter for different values of Qave/Qmax.

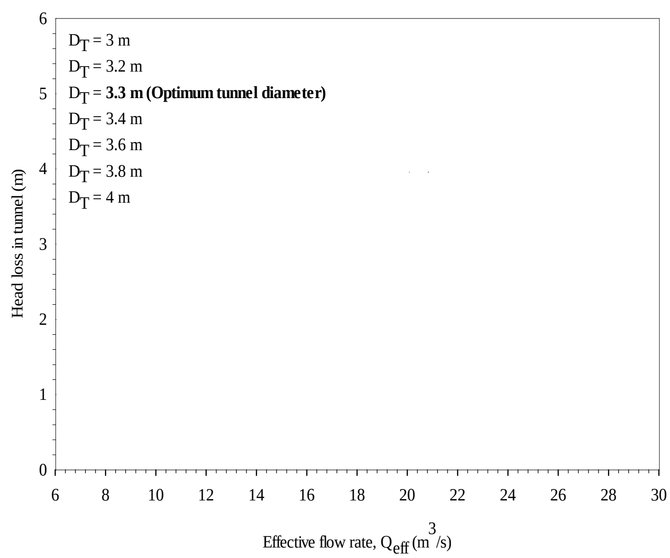

Fig. 9. Head losses depend on effective flow rates and tunnel diameter for 0.014 of Manning's friction coefficient.

The variation of head losses depending on effective flow rates and tunnel diameter are shown in Figure 10 and Figure 11 for 0.015 and 0.016 of Manning's friction coefficient, respectively. Manning's friction coefficient increases the head loss in a tunnel. When Manning's friction coefficient in a tunnel is taken as 0.014, 0.015 and 0.016, the head losses are 3.38 m, 3.88 m and 4.41 m, respectively, for 3.3 m of optimum tunnel diameter and 21.13 m^3/s of effective flow rate. So, depending on Manning's friction coefficient, coating quality decreases head losses by 1.03 m.

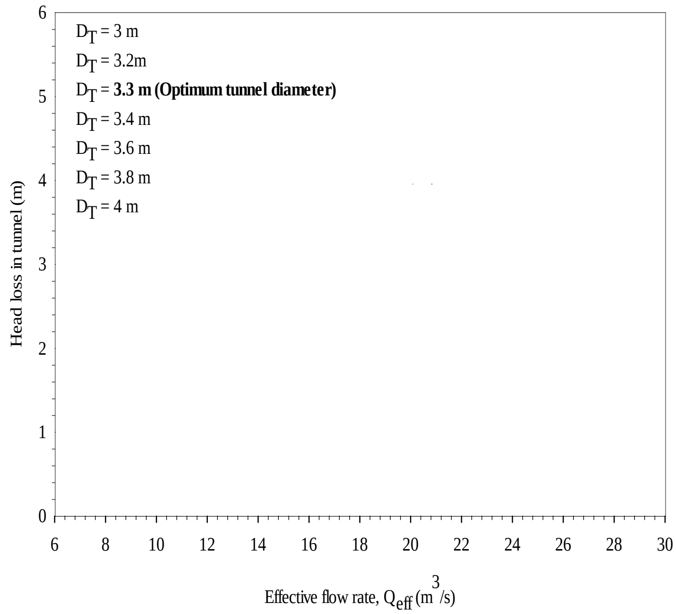

Fig. 10. Head losses depend on effective flow rates and tunnel diameter for 0.015 of Manning's friction coefficient.

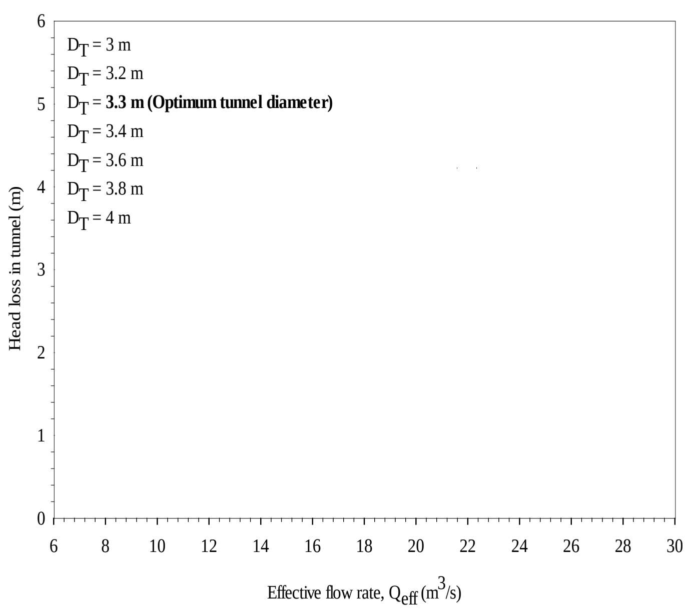

Fig. 11. Head losses depend on effective flow rates and tunnel diameter for 0.016 of Manning's friction coefficient.

