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OPTIMIZING ENERGY GENERATION: CAPACITY ANALYSIS FOR HYDROPOWER

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Article Info

Keywords: hydropower, renewable energy, run-of-river, small hydropower plant, diversion weir, capacity, energy yield, catchment area, flow duration curve, gross head, net head.

Abstract

Hydropower plants play a vital role in the renewable energy sector, particularly in Asian countries like China, India, Indonesia, Malaysia, and Nepal. These plants are categorized based on factors such as plant capacity, water utilization method, and diversion structure height. Capacities vary from pico hydro-power plants (< 5kW) to large hydropower plants (>100MW). Additionally, hydropower plants can be classified as run-of-river, storage, or pumped storage plants based on water resource utilization.

Among the various hydropower schemes, the small hydropower plant (SHP) with a run-of-river (ROR) concept has gained significant attention. ROR plants do not require water storage and generate power in accordance with streamflow availability, which primarily relies on catchment area, characteristics, and rainfall distribution. Flow duration curves represent the available flow over time. SHPs with ROR concepts usually employ low diversion weirs, resulting in lower environmental impacts compared to large-scale storage hydropower schemes. Consequently, these systems are considered cost-effective and environmentally friendly options for rural electrification in both less developed and developed countries.

This paper focuses on a high head run-of-river scheme with a gross head/net head of 262.5m/246.75m and a catchment area of 47.2 km2. The study aims to determine the optimum installed capacity, energy yield, and plant factor of the scheme, with the simulated installed capacity ranging from 4MW to 7.5MW. The design flow is established based on the intended installed capacity, providing essential insights for further discussion.

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1. Introduction

The hydropower plant is an important component in the renewable energy sectors in Asian Countries such as China, India, Indonesia, Malaysia, Nepal, etc. The hydropower plants can be categorized based on various criteria, such as plant capacity, the way of water is utilized, and the height of the diversion structure. Based on the capacity, the hydropower plants can be categorized as pico hydro-power plants with a capacity < 5kW, micro-hydropower plants (5kW to 100 kW); mini-hydropower plants (100 kW to 1 MW); small hydropower plants (1MW and 10 MW), in some countries the upper limit for the small plant varies in some cases may be as high as 30 MW; medium hydropower plants (10MW to 100MW) and large hydropower plants with capacity >100MW [1], [2], [3]. Meanwhile, in the way how water resources are being utilized, hydropower can be categorized as run-of-river plants, storage plants, and pumped storage plants [2].

One of the most widely developed hydropower schemes is the small hydropower plant (SHP) with a run-of-river (ROR) concept. Run-ofriver implies that there will be no necessity for water storage and that power generated will fluctuate with the streamflow availability [4]. The stream flow mostly depends on the catchment area, characteristics of the catchment area, and rainfall distribution in the catchment [5]. The available flow over the year is represented by a flow duration curve. Generally, the small hydropower schemes with a run-ofriver concept require a low diversion weir and the environmental impact is less significant than large-scale storage hydropower schemes [2], [6], [7]. The systems with low diversion weir structure would be one of the most cost-effective and environmentally friendly for rural electrification in less developed countries and developed countries for further hydro developments [8].

In respect to the run-of-river, the schemes can be categorized as high head, low head and low diversion structure schemes [9]. In this paper, a case of high head scheme with gross head/net head of 262.5m/246.75m and catchment area of 47.2 km^2 has been studied to obtain the optimum installed capacity, energy yield and plant factor of the scheme. The simulated installed capacity was in range of 4MW to 7.5MW. The design flow has been determined based on the intended installed capacity and will be discussed further in the next section.

2. Literature Review

2.1 Small Run-of-River Hydropower Plant

Small run-of-river hydropower (ROR) concept especially on the high head schemes very adaptable to the site topography [4] and relatively less ecological impact where certain amount of the flow shall continuously be spilled over the spillway to ensure the less disturbance on the ecological system. [10] stated that by adopting current technology, the ecological impact and other environmental constraint are possible to be mitigated. In addition, the adoption of ROR concept will allow the optimization of the turbine efficiency by configuring the proper size of the turbines [11].

