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Techno-economic analysis of a regulator-type hydropower plant

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ABSTRACT

In this study, an economic analysis of a regulator-type hydropower plant was performed by using MS Excel software. Intact, moderate intact, weak and very weak rock formations were taken into consideration for economic evaluation of the water transmission tunnel. The amounts of firm (primary) and secondary energy, approximate cost of plant elements, income, outgoings, and profitability of plant and unit cost of energy were calculated. Annual firm energy, secondary energy and total energy were calculated as 55.4, 90.5 and 145.9 GWh, respectively. Unit investment cost of water transmission tunnel for fresh surface was determined to be 3281 USD/m, whereas it was 7264 USD/m for externally reinforced penstock with constant wall thickness and constant diameter, 410 USD per kW for electromechanical facilities, 1004 USD/kW for the unit investment cost of the plant and 28.24 million USD for total investment cost. Annual net income, unit energy cost and profitability were calculated to be 3.27 million USD, 0.0209 USD/kWh and 2.07, respectively. The increase in cost is about 20% between the intact rock and moderate intact rock, 55% between intact rock and weak rock, and 80% between intact rock and very weak rock for the same diameter and length of tunnel.

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1. INTRODUCTION

Hydropower is a renewable and sustainable energy source as it does not produce toxic waste and emissions and also it is the most efficient and least expensive method when compared to all other energy sources to generate electricity [1]. The hydropower plants in the world are generally small types and called run of the river (RoR) or regulator-type hydropower plants. In regulator-type hydropower plants, the water is taken from the river bed and transferred to the sedimentation pond to precipitate the drifted material not to damage the water transmission line and turbine blades [2]. The turbines are rotated when the water passes over the turbine blades and the mechanical energy is converted into electrical energy in the generators directly connected to the turbines. The electrical energy is regulated to appropriate values with different electrical equipment and then sent to the transmission line [2].

Regulator-type hydropower plants have a lower impact on the ecosystem (e.g. during their construction), are less complex and require lower investment, operational, and maintenance costs and are more suitable for smaller water heads and their construction time is significantly shorter [1]. Regulator-type hydropower plants are generally considered environmentally friendly, flexible to operate, and ideally suited for localized energy production [1]. Regulator-type hydropower plants have little or no water storage capacity and so the electricity generation changes depending on seasonal river flows and will only operate when there is sufficient flow in the river. The main negative environmental impacts of RoR hydropower plants are a lack of proper fish and wildlife passages and inadequate rehabilitation and restoration of habitat [3].

In their earlier work, Cüce et al. studied the design of a regulator-type hydropower plant in the Eastern Black Sea region in Turkiye [2]. Depending on the project volumetric flow rate, they determined the optimum tunnel diameter, optimum penstock diameter, installed power capacity, and turbine type. In addition, they estimated the annual average volumetric flow rate, effective volumetric flow rate, the water amount as well as friction losses, local losses, net head, and amounts of the firm (primary) and secondary energy by using MS Excel software. They calculated the annual total energy as 145.9 GWh, optimum tunnel diameter as 3.30 m, and optimum penstock diameter as 2.75 m for 35 m^3/s of maximum flow rate. Three turbines were used for 28.1 MW of installed power, and 9.97 MW of turbine was selected for 11.2 m^3/s of flow rate and 98.7 m of the net head. Voith brand of Francis Turbine with 518 rpm, 166 m-kW of specific speed, and 0.92 efficiencies and generators with 500 rpm of synchronous speed, 50 Hz, 14 double pole numbers are selected.

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Yildiz and Vrugt performed a study to determine energy production, technical performance, operational and maintenance costs, and economic profit of run of the river hydropower plant by using the HYdroPowER (HYPER) model [4]. They found that energy production is highly enhanced as two turbines are used in parallel, and investment and maintenance costs are increased significantly. Cavazzini et al. proposed a new model to estimate the cost of electromechanical equipment including turbine, automatic valve, regulation elements, and generator costs [5]. Their correlation depends on three terms power, net head, and design flow rate. Ogayar and Vidal developed a series of equations based on power and net head to determine the cost of the electromechanical equipment such as Pelton, Francis, Kaplan, and semi-Kaplan turbines of a small hydropower plant [6]. Singal et al. suggested correlations for cost including civil works components and electromechanical equipment components of low-head RoR small hydropower projects [7]. On the other hand, some studies were performed to determine the optimum installed capacity of small hydropower plants based on the technical and economic indices [8, 9]. Researchers also determined the potential of small hydropower plants for different rivers or locations based on different economic approaches [10-15]. Optimization of small hydropower plants was carried out by using numerical or mathematical models in terms of turbine numbers or types [16, 17]. Santolin et al. presented a techno-economical method for the capacity sizing of a small hydropower plant by considering technical and economical parameters such as machine dimensions, turbine type, maximum installation height, annual energy production, net present value, internal rate of return and machine cost [18].

This study aims to conduct an economic analysis of a regulator-type hydropower plant in the Eastern Black Sea region in Türkiye, firstly. In this scope, intact, moderate intact, weak, and very weak rock formations were taken into consideration for the economic evaluation of the tunnel. The amounts of the firm and secondary energy, approximate cost of plant elements, incomes of the facility, outgoings of the facility, profitability of facility, and unit cost of energy were calculated. This study includes a detailed evaluation of a regulator-type hydropower plant in Türkiye's Eastern Black Sea region which can be used by researchers in academia and, industry. The first part of this study is on the conceptual design of a regulator-type hydropower plant which was presented by Cüce et al. elsewhere in the literature [2].

2. ANALYSIS

The details of the calculation procedure and assumptions relating to design of a regulator-type hydropower plant were estimated by Cüce et al. in the literature [2]. A schematic view of a regulator-type hydropower plant is given in Figure 1.

Estimated costs for electromechanical equipment and fixed installations are estimated using Equation (1) for 5-1000 MW and Equation (2) for 0.5-5 MW installed power capacities, respectively [2, 5-7, 18- 20].

$$EC_{EME} = 3.3x10^{6}P^{0.92}H_n^{-0.32P^{0.058}} \tag{1}$$

$$EC_{EME} = 4.61x10^{6}P^{0.7}H_n^{-0.35} \tag{2}$$

where, P and H_n are installed power and net head, respectively.