The head losses are presented in Figure 12 depending on 3.3 of optimum tunnel diameter and different Manning's friction coefficients. The water transmission tunnel's water velocity is obtained as 2.60 m/s, 2.65 m/s and 4.38 m/s for average, effective and maximum flow rates, respectively. As seen in Figure 13, the critical velocity limit (3 m/s) is not exceeded even above the values of the maximum flow rate (35 m^3/s) in the water transmission tunnel. The critical velocity limit is exceeded in a water transmission tunnel when the maximum flow rate is between 26.08 m^3/s and 35 m^3/s, which exist 35% and 22%-time flow exceeded, respectively.

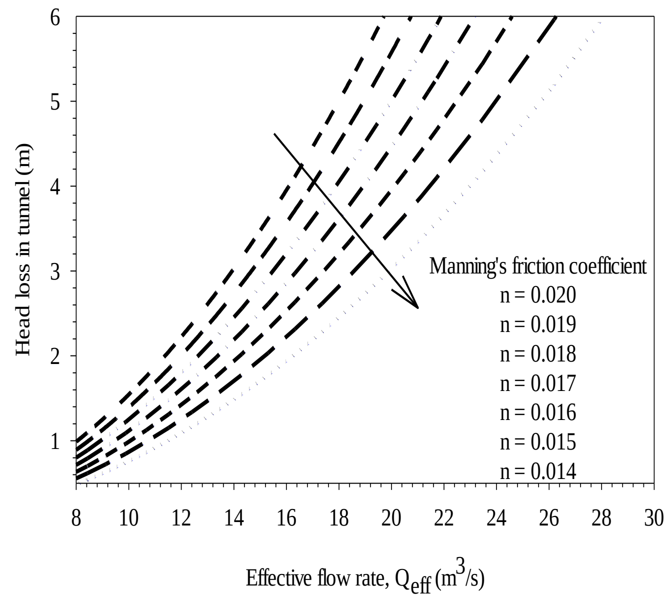

Fig. 12. Head losses depend on Manning's friction coefficient and effective flow rate for optimum tunnel diameter.

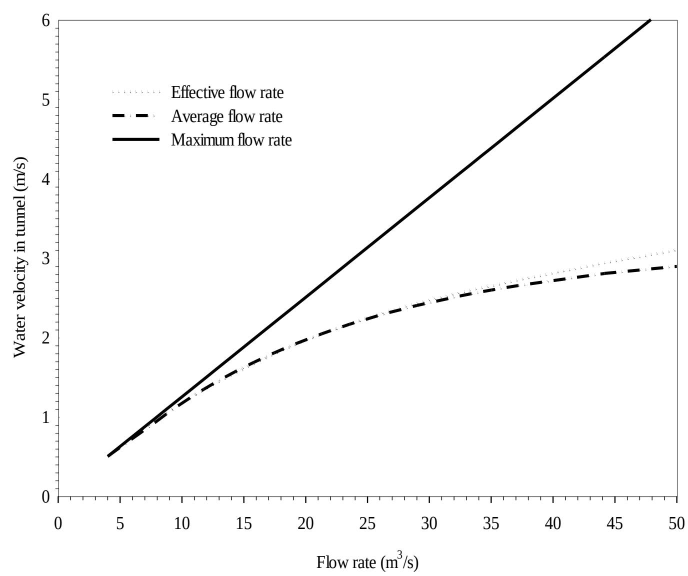

Fig. 13. Variations of water velocity in air-shared transmission tunnel for optimum tunnel diameter.

Because different average flow rates occur for each maximum flow rate, Q_{ave}/Q_{max} used as a variable in calculating optimum penstock diameter varies. Variations of penstock wall thickness and penstock mass depending on the penstock diameter are given in Figure 14. As seen in Figure 14, when the penstock diameter rises, the penstock wall thickness and penstock mass increase.