In adopting small run-of-river hydropower concept, certain components should be incorporated into the design concept of the schemes. These components should consider the optimized design of the installed capacity and its optimized design parameters. The components should include civil works, hydromechanical works, electromechanical works and interconnection facilities. The conceptual design for the scheme configuration is based on good engineering practices, relevant guidelines and regulations and the appropriate application of the small hydropower plant technology. The typical arrangement of the scheme is shown in Figure 1. In adopting this concept, the following considerations should be considered.

a. Simply arrangement of the intake structure
b. Minimize environmental impact on the surrounding area.
c. Optimum waterway configuration

d. Utilized/blending to the local terrain and minimize disturbance to the surrounding.
e. Utilization of existing logging tracks
f. Optimize the cost of the SHP using appropriate technology and common facilities

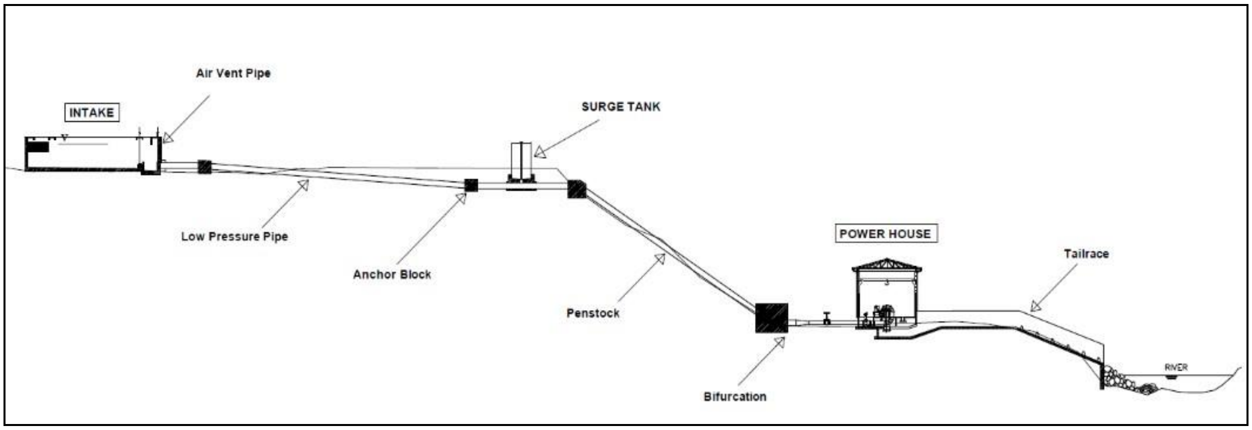

Fig 1. Typical arrangement of small run-of-river hydropower plant

Reference [12] categorized the intake structures into three categories namely (1) the intake structure diverts the flow directly to the waterway or penstock; (2) the intake structure which utilizes the additional structure to take the flow and divert to the waterway; and (3) an intake structures attached to a reservoir. In this study, the second concept has been considered in the study of the plant system.

2.2 Flow Derivation

Hydrological data is vital in planning, execution and operation of the hydropower projects. The estimation of availability of flow and flood likely to impinge on the structure are essential for planning, design and operation of small hydro especially on the Run-off River (ROR) concept. The characteristic of catchment area will play major rule in the water resources [13], [14], [15] especially for the hydropower. A water catchment is an area of land where water is collected by the natural landscape and flows to a single stream, river, lake, even ocean or even into the groundwater system. In the hydropower system, as the available power and energy output is proportional to the flow [3]. The accuracy of the flow estimation is very important to ensure the reliability of the energy output for the whole live of the plant.