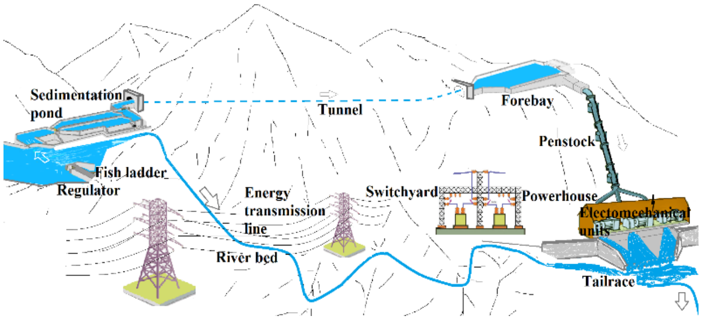


Fig. 1. A typical regulator-type hydropower plant schematic.

For intact rock formation, the unit estimated cost of the water transmission tunnel (EC_T) is obtained from Equation (3) [19].

$$EC_T = 287D_T^{1.676}L_T^{0.168} \tag{3}$$

where, D_T and L_T are the diameter and length of the water transmission tunnel, respectively.

The unit estimated cost of tunnel for moderate intact, weak, and very weak rock formations is calculated from Equation (4), Equation (5), and Equation (6), respectively [19].

$$EC_T = 341D_T^{1.676}L_T^{0.168} \tag{4}$$

$$EC_T = 446D_T^{1.676}L_T^{0.168} \tag{5}$$

$$EC_T = 516D_T^{1.676}L_T^{0.168} \tag{6}$$

The unit estimated cost of exposed penstock (EC_P) is obtained from Equation (7) and Equation (8) for H<120 and H≥120, respectively [2]. The unit cost of penstock is taken as 4.34 USD/kg [2, 20].

$$EC_P = 8.635\pi D_P(6D_P + 2)(UC)_P \tag{7}$$

$$EC_P = 0.4663\pi H D_P^2(UC)_P \tag{8}$$

where, D_P, $(UC)_P$, and H are the diameter and unit cost of penstock and head, respectively.

By considering the depreciation, maintenance, and renovation outgoings, the annual outgoings (AO) of the facility are estimated from Equation (9) [2, 20].

$$AO = ADO + AMO + ARO \tag{9}$$

where, ADO, AMO, and ARO are annual depreciation outgoings, annual maintenance, outgoings, and annual renovation outgoings, respectively.

Investment cost (IC), annual depreciation, maintenance, renovation, and yearly outgoings of the water transmission tunnel are given in Equations (10) to (14), respectively [2, 20].

$$IC_T = 380.26D_T^{1.676}xL_T^{0.168} \tag{10}$$

$$ADO_T = 36.52D_T^{1.676}L_T^{0.168} \tag{11}$$

$$AMO_T = 1.58D_T^{1.676}L_T^{0.168} \tag{12}$$

$$ARO_T = 0.01D_T^{1.676}L_T^{0.168} \tag{13}$$

$$AO_T = 38.11D_T^{1.676}L_T^{0.168} \tag{14}$$

Facility cost (FC), project cost (PC), and investment cost (IC) of permanent equipment are calculated from Equations (15) to (17), respectively [2, 20].

$$FC_{pe} = 5.57Q^3_{max}D_T^{-16/3} \tag{15}$$

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

$$IC_{pe} = 6.41Q^3_{max}D_T^{-16/3} \tag{17}$$

Annual outgoings of decreasing permanent equipment are obtained from Equation (18) [2, 20].

$$AO_{dpe} = 0.76Q^3_{max}D_T^{-16/3} \tag{18}$$

The total annual outgoings of the water transmission tunnel (TAO_T) are given in Equation (19) [2, 20].

$$TAO_T = 38.11D_T^{1.676}L_T^{0.168} + (9.607\alpha^3 - 0.76)Q^3_{max}D_T^{-16/3} \tag{19}$$

where α is the ratio of the annual average flow rate (Q_{ave}) to the maximum flow rate (Q_{max}) or the ratio of the annual effective flow rate (Q_{eff}) to the maximum flow rate (Q_{max})

Annual depreciation, maintenance, renovation, and total outgoings of penstock are calculated from Equation (20) to (23), respectively [2, 20].

$$ADO_P = (DF)_P(IC)_P \tag{20}$$

$$AMO_P = (MF)_P(FC)_P \tag{21}$$

$$ARO_P = (RF)_P(FC)_P \tag{22}$$

$$AO_P = ADO_P + AMO_P + ARO_P \tag{23}$$

Estimated and investment costs of penstock are given in Equation (24) and Equation (25), respectively [2, 20].

$$EC_P = 180.385\pi D_P t \tag{24}$$

$$IC_P = 1.21(EC)_P \tag{25}$$

Annual outgoings of penstock are obtained from Equation (26) [2].

$$AO_P = 90.54D_P^2 + 30.18D_P \tag{26}$$

Facility and investment costs of decreasing permanent equipment are obtained from Equations (27) and (28), respectively [2, 20].

$$FC_{dpe} = 3.38Q^3_{max}D_P^{-16/3} \tag{27}$$

$$IC_{dpe} = 3.73Q^3_{max}D_P^{-16/3} \tag{28}$$

Annual outgoings of decreasing permanent equipment (AO_{dpe}) are calculated from Equation (29) [2, 20].

$$AO_{dpe} = 0.39Q^3_{max}D_P^{-16/3} \tag{29}$$

where D_P is the diameter of the penstock.

Total annual outgoings of penstock (TAO_P) are estimated by using Equation (30) [2, 20].

$$TAO_P = 90.54D_P^2 + 30.18D_P + 8.04Q^3_{max}\alpha^3D_P^{-16/3} - 0.39Q^3_{max}D_P^{-16/3} \tag{30}$$

3. RESULTS

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

The estimated cost of electromechanical equipment, water transmission tunnel, and penstock are calculated by using Equation (1), Equation (3), and Equation (7), respectively. Estimated costs of other main parts for regulator-type hydropower plants are obtained by using a certain ratio of permanent equipment. The estimated costs of parts for regulator-type hydropower plants are given in Figure 2.