Figure 15 shows the variation of penstock diameter with Q_{ave}/Q_{max}. It is seen that penstock diameter rises to Q_{ave}/Q_{max} = 0.52 and then decreases when Q_{ave}/Q_{max} increases. The optimum penstock diameter is estimated as 2.77 m when the Q_{ave}/Q_{max} = 0.59 for 35 m^3/s of maximum flow rate and 20.73 m^3/s of average flow rate. As shown in Figure 15, large penstock diameters are economical for high values of maximum flow rate. The optimum penstock diameter is taken as 2.75 m.

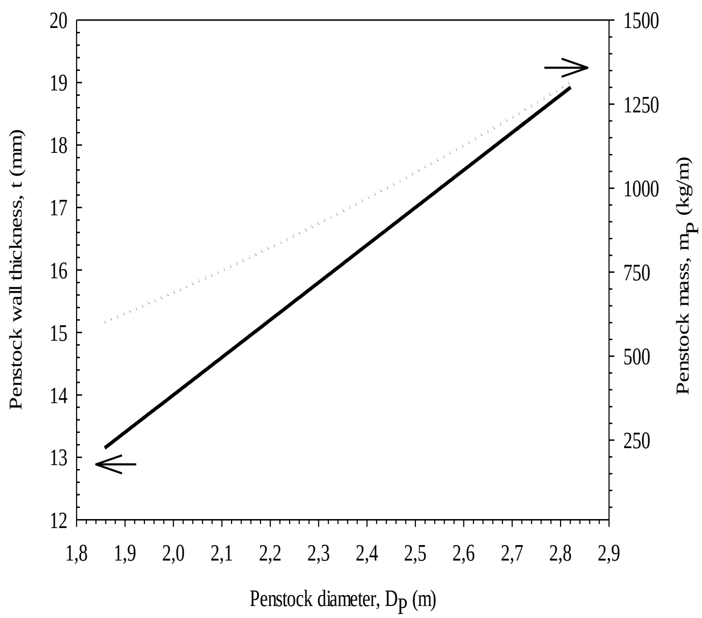

Fig. 14. Variations of penstock wall thickness and penstock mass depend on the penstock diameter.

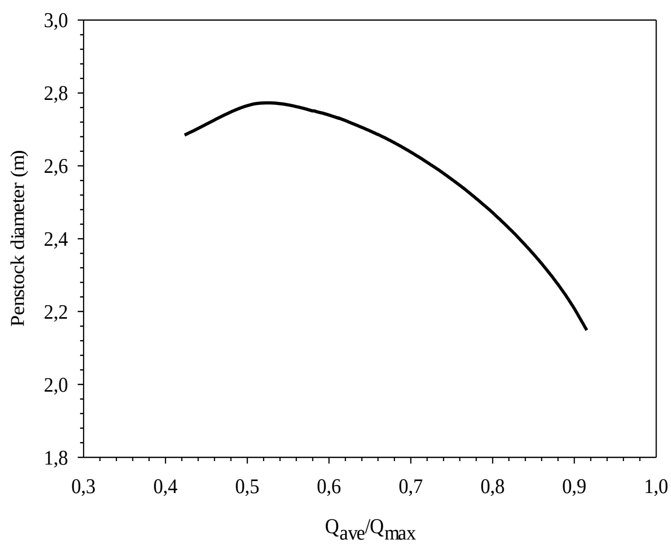

Fig. 15. Variation of penstock diameter with Q_{ave}/Q_{max}.

Head losses are presented in Figure 16 for different effective flow rates and penstock diameters. It is seen that when the effective flow rate increases and penstock diameter decreases, head loss in penstock rises. It shows that selecting the optimum diameter in penstock, which has a highly effective flow rate, is very important. If the penstock diameter is chosen as 2.4 m instead of 2.75, head loss in the penstock is more than twice.

Figure 17 gives the variation of penstock diameter depending on flow rate and the number of the penstock. As in Figure 17, penstock diameter decreases with the increase of penstock number. Also, penstock diameter rises when the flow rate increases.

