The Journal of Energy: Engineering & Management
Vol. 12, No. 4, Winter 2023, P. 44-53
Research Article

Technical and Economic Evaluation of Micro-hydropower Plant Design on Water Transmission Lines (A Case study of Chaharmahal and Bakhtiari Province)

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Received: 26/11/2022 **Accepted:** 31/01/2023

Abstract

The production of electricity from the pressure difference inside the water transmission lines is one of the new issues in the renewable energy fields, which is achieved by replacing pressure relief valves with micro-hydropower. For this purpose, extensive research has been done for the technical and economic evaluation of the construction of micro-hydropower on different points of water transmission lines. The main challenge in conducted studies is that these studies cannot be generalized to other points. In other words, considering that the hydraulic parameters of the lines and their operating conditions are completely different, so each line needs feasibility and separate studies. To this end, in this paper, different stages of designing micro-hydropower from a technical and economic point of view were described; then, these steps were carried out for a real case study, that is, the Kohrang-Shahrkord water transmission line. The design of micro-hydropower in this paper was done with the cost function of the ratio of income to initial capital. The results of the designs for different scenarios showed the importance of studying the daily flow rate changes that may have been affected by climate change. Also, the results showed that by choosing the Crossflow turbine for the points with large flow rate changes, the highest value of the profit index was obtained at the cost of 1.92, which led to the production of 2742,000 kW-hr of energy per year. In similar hydraulic conditions, with the choice of Torgo turbine, the value of this index was 1.34 and the annual energy production was 2141,000 kW-hr.

Keywords: renewable energy, micro-hydropower, technical evaluation, economic evaluation.

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doi: 10.22052/jeem.2023.113682

1. Introduction

The use of renewable energy has had its ups and downs throughout history. These types of energy were used early; then, with the growth and development of human societies and the availability of fossil fuels, thermal power plants replaced these sources. However, in recent decades, due to the limitations and disadvantages of fossil fuels, renewable resources have been given attention again as the exploitation of these resources is considered one of the indicators of development in the world. Among these sources, hydraulic energy plays the largest role in electricity supply; for example, in Norway up to 98% and in Brazil up to 86% of the energy consumption is provided through hydraulic energy [1].

Electric power plants that are based on hydraulic energy are considered the most flexible source of electricity supply in the world as they can respond to fluctuations in demand within a few minutes [2]. In hydropower plants, electricity is produced by using the energy of water behind dams and the flow of permanent rivers that have a favorable height potential. These power plants, which are also known as hydropower, are categorized into large, small, mini, micro, and pico scales [2]. Recently, the use of mini and micro-hydropower in transmission lines and in water distribution networks has been introduced as a potential for the exploitation of electric energy [3]. Electricity generation from the pressure differences inside water transmission lines is one of the new topics in the field of renewable energy.

In water transmission and distribution networks, in order to prevent additional pressure on downstream equipment, pressure breaker valves are often used to adjust water energy. From a technical point of view, due to differences in the height of the source and destination of water transmission, if micro-hydropower is installed instead of the pressure breaker valve on the side of the transmission lines, it will be possible to produce clean energy. In this case, due to the change of excess water pressure to energy, not only will the lifespan of the water network equipment increase and the repair and maintenance costs decrease, but also the water and wastewater industry will enjoy the economic and environmental benefits of renewable energy production; that is, an improvement in productivity in different dimensions.