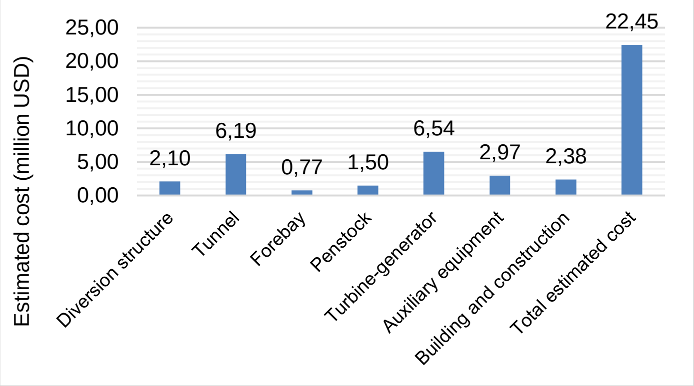


Fig. 2. Estimated costs of main parts for the regulator-type hydropower plant.

Facility cost is obtained by adding unknown costs to predicted cost and project cost is calculated by adding expropriation cost and cost of transportation roads to facility cost. The investment cost is calculated by adding the interest amount to the project cost during the construction period and is presented in Figure 3.

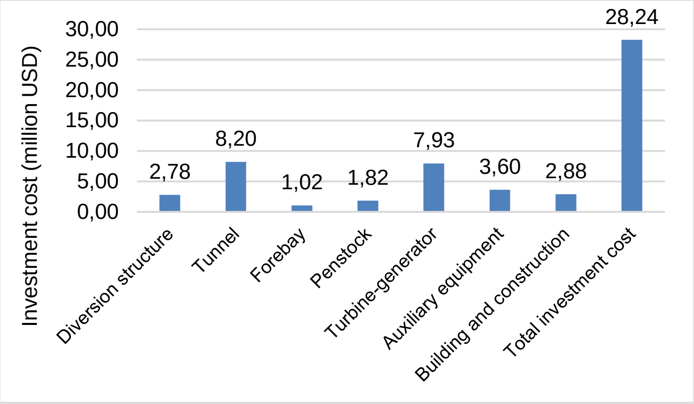


Fig. 3. Investment costs of main parts regulator type hydropower plant.

The unit estimated and investment costs of electromechanical equipment are calculated as 338 USD/kW and 410 USD/kW, respectively. The cost of electromechanical equipment depends on the type and origin of the selected turbine.

Table 1. Investment costs, unit costs, and net income for optimum tunnel diameter and different flow rates.

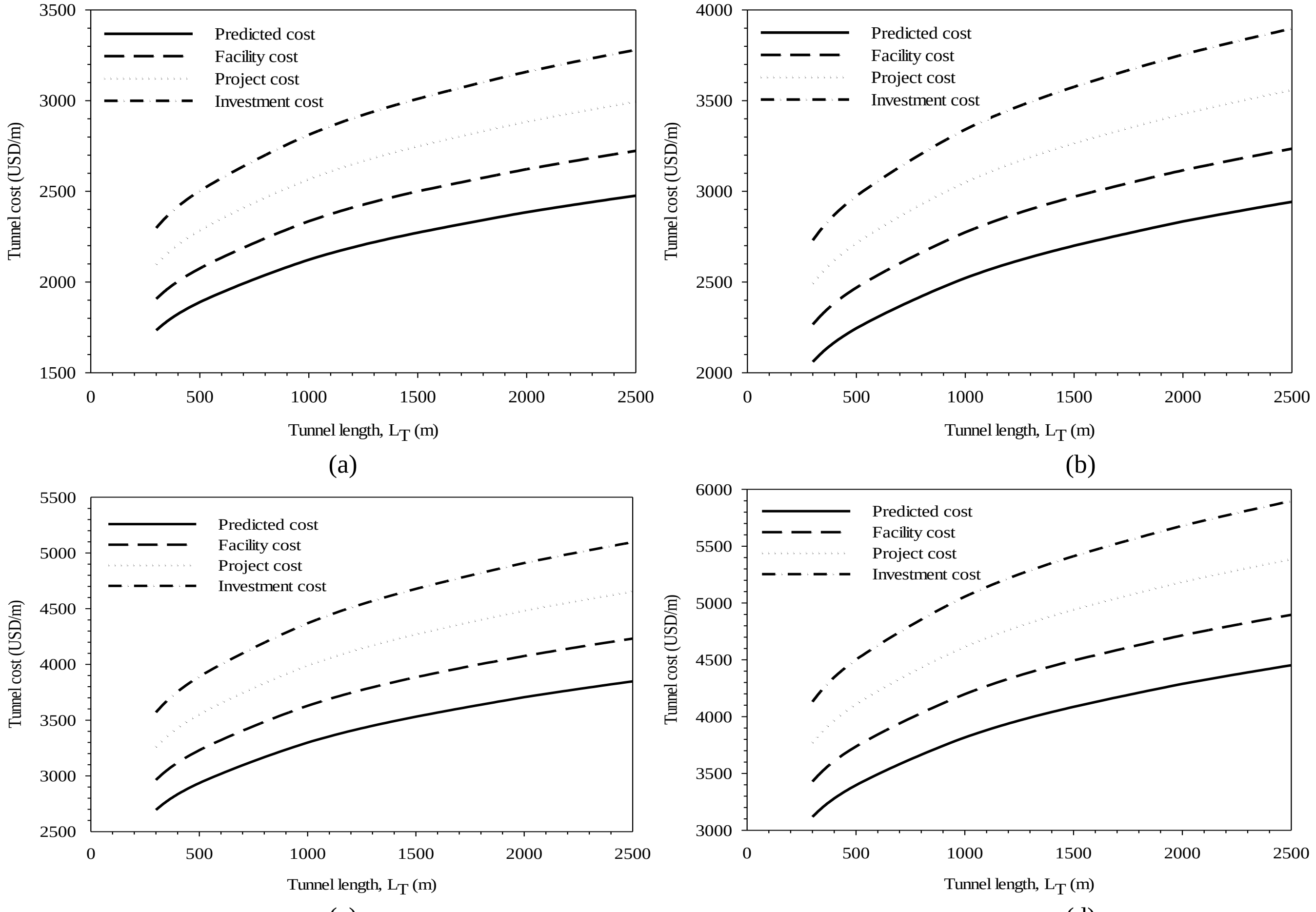
Flow rate (m^3/s)	*Average flow rate (m^3/s)*	*Capacity (MW)*	*Cost (million USD)*	*Energy income (million USD)*	*Outgoings (million USD)*	*Net income (million USD)*	*Unit cost (USD/kW)*
7.90	7.51	6.66	15.60	3.32	1.64	1.68	2,342
8.73	8.27	7.35	16.08	3.51	1.69	1.82	2,188
9.64	9.07	8.11	16.59	3.70	1.75	1.95	2,046
10.64	9.89	8.93	17.13	3.90	1.81	2.09	1,918
10.64	9.89	8.93	17.13	3.90	1.81	2.09	1,918
11.75	10.75	9.84	17.72	4.10	1.87	2.23	1,801
12.97	11.64	10.84	18.36	4.31	1.94	2.37	1,694
14.32	12.55	11.94	19.05	4.52	2.02	2.50	1,596
15.81	13.48	13.14	19.79	4.73	2.10	2.63	1,506
17.46	14.42	14.46	20.59	4.95	2.19	2.76	1,424
19.28	15.38	15.91	21.45	5.16	2.29	2.87	1,348
21.30	16.34	17.51	22.38	5.38	2.39	2.99	1,278
23.55	17.29	19.28	23.39	5.59	2.51	3.08	1,213
26.08	18.24	21.25	24.50	5.79	2.63	3.16	1,153
29.00	19.19	23.51	25.75	5.99	2.77	3.22	1,095
32.52	20.15	26.22	27.22	6.19	2.93	3.26	1,038
33.33	20.35	26.85	27.56	6.23	2.97	3.26	1,026
34.20	20.55	27.51	27.91	6.27	3.01	3.26	1,015
35.00	**20.73**	**28.13**	**28.24**	**6.31**	**3.04**	**3.27**	**1,004**
36.00	20.95	28.89	28.64	6.35	3.09	3.26	991
37.16	21.19	29.77	29.10	6.40	3.14	3.26	978
44.14	22.40	35.01	31.79	6.63	3.15	3.45	908
56.45	23.90	43.98	36.24	6.88	3.94	2.94	824
81.44	25.70	61.68	44.53	7.12	4.86	2.26	722
136.00	26.90	112.93	66.34	7.95	7.29	0.66	587