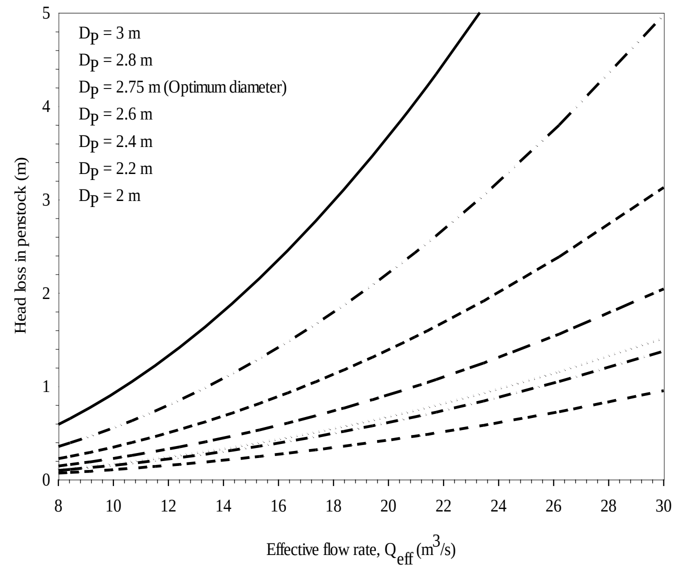

Fig. 16. Head losses for different effective flow rates and penstock diameters.

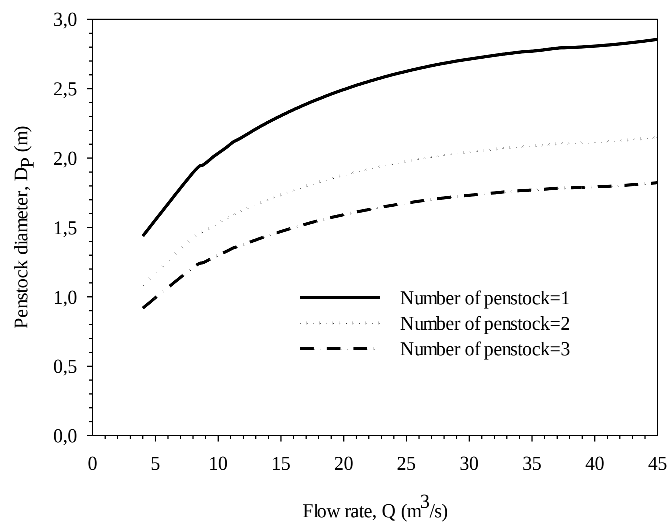

Fig. 17. Variation of penstock diameter depending on flow rate and the number of the penstock.

The specific velocities calculated based on the net head take different values for different turbine manufacturers. Turbine speed (rpm) varies according to a particular speed, flow rate and head.

The effect of turbine type and capacity on the installed power optimization should be checked. The generator speed closest to the calculated turbine speed should be preferred. The generated alternating current and voltage are only changed inversely proportional in transformers. Transformer selection should be made according to the suitable voltage level used in the country.

Turbine power calculated by the net head, flow rate and turbine efficiency is given in Figure 18. Different turbine efficiencies for the same flow rate generate quite different power. It is clear that (see Figure 18) a high-efficiency turbine must be selected. For 35 m^3/s of flow rate, the net head is 94.63 m. Turbine power was calculated as 29893 kW for these values by selecting turbine efficiency as 0.92. If three turbines are chosen, the net head is 94.47 m, and the total power of the three turbines is 29842 kW.

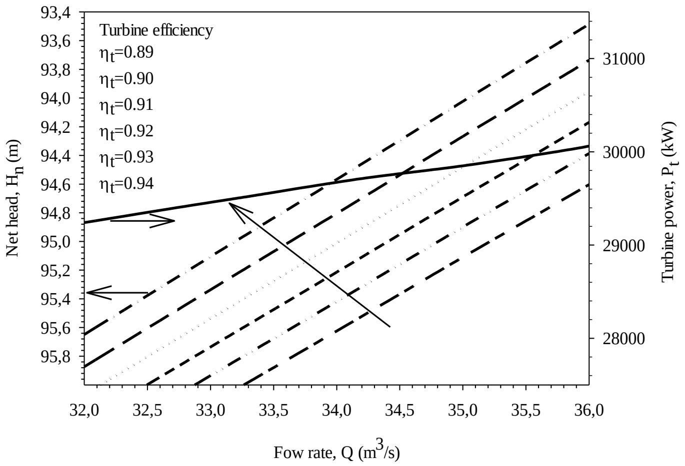

Fig. 18. Variation of turbine power for different flow rates, net head and turbine efficiency.

To obtain 29842 kW power depending on the net head, the speed of the turbines produced by different turbine manufacturers is calculated according to the specific speed and is given in Figure 19. Turbine power is 7067 kW for 7.90 m^3/s of the reliable flow rate and 0.92 of turbine efficiency.

Two turbines with equal capacity are preferred to use secondary flow rates other than the reliable flow rate at different times during the year. If more than one turbine is used, the determination of the turbines capacities changes depending on whether the flow data is regular and the variation of flow rate during the year. In turbine capacity determination, turbine efficiency should be examined depending on the rate of turbine capacity utilization and decided according to this.