In order to develop the use of these types of generators in water transmission networks, extensive research has been done for technical and economic evaluation [4,5]; for example, in [6] the economic and environmental analyses of the development of this type of power plant in Iran has been reported. In [7], the potentials in the water and sewage industry for the production of clean energy using micro-hydropower have been evaluated in a case study of Tehran. The main challenge in the conducted studies was that the results of these studies could not be generalized to other places. In other words, due to the fact that the hydraulic parameters of the water transmission lines and their operating conditions are completely different, each line needs feasibility studies. For example, Mirzagli et al. [8] presented a technical and economic evaluation report on the construction of a 400-kW micro-hydropower based on a reverse pump, in the water transmission lines of the city of Mashhad. Noorollahi et al. [9] investigated the feasibility and potential of electricity generation using small hydropower plants based on the average rainfall, average temperature, and the area of each basin in Kurdistan province. The obtained results showed the possibility of building 3411 micro-hydropower plants with the capacity of producing 432 megawatts of electricity. Hadi Dehghan in [10] investigated the existing potentials for energy recovery and electricity production in Khorasan Razavi province by measuring the parameters related to differences in the height and flow of incoming water. The obtained results indicated the possibility of building 3 micro-hydropower plants in the water transmission lines of Khorasan Razavi province with the capacity of producing 8988628 kW-hr of electricity. Mohammadi et al. [11] evaluated the power generation capacity of water supply lines in Ilam; they reported the benefits of using reverse pumps. Pourrajbian et al. [12] analyzed the main water transmission lines of Kermanshah city in order to measure the potential of energy supply for electricity generation by micro-hydropower. The results of their studies showed that it was possible to build a micro-hydropower plant with a capacity of at least 2.4 megawatts in this province. Mohammadi et al. [13] by considering five indicators--production energy, construction cost, distance from the place of consumption, distance from the main road, and the ease of operation using multi-criteria methods--prioritized the construction of micro hydropower for transmission networks. They did it on water networks in Ilam province. In this paper, regarding the development of micro-hydropower, the water transmission line of Shahrekord is examined, and the potential points for the construction of micro-hydropower are determined. Similar studies have been reported in other countries [14-16] to develop the use of micro-hydropower.

A research gap that has been neglected in studies and feasibility studies is the changes in climatic conditions that affect the hydraulic parameters of transmission lines. In some studies, these parameters (flow rate and net height) have been considered constant and proportional to the capacity of the transmission line [6, 7]. In some other studies, the average value of these parameters were taken into account to evaluate the line [9, 10], but, in none of the studies, changes in climatic conditions affecting Hydraulic parameters, especially flow rate, were not considered in the feasibility process. Meanwhile, the climatic condition is an effective factor in deciding the location, the capacity, and the turbine type of micro-hydropower. In other words, the study of these changes (such as the reduction of line flow), which may occur suddenly or gradually, is necessary both technically and economically since they may cause the power plant to stop for a short period of time.

In this paper, to evaluate the construction of a micro-hydropower plant comprehensively, these steps were taken. First the problem is expressed both from the technical and economic point of view. Then, this problem is presented in the scenarios of 1) fixed hydraulic parameters based on the capacity of the transmission line, 2) the average value of hydraulic parameters, 3) daily hydraulic parameters affected by climatic conditions solved for Kohrang-Shahrkord water transmission line. In short, the typesetting of this paper includes the following:

- A comprehensive expression of the problem of optimal design of micro-hydropower both from the technical and economic aspects based on the comprehensive cost function of income to investment cost based on the benefit-to-cost index.
- Demonstrating the importance of studying climatic changes affecting hydraulic conditions in the design of micro-hydropower (turbine and generator).
- Introducing the potentials of building micro-hydropower in the Kohrang-Shahrkord transmission line.

The rest of this paper consists of these parts: 2) a statement of the problem including technical and economic perspectives; 3) a case study including the technical and economic evaluation, and finally 4) a conclusion.