Net annual income rises 31,126 USD/year, and unit investment cost and total investment cost decrease 7 USD/kW and 0.37 million USD, respectively, based on optimum tunnel diameter and optimum penstock diameter for 35 m^3/s of project flow rate.

Unit energy costs are calculated as 0.0192 USD/kWh, 0.0212 USD/kWh, and 0.0209 USD/kWh depending on the estimated costs, critical speed, and optimum diameter, respectively.

Predicted, facility, project, and investment costs in horseshoe-cross section air-shared transmission tunnel are estimated depending on tunnel length for 3.30 meters of optimum tunnel diameter in intact rock formation and given in Figure 4(a). These costs are also estimated for moderate intact, weak, and very weak rock formations and are presented in Figure 4(b), (c), and (d), respectively, for the same optimum tunnel diameter.

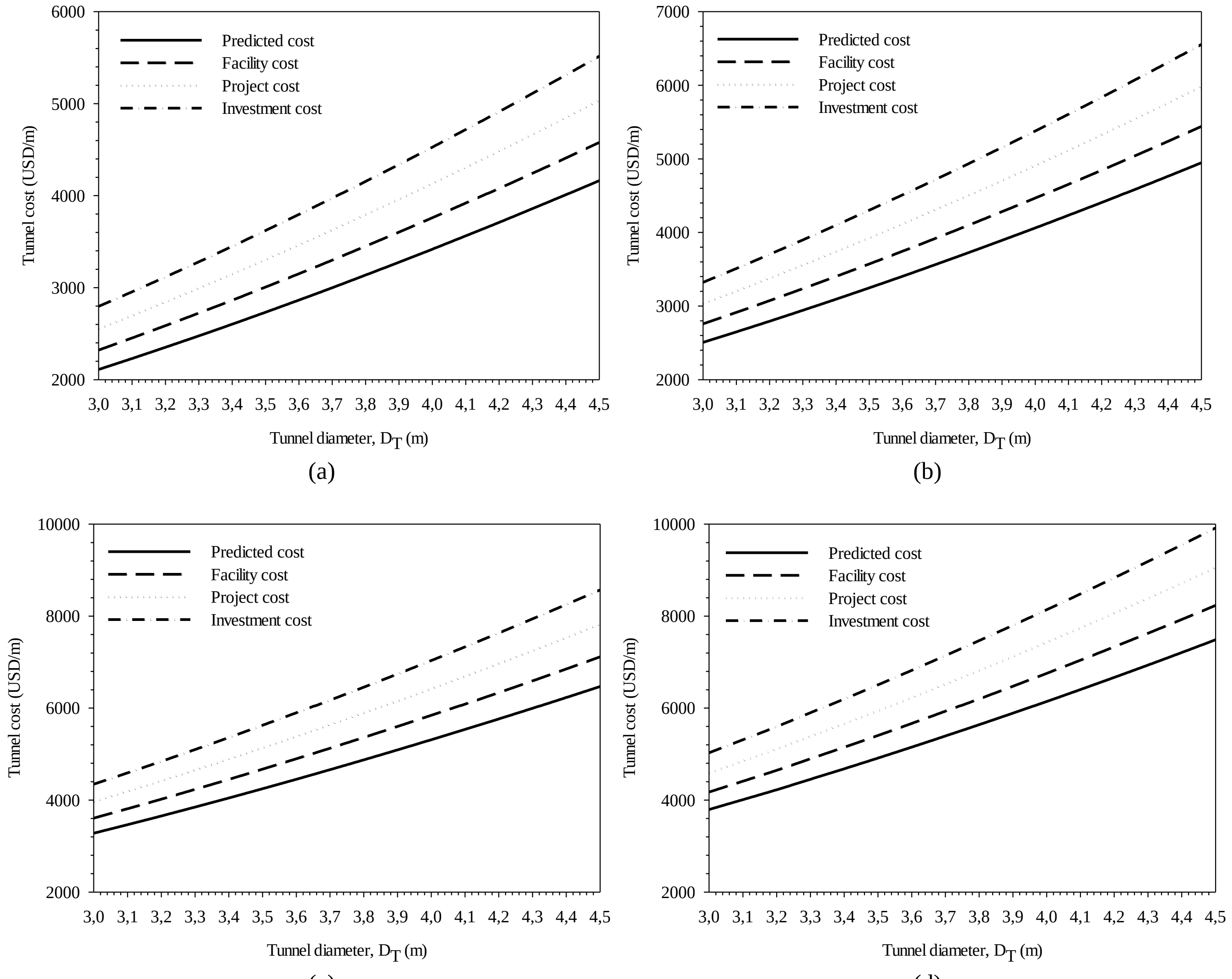
It is seen that the unit costs vary in different strength rocks and tunnel lengths for the same diameter. Unit predicted costs are 2,476 USD/m, 2,942 USD/m, 3,848 USD/m, and 4,452 USD/m in intact, moderate intact, weak, and very weak rock formations, respectively, for tunnels with a length of 2500 m. As can be seen from Figure 5(a), (b), (c), and (d) rock formation is a very important parameter for tunnel cost. The cost difference between the very weak and intact rock formations is about 1.5 times. Also, it is observed that when the tunnel length increases the cost of the tunnel rises.