Turbine speeds corresponding to the turbine specific speed for different turbine manufacturers are given in Figure 20. As seen in Figures 18, 19 and 20, turbine speed varies as a function of flow rate, net head and turbine specific speed. The exact turbine speed reflects its characteristic, which varies with the net head. The closest speed to the synchronous generator speed is selected as turbine speed.

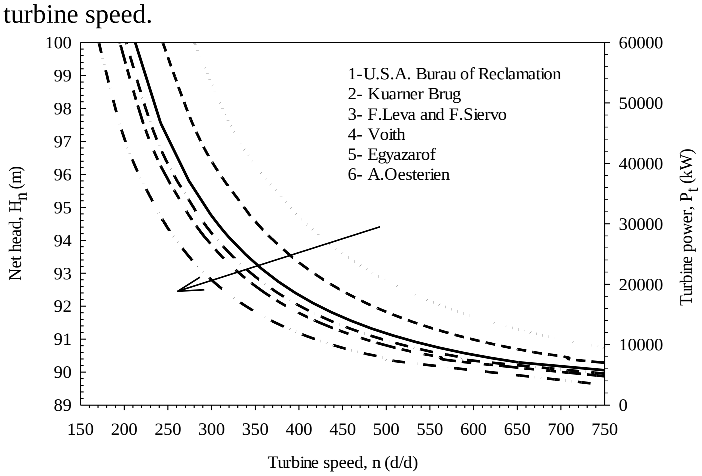

Fig. 19. Different turbine manufacturers give turbine speeds to obtain total turbine power depending on the net head.

If the Voith brand Francis Turbine with 518 rpm and 0.92 efficiencies is selected, 9947 kW of power is generated with 98.66 m of net head and 11.20 m^3/s of flow rate for firm energy production. Since the efficiency of Francis turbines does not change much, up to 60% of the capacity, the capacity usage is % 71 for the turbine used in reliable energy production. This value is over 60% and is within acceptable limits.

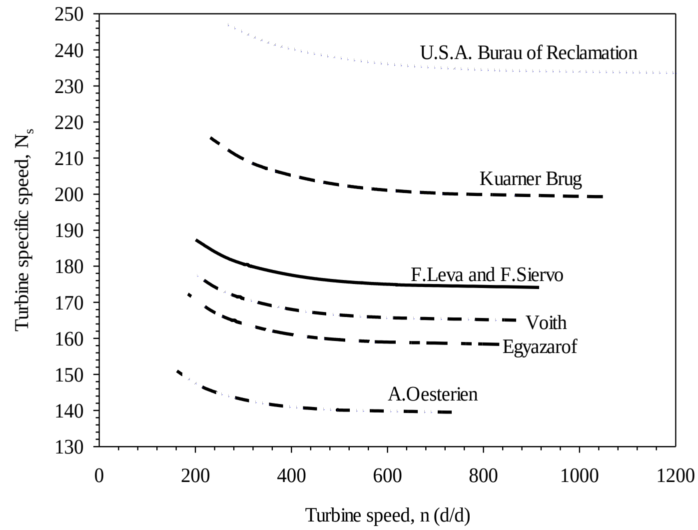

Fig. 20. Variation of turbine speeds depending on the turbine specific speed for different turbine manufacturers.

To obtain secondary energies and process varied flow rates with minimum cavitation high turbine efficiency, three different turbines of the same power are used, totaling 29919 kW. This turbine power corresponds to 28147 kW electrical power with 0.96 generator efficiency and 0.98 transformer efficiency. This is close to the installed capacity of 28129 kW calculated according to the net income. Generators with 500 rpm of synchronous speed, 50 Hz, 14 double pole numbers, close to the turbine speed of 518 rpm are preferred.

4. CONCLUSION

The conceptual design of a typical regulator-type hydropower plant has been performed in detail for the flow rates in the stream bed in the Eastern Black Sea region in Turkey firstly. In this regard, the following concluding remarks can be drawn:

— 7.90 m^3/s of flow rate is selected as reliable flow rate, which exists at 95% of all time during the year according to flow data.
— The predicted maximum flow rate is 26.08 m^3/s, total net income.
— Tunnel diameter is estimated as 3.45 m for predicted maximum flow rate and three m/s of critical velocity.
— Penstock diameter is determined as 2.45 m by considering constant diameter and constant wall thickness penstock.
— Head loss in the tunnel, head loss in penstock, local losses, total head loss and net head are calculated as 2.67 m, 1.39 m, 1.22 m, 5.28 m and 94.72 m, respectively, for diameter estimated depending on critical velocity.