2. Statement of the Problem

Figure (1) shows the general schematic of micro-hydropower, main and general components of which are: turbine and generator, civil structures, and energy control and distribution systems. Among the various elements of a power plant, turbines and generators are the most significant elements. The optimal design of these vital elements with an aim of maximizing the ratio of income to initial capital, as a cost function, equation (1), is the main problem. In other words, in the design of micro-hydropower, the main problem is to determine the type and size of the turbine and the generator to make them technically suitable for the hydraulic conditions of the line since it leads to higher efficiency, and from an investment point of view, it has economic justification. The outcome will be a guaranteed return of investment. In the following, the design of micro-hydropower is illustrated from a technical and economic point of view.

$$Max\left\{\frac{\sum Income}{\sum Investment}\right\} \tag{1}$$

$$\textit{subject to size and type of turbine}$$

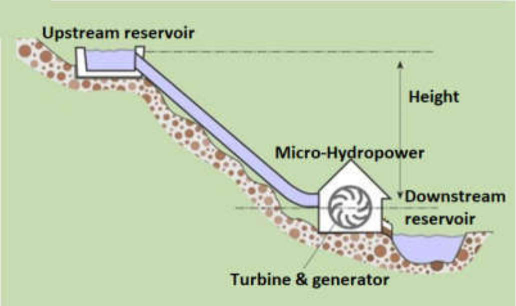

Fig. 1: Schematic of micro-hydropower

2.1. Technical Point of View

Turbines: The types of turbines used in hydropower plants can be divided into two categories in terms of performance: the impact turbine (such as Pelton and Turgo turbines), and the reaction turbine (such as Kaplan turbine) [17]. When the flow rate is low, and the height is high (high pressure), an impact turbine is used; when the flow rate is high and the height is low, a reaction turbine is preferred. Different turbines are also classified into three categories in terms of height [17]:

1- Turbines with short height (up to 40 meters): Kaplan turbine.

2- Turbines with medium height (40 to 100 meters): Francis, Pelton, Turgo, Crossflow turbines, and reverse pump.

3- Turbines with high height (more than 100 meters): Pelton and Turgo turbines.

This classification is based on the maximum efficiency and the main structure of the turbines, but different designs may be used in practice. For example, Kaplan turbines have the highest efficiency at a high flow rate and a height of 1.5 to 15 meters, but it is also possible to design this type of turbine up to a height of 50 meters. Figure (2) shows the performance ranges of turbine types in terms of height and flow rate as well as output power. By determining the type of turbine, the amount of energy extracted by the turbine with the efficiency η can be calculated from equation (2).

$$P = \frac{\gamma Q H \eta}{1000} \tag{2}$$

where P is the output power of the turbine in kilowatts; Q is the turbine flow rate in m^2/sec; H is the net height in meters, and γ is the specific weight of water in N/m^2 (~9810 N/m^2). Equation (3) is used to calculate the amount of output energy.

$$E = P \times t \tag{3}$$

where E is the energy produced in kW-hr, and t is the time in hours. By having the value of E and the purchase price of energy, the income of a power plant is possible to be calculated for a certain period of time.

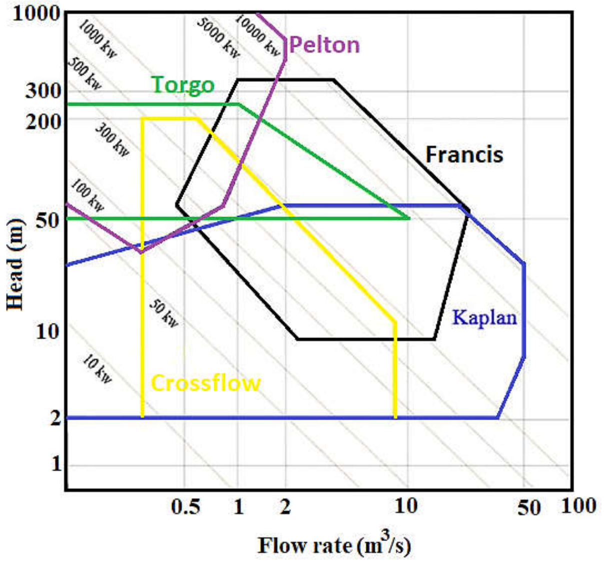

Fig. 2: Performance ranges of turbine types according to height and flow rate [18]

Generators: In the micro-hydropower, two types of induction generators (less than 10 kW) and synchronous generators (for higher powers) are used [19].