(a) (b)

(c) (d)

Fig. 4. The costs of transmission tunnel as a function of tunnel length for 3.30 m of optimum tunnel diameter (a) intact rock formation, (b) moderate intact rock formation, (c) weak rock formation, (d) very weak rock formation.



(a) (b)

(c) (d)

Fig. 5. The costs of transmission tunnel as a function of tunnel diameter for 2500 m of tunnel length (a) intact rock formation, (b) moderate intact rock formation, (c) weak rock formation, (d) very weak rock formation.

Facility cost is obtained by adding unknown costs to the predicted cost, the project cost is calculated by adding expropriation, project supervision costs to facility cost, and investment cost is estimated by adding the interest and depreciation costs to the project cost. The unit costs are calculated by assuming the tunnel is opened from two opposite mirrors.

Predicted, facility, project, and investment costs in horseshoe-cross section air-shared transmission tunnel are estimated depending on tunnel diameter for 2500 m of tunnel length in intact rock formation and given in Figure 5(a).

These costs are also estimated for moderate intact, weak, and very weak rock formations and are presented in Figure 5(b), (c), and (d), respectively, for the same tunnel length. It is seen that; when the tunnel diameter rises the cost of the tunnel also increases for 2500 m of tunnel length. For the same diameter and length tunnel, the increase in cost is about 20% between the intact rock and moderate intact rock, 55% between an intact rock and weak rock, and 80% between an intact rock and very weak rock.

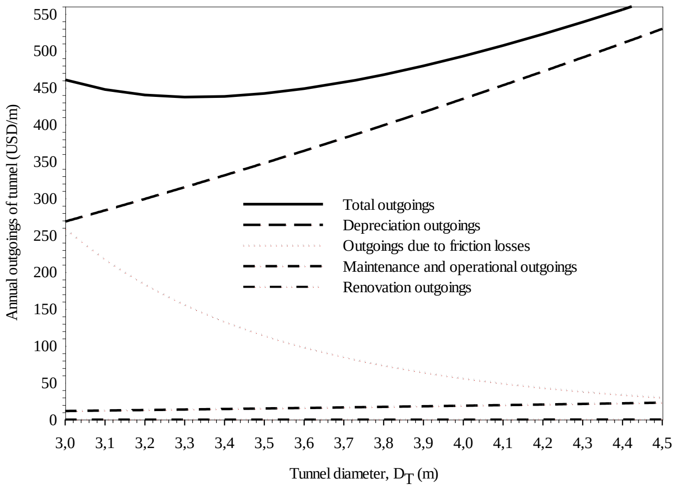


Fig. 6. Annual outgoings and total annual outgoings as a function of tunnel diameter for 2500 m of transmission tunnel length.

Annual depreciation costs, annual costs due to friction losses, annual maintenance, and operational costs, annual renovation costs, and total annual costs are given in Figure 6 as a function of tunnel diameter for 2500 m of tunnel length. It is seen that the least outgoings are renovation outgoings, maintenance and operational outgoings, outgoings due to friction losses, and depreciation outgoings in the tunnel, respectively. While renovation outgoings, maintenance, operational outgoings, and depreciation outgoings increase with the rising of tunnel diameter, outgoings due to friction losses decrease with increasing in tunnel diameter. However, total annual outgoings decrease up to 3.3 m of tunnel diameter (optimum tunnel diameter) and then increase with the rising of tunnel diameter.

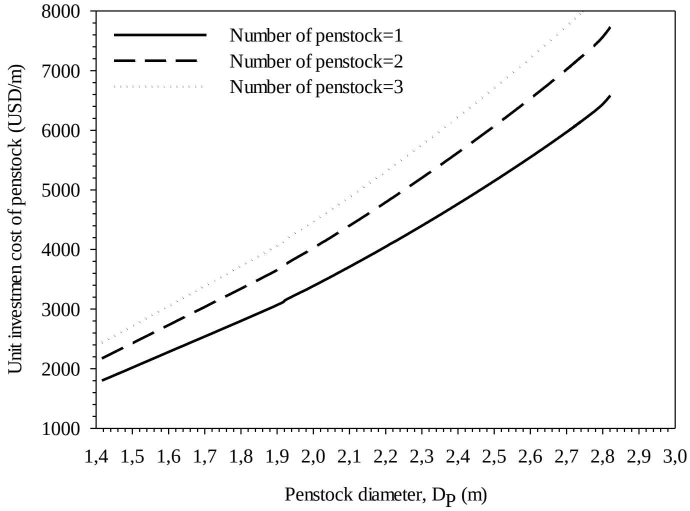


Fig. 7. The unit investment cost of penstock as a function of penstock diameter in case of using a different number of penstocks.