- Flow rate, which is maximised net income, is estimated as 35 m^3/s by using net head calculated from the critical velocity method.
- Total flow rate, flow rate used for firm energy, flow rate used for secondary energy are calculated as 653,892,653 m^3/year, 236,677,680 m^3/year and 417,214,973 m^3/year, respectively, and the average flow rate is determined as 20.73 m^3/s.
- The optimum tunnel diameter is obtained as 3.30 m using the maximum net income method for 35 m^3/s of maximum flow rate.
- The optimum penstock diameter is 2.75 m using the maximum net income method for 35 m^3/s of maximum flow rate.
- Head loss in the tunnel, head loss in penstock, local losses, total head loss and net head are calculated as 3.38 m, 0.75 m, 1.24 m, 5.37 m and 94.63 m, respectively, for diameter calculated depending on maximum net income.
- The optimum tunnel slope is calculated as 0.0037.
- Penstock diameters are estimated as 2.09 m and 1.77 m if two and three penstocks are used, respectively.
- Annual firm, secondary and total energies are estimated to be 55.399, 90.500 and 145.899 GWh, respectively.
- 9.973 MW of turbine is selected for 11.20 m^3/s of flow rate and 98.71 m of the net head. Three turbines are used for 28.129 MW of installed power.
- Voith brand Francis Turbine with 518 rpm, 166 m-kW of specific speed and 0.92 efficiencies is selected. Generators with 500 rpm of synchronous speed, 50 Hz, 14 double pole numbers, close to the turbine speed of 518 rpm are preferred.

This study is the first part of a regulator-type hydropower plant in Turkey's Eastern Black Sea region, including conceptual design. The second part of this study has been planned as an economic analysis of a regulator-type hydropower plant. It is expected that these studies will contribute to researchers, scientists, and the private sector.

Nomenclature

ADO	Annual Depreciation Outgoing (USD)
AMO	Annual Maintenance Outgoing (USD)
AO	Annual Outgoing (USD)
ARO	Annual Renovation Outgoing (USD)
B	Width of Sedimentation Pond (m)
c	Renovation Ratio (%)
CE	Cost of Energy (USD)
CPE	Cost of Permanent Equipment
DF	Depreciation Factor
DO	Depreciation Outgoing (USD)
D	Diameter (m)
EC	Estimated Cost (USD)
FC	Facility Cost (USD)
g	Gravitational Acceleration (m/s^2)
H	Head (m)
HPP	Hydropower Plant
Hz	Hertz
IC	Investment Cost (USD)
IEA	International Energy Agency
i	Social Discount Rate
J	Slope of Sedimentation Pool Channel (%)
L	Length (m)
MC	Maintenance Coefficient
MF	Maintenance Factor
MO	Maintenance Outgoing (USD)
n	Number of Penstock, Renovation Period, Manning Friction Coefficient, Turbine Speed (d/d)
P	Installed power (kW)
PC	Project Cost (USD)
Q	Flow Rate (m^3/s)
R	Radius of Penstock (m)
RF	Renovation Factor
RO	Renovation Outgoing (USD)
S	Slope (%)
TARO	Total Annual Renovation Outgoing (USD)
ΔH	Head Loss (m)
t	Wall Thickness of Penstock (mm)
TAO	Total Annual Outgoings (USD)
UC	Unit Cost (USD/m, USD/kW)
UFEC	Unit Facility Estimated Cost
V	Velocity (m/s)
WTT	Water Transmission Tunnel
α	Qe/Qmaks, Qort/Qmaks
ρ	Density (kg/m3)
η	Efficiency (%)
ϕ	Diameter of Precipitated Particle (mm)
π	Pi Number

Subscripts

ave	Average
eff	Effective
dpe	Decreasing Permanent Equipment
E-loss	Energy losses
g	Generator
max	Maximum
n	Net
T	Tunnel
t	Turbine
tot	Total
tr	Transformer
opt	Optimum
p	Precipitating
P	Penstock
pe	Permanent Equipment
Pn	Number of Penstock
rel	Reliable
SP	Sedimentation Pond.

References

[1] International Energy Agency, Key world energy statistics 2017, 2017. [Online]. Available: https://doi.org/10.1787/key_energ_stat-2017-en [Accessed: February 6, 2020].