The use of synchronous generators is more efficient [20]. However, in this type of generator, reducing the cogging torque, created as a result of the mutual effect of the magnetic field of the rotor and the stator itself, is a challenge.

Because of their well-known characteristics, induction generators are prefered for small hydropower plants. High power density, reduced need for maintenance, simple design, self-care, lack of need for an excitation system, low cost, and the capability to work both connected and separated from the network are the advantages of these generators. However, the need for a capacitor bank to provide the terminal voltage s well as more difficult power control, compared to the synchronous generator, are the disadvantages of this type of generator [8]. Figure (3) shows the micro-hydropower schematic based on the induction generator, which includes a capacitor bank.

Induction generators are usually connected to the grid through the inverters; the inverters work in AC/DC/AC mode and by adjusting the frequency (rotor speed), they adjust the operation of the generator at a certain working point.

On the other hand, the control of synchronous generators is easier and more reliable than the asynchronous type. The control of these generators is gained using an automatic voltage regulator (AVR). The AVR adjusts the output power factor by varying the excitation current at a specified value. However, these generators are more expensive and more difficult to maintain than induction generators [16]. Figure (4) shows how these generators are connected to the network.

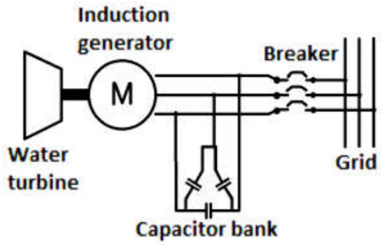

Fig. 3: Schematic of hydroelectric power plant with an induction generator and a capacitor bank

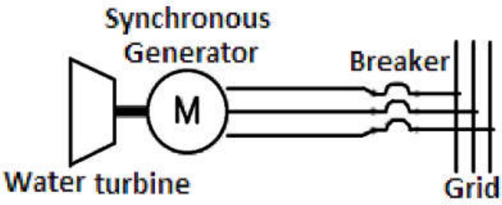

Fig. 4: Schematic of a hydroelectric power plant with a synchronous generator

2.2. The Economic Point of View

The economic analysis of small hydroelectric power plants is completely different from traditional hydroelectric power plants. Low operating costs and compatibility with nature are the best two features of small hydroelectric power plants compared to big power plants. On the other hand, the ratio of the cost of electromechanical equipment to the total cost of the project in small power plants is nearly 52% (35 to 70 percent). This ratio is about 20% in big power plants [21]. Therefore, it is necessary to consider an economic analysis before building a power plant in order to ensure its profitability. The economic analysis of small hydropower plants includes three parts:

1) Cost: cost includes investment and exploitation. Investment cost includes the cost of electromechanical equipment, constructing distribution lines, and project engineering. Exploitation cost includes things such as the cost of maintenance, office building, distribution line Exploitation, and so on [21]. The cost of building a power plant or the required initial capital can be calculated based on equation (4) [22],

$$C_0 = L.K\left(P.H^{-0.3}\right)^{0.82} \tag{4}$$

where C_0 is the cost of building a power plant in terms of dollars;, L is a fixed coefficient equal to 0.7, and K is an experimental coefficient of the implementation of small power plants. The value of coefficient K in Iran is between 6500 and 7500, depending on the turbine technology and the type of generator.

2) Profits: There are different methods to determine the profitability of an investment. The benefit/cost ratio (B/C) is the most well-known of them. Benefit/cost analyses can be used as a determining factor for whether an investment is feasible or not. In benefit/cost analyses, the benefit/cost ratios of a project are calculated for a certain period by taking into account inflation and bank interest rates.

Another common factor for evaluating investments is calculating the Internal Rate of Return (IRR). This factor is also known as Discounted Cash Flow (DCF) factor. IRR is usually expressed as a percentage, and if it is higher than the rate of return in other investments, it means that this investment may be worth choosing and participating in.