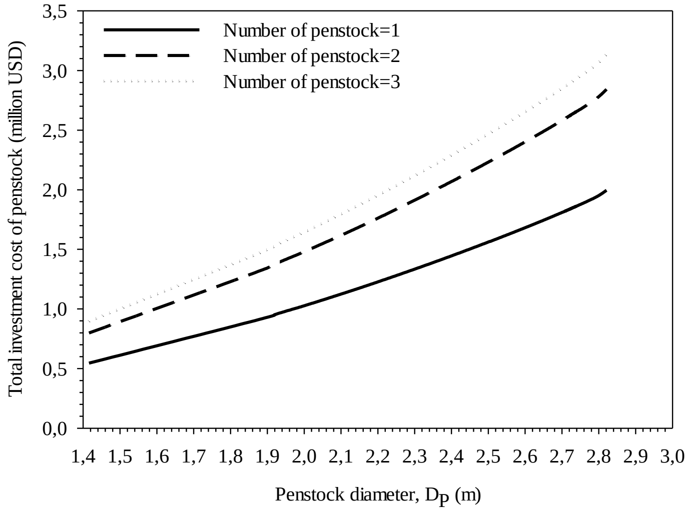


Fig. 8. The total investment cost of penstock as a function of penstock diameter in case of using a different number of penstock for 250 m of penstock length.

The number of penstocks may be more than one for the efficient generation of secondary energies. The cost of unit penstock varies if different numbers of penstock are used. The unit investment cost is calculated for the different numbers of penstocks (see Figure 7) and the total investment cost of penstock is given in Figure 8 for 250 m of penstock length. If 3 and 2 penstocks are used instead of 1 penstock, the unit penstock cost increases by approximately 1.298 and 1.175 times, respectively.

The optimum diameter of penstock is calculated as 2.77 m but it is taken as 2.75 m, in practice. The effect of this situation on the net head is 94.63 m instead of 94.67 m. The unit cost of penstock decreases from 6,081 USD/m to 5,994 USD/m. Also, it is observed that when the penstock diameter increases the total investment cost of the penstock rises.

Annual depreciation costs, annual maintenance, and operational costs, annual renovation costs, and total annual costs are given in Figure 9 as a function of penstock diameter for 3 penstocks. It is observed that the highest outgoings are depreciation ones, followed by maintenance and operational, and renovation outgoings, respectively. Depreciation, maintenance operational, and renovation outgoings are 919 USD/m, 87 USD/m, and 7 USD/m, respectively, for a 1.74 m equal diameter of 3 penstocks.

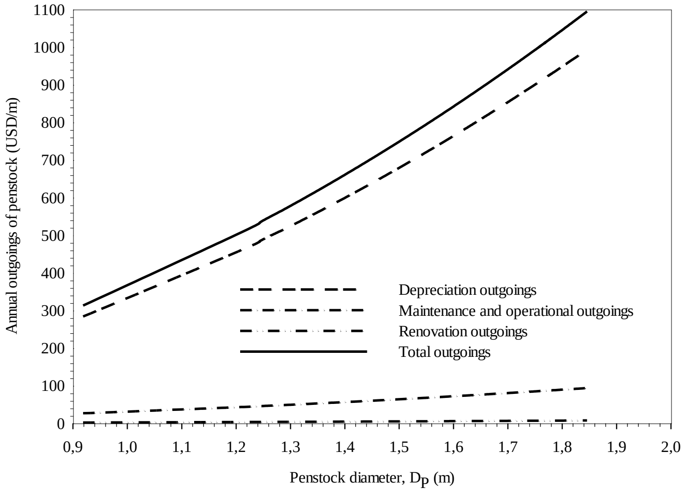


Fig. 9. Variation of annual outgoings as a function of penstock diameter for 3 penstocks.

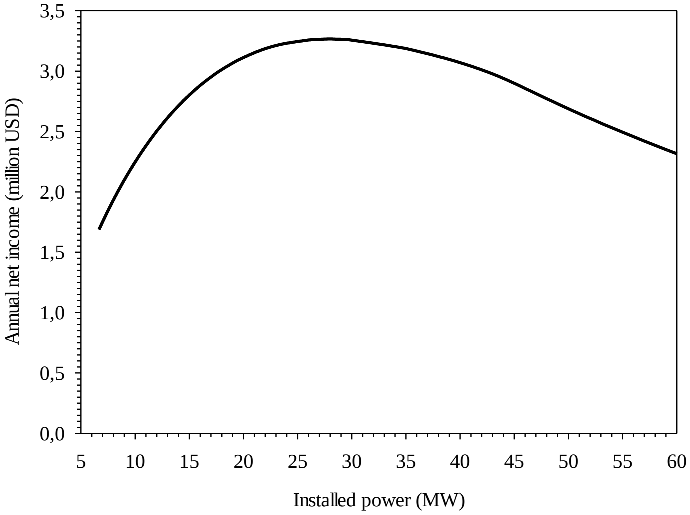


Fig. 10. Variation of net income with the installed power capacity.

Net income depending on installed power is presented in Figure 10. Annual net income is a maximum (3.27 million USD) for 28.1 MW of installed power (see Table 1). The firm energy is obtained 95% of the year, maximum energy is generated 22% of the year and secondary energy is produced 78% of the year when the flow duration curve is taken into the consideration [2, 20]. Net income increases up to the maximum installed power value corresponding to the maximum flow rate. Although the flow rate increases for the capacity values larger than the installed power, the produced energy does not increase at the same rate as the drop losses also increase. In addition, since the increase in the installed power rises depreciation, maintenance, and operational and renovation costs net income decreases. Variations of annual income, annual outgoings, and annual net income depending on the flow rate are given in Figure 11.

It is seen that when the flow rate goes up annual outgoings and annual income rise but an increase in annual income is highly low after 35 m^3/s of flow rate. However, annual net income increases up to 35 m^3/s of flow rate (project flow rate) and then decreases with the rising flow rate.