[2] A. Cüce, "Design and cost analysis of regulator type a hydropower plant," MSc Dissertation, Recep Tayyip Erdogan University, Rize, Turkey, 2019.

[3] European Small Hydropower Association, Guide on how to develop a small hydropower plant, 2004. [Online]. Available:

http://www.canyonhydro.com/images/Part_1_ESHA_Guide_on_how_to_develop_a_small_hydropower_plant.pdf [Accessed: February 6, 2020].
[4] V. Yildiz and J. A. Vrugt, "A toolbox for the optimal design of run-of-river hydropower plants," *Environmental Modelling and Software*, vol. 111, pp. 134-152, 2019.
[5] Ş. Cofcof, *General Sizing Principles in Regulator-type Plants*. DOLSAR Engineering Limited Company, Ankara, 1996.
[6] J. S. Anagnostopoulos and D. E. Papantonis, "Optimal sizing of a run-of-river small hydropower plant," *Energy Conversion and Management*, vol. 48, pp. 2663-2670, 2007.
[7] P. R. Gingold, "The optimum size of small run-of-river plants," *Water Power and Dam Construction*, 33(11), pp. 35-39, 1981.
[8] F. Fahlbush, "Optimum capacity of a run-of-river plant," *Water Power and Dam Construction*, 35(3), pp. 45-48, 1983.
[9] L. Da Deppo, Datei C, V. Fioretto and A. Rinaldo, "Capacity and type of units for small run-of-river plants," *Water Power and Dam Construction*, 36(10), pp. 33-38, 1984.
[10] D. E. Papantonis and G. Andriotis, "Optimisation of the size and number of turbines for a small hydropower plant," *Proceedings, Hidroenergia*, vol. 3, pp. 59–68, 1993.
[11] S. M. H. Hosseini, F. Forouzbakhsh and M. Rahimpoor, "Determination of the optimal installation capacity of small hydropower plants through the use of technical, economic and reliability indices," *Energy Policy*, vol. 33, pp.1948-1956, 2005.
[12] O. B. Haddad, M. Moradi-Jalal and M. A. Marino, "Design-operation optimisation of run-of-river power plants," *Proceedings of the Institution of Civil Engineers - Water Management*, vol. 164, pp. 463-475, 2011.
[13] N. Voros, C. Kiranoudis and Z. Maroulis, "Short-cut design of small hydroelectric plants," *Renewable Energy*, vol. 19, pp. 545-563, 2000.
[14] R. Montanari, "Criteria for the economic planning of a low power hydroelectric plants," *Renewable Energy*, vol. 28, pp. 2129-2145, 2003.
[15] Y. Liu, L. Ye, I. Benoit, X. Liu, Y. Cheng, G. Morel and C. Fu, "Economic performance evaluation method for hydroelectric generating units," *Energy Conversion and Management*, vol. 44, pp. 797-808, 2003.
[16] J, Kaldellis, D, Vlachou and G. Korbakis, "Techno-economic evaluation of small hydropower plants in Greece: a complete sensitivity analysis," *Energy Policy*, vol. 33, pp. 1969-1985, 2005.
[17] L. Barelli, L. Liucci, A. Ottaviano and D. Valigi, "Mini-hydro: a design approach in case of torrential rivers," *Energy*, vol. 58, pp. 695-706, 2013.
[18] G. Cavazzini, A. Santolin, G. Pavesi and G. Ardizzon, "Accurate estimation model for small and micro hydropower plants costs in hybrid energy systems modelling," *Energy*, vol. 103, pp. 746-757, 2016.
[19] Ö. Yüksek, T. Anılan and F. Saka, "Problems and possible solutions to environmental impacts of small hydropower plants in Turkey," *Turkish Journal of Electromechanics & Energy*, 5(2), 37-47, 2020.
[20] C. Monteiro, I. J. Ramirez-Rosado and L. A. Fernandez-Jimenez, "Short-term forecasting model for electric power production of small-hydro power plants," *Renewable Energy*, vol. 50, pp. 387-394, 2013.
[21] K. Yıldız, *Calculation Principles and Projecting of Hydroelectric Power Plants*. General Directorate of State Hydraulic Works, Ankara, 1992.
[22] Ş. Cofcof *Water Transmission Line and Forebay in Regulator-type Plant*s. DOLSAR Engineering Limited Company, Ankara, 2008.
[23] H. Başçeşme, *Hydroelectric Power Plants and Hydroelectric Power Plant Facilities*. Electricity Generation Inc., Directorate of Hydroelectric Power Plants, Ankara, 2003.
[24] Hidayat, Arnita, Cahayahati, M. Zoni and S. Jamaan, "Determination of optimal power capacity for run of river hydropower plant based on flow duration curve using Newton's interpolation method," *International Conference on High Voltage Engineering and Power System*, Bali, Indonesia, 2-5 October 2017, pp. 383-387.
[25] Ş. Cofcof, "Tunnel costs and a study on optimum diameter selection in energy tunnels," *DSİ Technical Bulletin*, vol. 77, pp. 69-78, 1992.
[26] Ş. Cofcof, "Optimum diameter selection in steel penstock," *DSİ Technical Bulletin*, vol. 78, pp. 47-57, 1993.
[27] O. Paish, "Small hydropower: technology and current status," *Renewable and Sustainable Energy Reviews*, 6(6), pp. 537-556, 2002.
[28] H. Sharma and J. Singh, "Runoff river plant: status and prospects," *International Journal of Innovative Technology and Exploring Engineering*, 3(2), pp. 210-213, 2013.
[29] V. K. Singh and S. K. Singal, "Operation of hydropower plants-a review," *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 610–619, 2017.
[30] V. Sammartano, L. Liuzzo and G. Freni, "Identification of potential locations for run-of-river hydropower plants using a GIS-based procedure," *Energies*, vol. 12, pp. 3446, 2019.
[31] B. Ogayar and P. G. Vidal, "Cost determination of the electromechanical equipment of a small hydropower plant," *Renewable Energy*, vol. 34, pp. 6–13, 2009
[32] S. K. Singal, R. P. Saini and C. S. Raghuvanshi, "Analysis for cost estimation of low head run-of-river small hydropower schemes," *Energy for Sustainable Development*, vol. 14, pp. 117-126, 2010.
[33] A. Santolin, G. Cavazzini, G. Pavesi, G. Ardizon and A. Rossetti, "Techno-economical method for the capacity sizing of the small hydropower plant," *Energy Conversion and Management*, vol. 52, pp. 2533-2541.
[34] F. Hakgören, "Planning and project principles of regulators (couplings)," *Atatürk University Journal of Agricultural Faculty*, 4(3), pp. 101-118, 1973.
[35] İ. Tanrıverdi, *Project Principles of Hydroelectric Power Plants*. General Directorate of State Hydraulic Works, Dams and Hydroelectric Power Plants Department, Ankara, 1991.