3) Return on investment period: By analyzing profits, cost, and the IRR factor, the period of return on investment can be calculated. In other words, the period of time in which all the expenses spent on the construction and exploitation of the power plant are returned in the form of profit is called the investment return period. If this period is less than the investment period, the investment is possible and profitable [21].

In short, the step-by-step flowchart of optimal design of micro-hydro power after determining the location is as follows:

1. Determining the hydraulic parameters on a daily basis
2. Determining the type and capacity of the turbine
3. Calculating income based on the annual extractable energy, equation (3)
4. Calculating the total cost of micro-hydropower construction, equation (4)
5. Calculating cost benefit and internal rate of return
6. Making decisions and prioritizing based on the previous step
7. The end

3. The Case Study

In this section, the technical and economic evaluation of the micro-hydropower plant construction for the Kohrang-Shahrkord transmission line is described.

Figure (5) shows the schematic of this line, with origination in the Kohrang spring in the city of Chalgerd, and the destination of Shahrekord. Along the route of this line, there are outlet branches and balance reservoirs, which are the potentials for installing micro-hydropower and pico-hydropower. Therefore the hydraulic analysis of the line is performed in the first step before the technical evaluation.

Fig. 5: Kohrang-Shahrkord transmission line

There are different methods to analyze a fluid transmission line; one solution is to use analysis methods based on Bernoulli's equations, which are accompanied by the simplification of long lines. In this paper, these calculations are based on the relations presented in the paper [12]. By performing these calculations, the amount of height loss caused by the loss of the transmission line is determined. In other words, the hydraulic height at the candidate points is determined. The amount of hydraulic energy can be determined by calculating the net height and water flow.

3.1. Technical Evaluation

Based on the analysis, field measurements, and checking the daily water flow curve of the Kohrang-Shahrkord transmission line, the following three scenarios can be considered for the construction of a micro-hydropower plant.

The first scenario: In this scenario, it is assumed that the working point of the line is such that we have the highest possible head in the candidate points. In other words, by leveling in the balance reservoirs, the output flow is set so that the maximum possible pressure at the inlet balancing reservoirs is created. It is possible to install Pelton or Turgo turbines as well. Table 1. presents the values of the parameters related to the analysis and design of this scenario.

Table 1: Parameters of the first scenario assuming constant flow rate and head

Location	Average flow rate (Lit/s)	Net height (m)	Turbine capacity (kW)	Turbine type
Hyderabad	400	40	144	Pelton (η = 90%)
Gardane Kholk	370	140	466	Pelton (η = 90%)
20000 Reservoir	146	120	157	Pelton (η = 90%)

Second scenario: In the field investigations, it was found that only the pressure breaker valve of Shahrekord reservoir 20000 was in the circuit, and the pressure breaker valves in Hyderabad and Gardane Kholak reservoirs were bypassed. Moreover, the pressure at the entrance of these two reservoirs was about 3-4 Bar. This scenario, due to technical reasons, is proposed for a situation where it is not possible to level water in the balance reservoirs (filling of water transfer pipes). Table 2. shows the calculations related to these conditions. In this case, it is suggested that the type of turbine for two locations of Hyderabad and Gardane Kholak be a Turgo turbine, and for the 20,000 Shahrekord reservoir be Pelton or Turgo turbine. Turgo turbine is a modified Pelton turbine that is suitable for low pressures. By installing the turbine, the output flow is adjusted so that the pressure in the place of the turbine is at least 3 bar (height 30 meters) and at most 4 bar (height 40 meters).

Table 2: Parameters of the second scenario assuming constant flow rate and actual head

Location	Average flow rate (Lit/S)	Net height (m)	Turbine capacity (kW)	Turbine type
Hyderabad	400	30	108	Turgo (η = 85%)
Gardane Kholak	370	40	133	Turgo (η = 85%)
Reservoir 20000	146	100	131	Pelton (η = 90%)

The third scenario: The two aforementioned scenarios are designed based on certain assumptions and fixed daily flow rate, and they can be implemented in a maximum of 10 to 15 changes of the flow rate. However, the analysis of the data related to the flow rate of the Kohrang-Shahrkord transmission line shown in Figure (6) shows that due to recent droughts changes in the flow rate are very high in some months of the year.