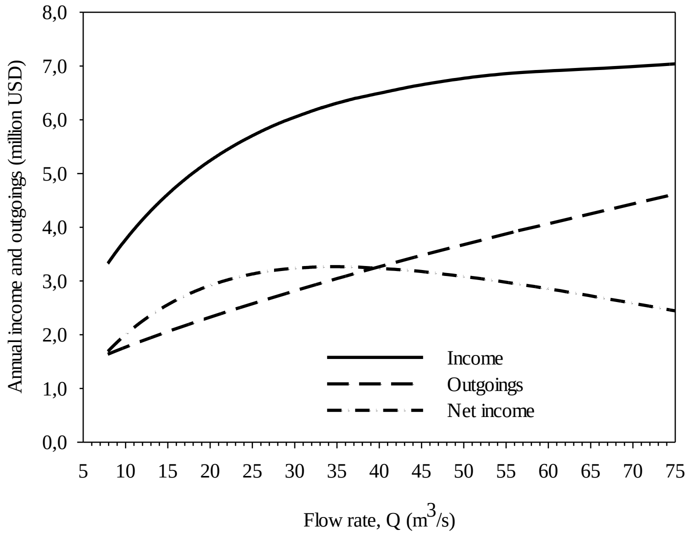


Fig. 11. Variation of annual income and outgoings with flow rate.

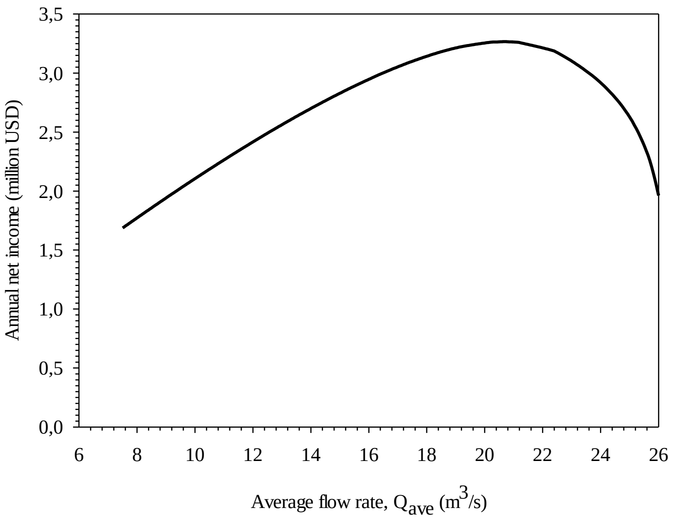


Fig. 12. Variation of annual flow rate with average flow rate.

The different average flow rates may occur for each selected flow rate because % time flow exceeded varies during the year. The average flow rate is determined as 20.73 m^3/s for 35 m^3/s of the flow rate (project flow rate). As shown in Figure 12, net income is the maximum at this average flow rate. The installed power capacity is calculated as 16.664 MW for 20.73 m^3/s of the average flow rate. In order to use different flow rates during the year, the installed power is calculated according to the maximum flow rate and it is estimated as 28.13 MW. The installed power is selected as 11.465 MW which is higher than the installed power capacity calculated according to the average flow rate to use different flow rates.

Variation of the unit energy cost is given in Figure 13 depending on flow rate. As seen in Figure 13, unit energy cost is minimum in the range of 20-35 m^3/s of the flow rate. The unit energy cost is estimated as 0.0209 USD/kWh for 35 m^3/s of flow rate. The unit energy cost varies between 0.02 USD/kWh and 0.03 USD/kWh.

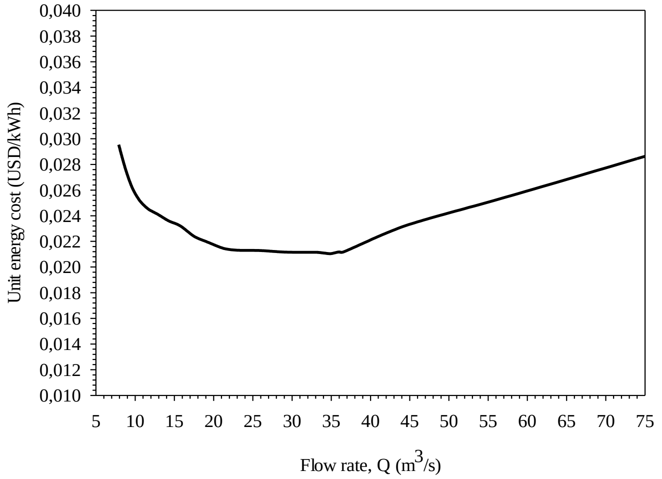


Fig. 13. Variation of unit energy cost with flow rate.

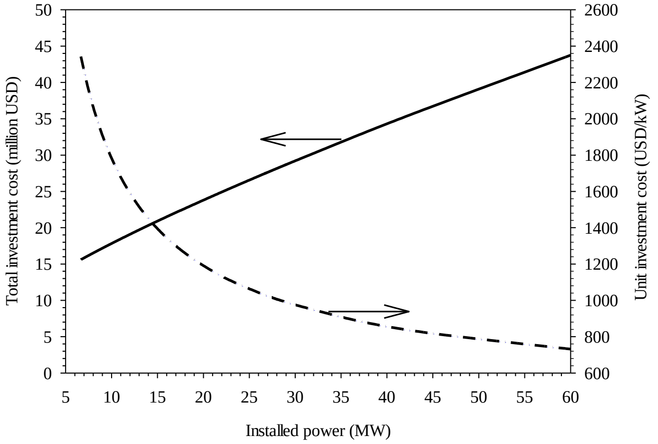


Fig. 14. Unit and total investment costs with installed power.

As it can be noted from Figure 14, the increase of installed power increases the investment cost but decreases the unit investment cost. The total investment cost for the calculated installed power of 28,129 MW is estimated at 28.24 million USD and the unit investment cost, which is the ratio of investment cost to installed power, is 1,004 USD/kW as seen in Table 1.

The cost of unit installed power is calculated as 1,011 USD/kW depending on critical velocity. However, the predicted cost of unit installed power is 900 USD/kW. Unit installed power and investment costs calculated depending on critical velocity and net income are given in Figure 15. It is seen that while the unit installed power cost decreases the investment cost increases with the increasing of flow rate. Unit installed power and investment costs fall below their predicted cost above values of project flow rate (35 m^3/s).