Acknowledgement

This work was produced from MSc. Thesis as A. Cüce, "Design and cost analysis of regulator type a hydropower plant," Recep Tayyip Erdogan University, Rize, Turkey, 2019.

Biographies

Ayhan Cüce received his B.Sc. degree from the Department of Mechanical Engineering, Yıldız Technical University, İstanbul, Turkey, in 1999 and M.Sc. degree from the Department of Mechanical Engineering, Recep Tayyip Erdoğan University, Rize Turkey, in 2019. He is currently a Mechanical Engineer at 22nd Regional Directorate of State Hydraulic Works, Trabzon, Turkey. His research interests include design and analysis of hydropower plants, fluid mechanics, design of mechanical systems and optimisation.

E-mail: ayhanncuce@gmail.com

Haydar Küçük received his B.Sc. degree from the Department of Mechanical Engineering, Yıldız University, İstanbul, Turkey, in 1993, M.Sc. and PhD degrees from the Department of Mechanical Engineering, Karadeniz Technical University, Trabzon, Turkey, in 1998 and 2003, respectively. He is currently a Full Professor in the Mechanical Engineering Department of the Faculty of Engineering and Architecture at Recep Tayyip Erdoğan University, Rize, Turkey. His research interests involve numerical heat transfer and fluid flow, drying and drying models, energy and exergy analyses and thermodynamics. He serves as a referee for prestigious international journals. He has participated in national and international research projects as a researcher.

E-mail: haydar.kucuk@erdogan.edu.tr

Adnan Midilli received his B.Sc., M.Sc. and PhD degrees from the Department of Mechanical Engineering, Karadeniz Technical University, Trabzon, Turkey, in 1993, 1996 and 2001, respectively. He is currently a Full Professor of the Department of Mechanical Engineering, Faculty of Mechanical Engineering, Yıldız Technical University, İstanbul, Turkey. He is an active member of various international scientific organisations and societies and serves as an editorial board member on various prestigious international journals. He is a recipient of several national research awards. He has been working as a researcher in national and international research projects. His research interest includes sustainable energy technologies, sustainable development, thermodynamic design and modelling.

E-mail: midilli@yildiz.edu.tr