As shown in figures (6) to (8), the flow rate has decreased at the Hydarabad reservoir from 400 to 200 lit/sec, at the Gardane Kholak reservoir from 370 to 130 lit/sec, and at the 20000 Shahrekord reservoir from 147 to 125 lit/sec (probably by cutting off the sub-branches). These flow rate changes are from April 2020 to June 2022, and if the conditions were the same in the previous years, the design and construction of the power plant based on two aforementioned scenarios would not be economically viable. In other words, this flow drop causes the power plant to be taken out of the circuit and shut down during the flow drop period.

This scenario, Table 3. is for the case where there are severe high flow rate changes. In this case, it is suggested to use the Crossflow turbine together with the induction generator for two reasons. The first reason is that such turbines and generators are simpler to design and implement in comparison with Pelton and Turgo turbines and synchronous generators. Hence, the implementation of this plan is cheaper; the result is lower initial investment. In other words, a decrease in income, caused by a decrease in turbine input flow rate, makes the ratio of initial investment to income increase. It means that the economic attractiveness of the project decreases. The second reason is that it is possible to design a Crossflow turbine for variable flow rates. In other words, the runner of this turbine can be designed in several sections. According to the input flow rate, this type of design, in order to have the maximum efficiency of the turbine, makes it possible to have only one, two, or three parts of the turbine in the circuit, figure (8) [23].

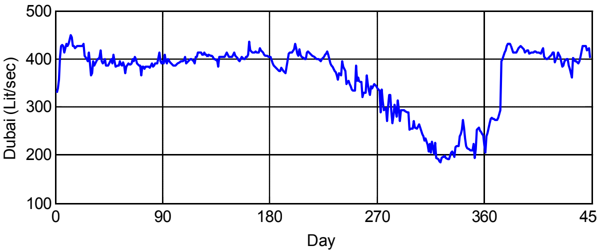

Fig. 6: Flow rate of Hyderabad reservoir from April 2020 to June 2022

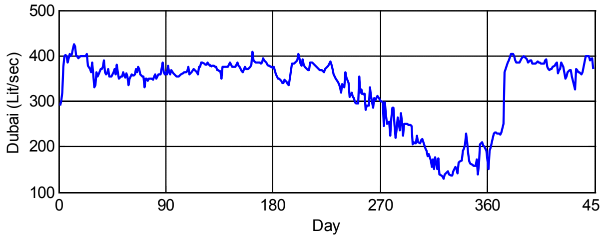

Fig. 7: Flow rate of Gardane Kholak reservoir from April 2020 to June 2022

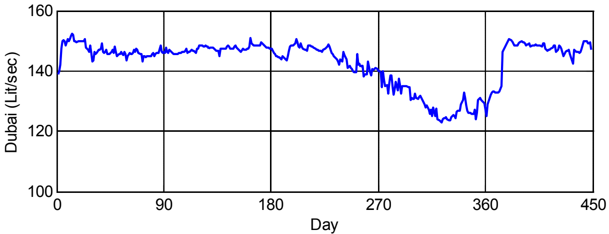

Fig. 8: Flow rate of 20000 reservoir from April 2020 to June 2022

As clear in Figure (9), the efficiency of the Francis turbine decreases significantly with a decrease in water flow rate. Also, with a decrease in the water inlet flow rate to less than 23%, the turbine practically has an efficiency equal to zero. However, in the Crossflow turbine, every time the flow rate decreases to 33% of the nominal value, a part of the turbine becomes inactive, and this makes the turbine efficiency be always close to its maximum value. It should be noted that it is possible to design a Pelton turbine with two runners and multiple nozzles for variable flow rates, but the cost of the turbine will increase significantly, which leads to an increase in the initial investment.