Investment cost depending on net income is 0.37 million USD cheaper than investment cost depending on critical velocity. Predicted installed power, investment cost and net income are estimated as 28.817 MW, 25.94 million USD, and 3.51 million USD/year, respectively.

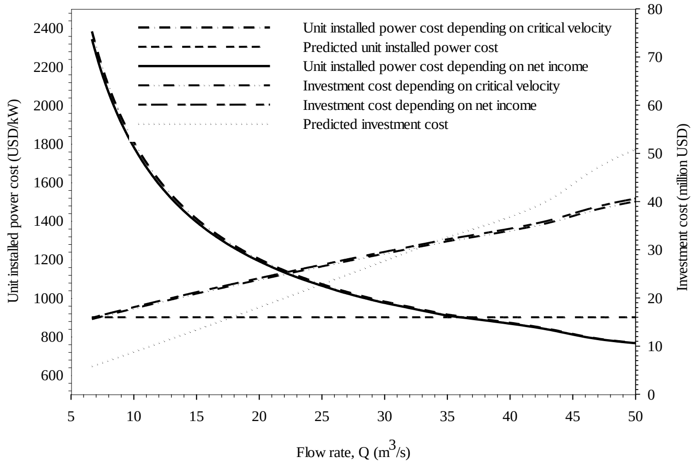


Fig. 15. Variations of unit installed power and investment costs with flow rate.

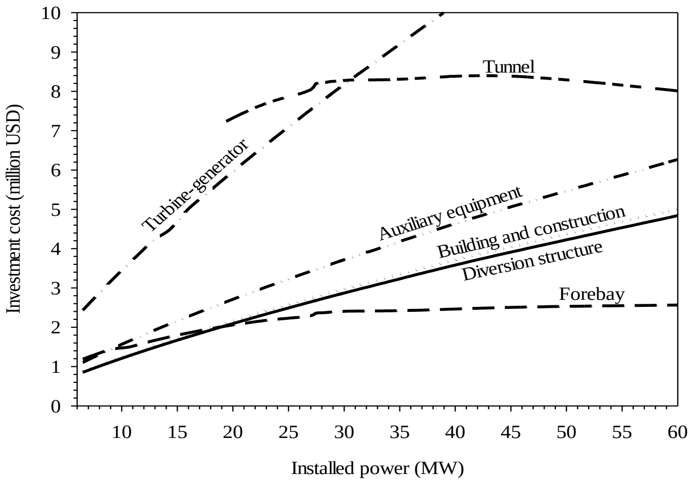


Fig. 16. Investment costs of hydropower plant main components for installed power.

The investment cost of the main components of hydropower plant such as diversion structure, tunnel, forebay, turbine-generator, auxiliary equipment and building and construction depending on the installed power are presented in Figure 16. The highest investment costs incurred are turbine-generator, tunnel, auxiliary equipment, building and construction, diversion structure and forebay, respectively, for 28.13 MW of installed power (35 m^3/s of project flow rate). It is seen that when the installed power increases the investment costs of turbine-generator, auxiliary equipment, building and construction, and diversion structure rise. However, the investment costs of the tunnel and forebay rise until 28.13 MW of installed power and after this value, the investment costs of this component are almost constant.

4. CONCLUSION

An economic analysis of a typical regulator-type hydropower plant was performed for the flow rates in the stream bed. Some concluding remarks are presented as follows:

The increase in cost is about 20% between the intact rock and moderate intact rock, 55% between an intact rock and weak rock, and 80% between an intact rock and very weak rock for the same diameter and long tunnel.

Total investment cost and maximum net income are calculated as 19.30 million USD and 3.70 million USD/year, respectively, for the predicted maximum flow rate of 35 m^3/s.

Total investment cost, installed power, total income, total outgoings, net income, and cost of unit installed power are estimated as 28.61 million USD, 28.303 MW, 6.32 million USD/year, 3.08 million USD/year, 3.24 million USD/year and 1,011 USD/kW, respectively, for critical velocity method.

Total investment cost, installed power, total income, total outgoings, net income, and cost of unit installed power are estimated as 28.24 million USD, 28.13 MW, 6.31 million USD/year, 3.04 million USD/year, 3.27 million USD/year and 1,004 USD/kW, respectively, for maximum net income method.

The investment cost of a tunnel having a 3.30 m diameter and 2500 m length is 37% of the total investment cost for intact rock.

Predicted cost of tunnel is 2,476 USD/m, 2,942 USD/m, 3,848 USD/m and 4,452 USD/m for intact, moderate intact, weak and very weak rock formations, respectively.

Annual depreciation costs, annual maintenance, and operational costs, annual renovation costs, and total annual costs of the tunnel for intact rock are 315 USD/m, 14 USD/m, 0.1 USD/m, and 329 USD/m, respectively, and annual costs due to friction losses are 156 USD/m.

Investment costs of penstock are calculated as 7,374 USD/m, 8,671 USD/m, and 9,574 USD/m in cases 1, 2, and 3 penstocks are used, respectively.

Nomenclature

ADO	Annual Depreciation Outgoings (USD)
AMO	Annual Maintenance Outgoings (USD)
AO	Annual Outgoings (USD)
ARO	Annual Renovation Outgoings (USD)
DF	Depreciation Factor
D	Diameter (m)
EC	Estimated Cost (USD)
FC	Facility Cost (USD)
H	Head (m)
HPP	Hydropower Plant
IC	Investment Cost (USD)
L	Length (m)
MF	Maintenance Factor
n	Number of Penstock

P	Installed Power (kW)
PC	Project Cost (USD)
Q	Flow Rate (m^3/s)
RF	Renovation Factor
t	Wall Thickness of Penstock (mm)
TAO	Total Annual Outgoings (USD)
UC	Unit Cost (USD/m, USD/kW)
α	Qeff/Qmax, Qave/Qmax
π	Pi Number (3.14159….)

Subscripts

ave	Average
dpe	Decreasing Permanent Equipment
eff	Effective
max	Maximum
n	Net
T	Tunnel
tot	Total
P	Penstock
pe	Permanent Equipment
EME	Electromechanical equipment

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