Table 3: Parameters of the third scenario for the actual flow rate values

Location	Average flow rate (Lit/S)	Net height (m)	Turbine capacity (kW)	Turbine type
Hyderabad	184-450	30	108	Crossflow (η = 75%)
Gardane Kholak	130-400	40	128	Crossflow (η = 75%)
20000 Reservoir	146	100	131	Pelton (η = 90%)

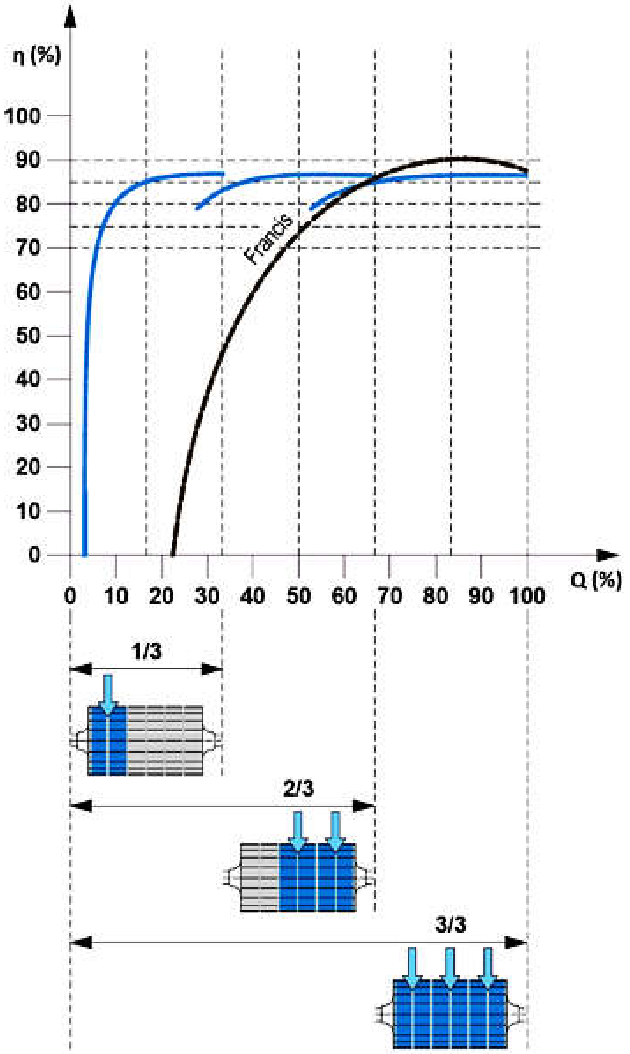

Fig. 9: Performance of Francis and Crossflow turbines in variable flow rates [23]

3.2. Economic Evaluation

For economic evaluation of a power plant, it is necessary to know different costs and annual income. Thus, in this section, the cost of building a power plant or the initial capital required is calculated based on equation (4). Other assumptions required to calculate the cost and income are presented in table 4.

Table 5. shows the economic evaluation results for three aforementioned scenarios, the flow rate for different points is based on figures (6) to (8).

From the evaluation of the economic results presented in Table 5., it can be inferred that the second scenario has the lowest B/C ratio and the lowest IRR value. These values have been calculated for a period of 10 years, and this means that after 10 years, in addition to the return on investment (including the annual interest rate), this investment will generate 21% profit; thus, it can be said, according to the interest rate Bank of 18%, this investment is profitable.

Table 4: Assumptions to calculate the cost and income

Annual exploitation costs	Electricity purchase rate	Dollars to Rials exchange rate	Bank interest rate
10% of the initial investment	5910 Rials	300,000 Rials	18%

Table 5: Economic evaluation of three scenarios

scenario	Annual total energy (kW. hr)	Initial investment (million Rials)	Annual total profit (million Rials)	B/C (for 10 years)	IRR (for 10 years)
1	4417000	140000	2610	1.86	28%
2	2141000	94200	1265	1.34	21%
3	2742000	84300	1620	1.92	30%

Figure (10) shows the sensitivity analysis of the B/C index for a 30% reduction in transmission line flow rate for different number of days. As can be seen, if the drop in the flow rate of the transmission line is not taken into account, the second scenario will become the first priority; however, if the drop in the flow of the line is more than two months a year, the first priority will be related to the third scenario.

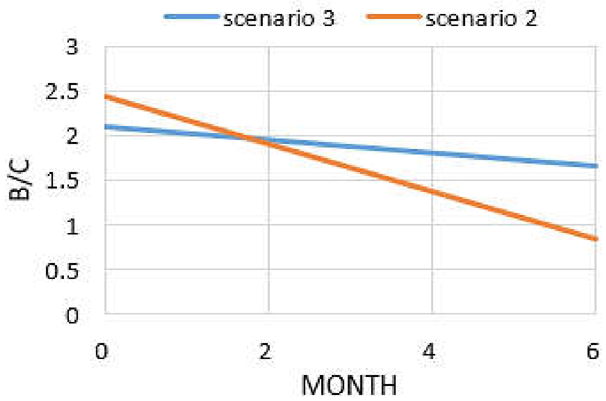

Fig. 10: The sensitivity of a 30% decrease in line flow rate in different days

Comparing the calculation results of the second and third scenarios, which have similar hydraulic conditions, clearifies that the second scenario is the weakest design and the third scenario is the best design for the construction of a micro-hydropower plant in the Kohrang-Shahrokord transmission line. In other words, the optimal design that maximizes the income-cost ratio, takes into account the actual flow rate due to drought is the third scenario. From a technical point of view, in the second scenario, turbines were completely inactive for four months when the flow has decreased drastically. This event led to a decrease in energy production. Besides, the construction of mico-hydropower with a Crossflow turbine, from an economic point of view, costs less than Pelton and Torgo turbines. This feature results in a reduction in the initial investment.

It should be noted that the hydraulic conditions of the first scenario are different from the other two scenarios. For this scenario, the production energy and the annual profits of the power plant as well as the amount of initial investment are the highest values. However, the values of B/C and IRR of this scenario, due to the inactivity of turbines for four months of the year, are lower than the second scenario.

By comparing the results of the economic evaluation of the first and second scenarios with the third one, it is concluded that the study of daily flow rate changes is necessary for the design of a micro-hydropower plant. In other words, in order to maximize the cost function of the ratio of income to initial investment, it is necessary to select turbines that are proportional to the daily changes of the hydraulic conditions of the line; one of these conditions that may be influenced by climatic changes is the flow rate of the line.

By calculating the values of B/C and IRR for different periods, it was determined that the return period for the first scenario is 6 years, for the second scenario 8 years, and for the third scenario 6 years.

4. Conclusion

Micro hydropower, as one of the renewable energy source, has recently received more attention. Several studies have been conducted to introduce and examine the feasibility of building these generators from different aspects. However, in none of the studies the effects of climate change on hydraulic parameters have been considered. Therefore, the main focus of this paper is to show the importance of the inclusion of climate effects in the design of micro-hydropower. For this purpose, the design of a micro-hydropower plant for a case study, the Kohrang-Shahrkord transmission line, was carried out through different scenarios. In the best scenario, technically and economically, it led to the production of 2,742,000 kW-hr of energy, with the required initial capital of 8,430 million Tomans, and a benefit-cost index, B/C, of 1.97. The evaluation of the sensitivity analysis of line flow rate reduction for scenarios also showed that the study of daily flow rate was necessary in the design of micro hydropower. Also, the results of the technical and economic evaluation showed that the Crossflow turbine is the best choice for places with large flow rate changes.

Acknowledgment

The author gratefully acknowledges the water and wastewater company of Chaharmahal & Bakhtiari province for their cooperation in conducting this research.

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