2.3 Electromechanical Equipment

The function of the electromechanical equipment is to transform the water potential energy to mechanical rotational energy. The pressure and velocity of the water will react with the runner of the turbine to produce a torque on the shaft. There are two basic type of hydropower turbines namely impulse and reaction turbines [16]. Impulse turbines are suitable for high heads and low flow rates [17]. Meanwhile, the reaction turbine is used for medium and low heads and high flow rate [8]. The geometry and dimensions of the turbine will generally besides other factors depend on water head, design flow, rotational speed and cavitation requirement.

3. Methods

3.1 Flow Duration Curve

The flow duration curve is one of the most fundamental pieces of information that feeds into the design of a hydropower project. The flow duration curve is a plot that shows the percentage of time that flow in a stream is likely to equal or exceed some specified value of interest. The FDC is employed to deduce the energy of the proposed scheme with known proposed design flow and gross water head, the energy is able to be calculated. The established FDC used in this study is shown in Figure 2. In the energy calculation, the ecological flow of 0.063 m^3/s has been considered and shall be continuously spilled over the spillway section of the weir structure.

Probability (%)	Flow (m^3/s)
0.1	11.51
5	4.40
10	3.25
15	2.67
20	2.28
25	2.03
30	1.84
35	1.68
40	1.55
45	1.43
50	1.33
55	1.24
60	1.17
65	1.10
70	1.04
75	0.96
80	0.90
85	0.82
90	0.75
95	0.65
100	0.51

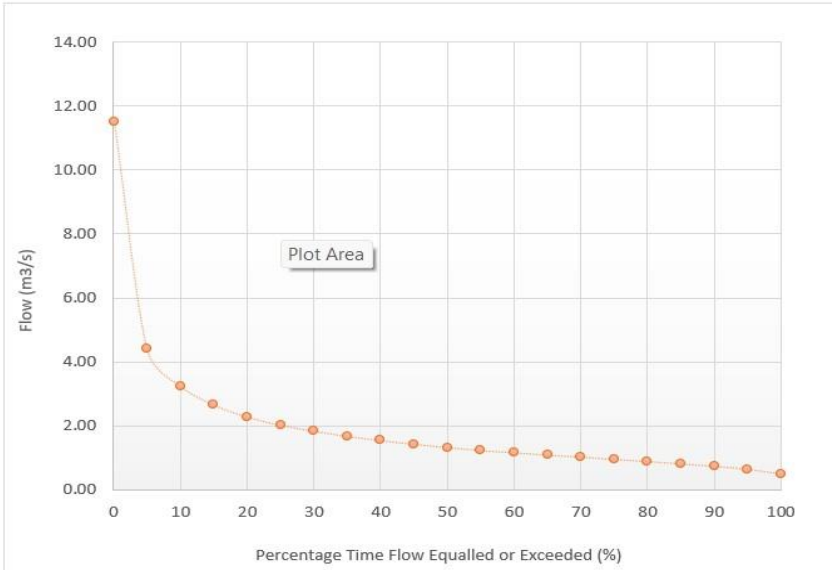

Fig 2. Flow duration curve of the scheme

3.2 Turbine Selection

The selection of turbine can be based on the specific speed (Ns) value of turbines [18]. The specific speed value is the speed of a geometrically similar turbine which develop unit power (one kilowatt) under unit head (one meter). The specific speed of a turbine can be calculated either based on imperial or metric unit. If the calculation is in metric system, the quoted specific speeds are correspondingly larger. The Specific Speed, Ns of the turbine is determined by the following formula.

$$N_s = \frac{n\sqrt{P}}{Hn^{5/4}} \tag{1}$$

Where n is the rated speed in rpm (rpm); P is the rated power output (kw); and Hn is the net effective pressure head (m).

The turbine selection range based on specific speed are shown in Table 1. Impulse turbines have the lowest N_s values while Kaplan turbines have the highest value as shown in Table 1. Fig. 4 shows typical layout for the impulse turbine (Pelton type) configurations.

Table 1. Specific Speed and Turbine Selection [19]

Specific Speed, Ns (Metric)	Type and Description of Turbine
4 to 35	Pelton wheel with one single nozzle
17 to 50	Pelton wheel with two nozzles
24 to 70	Pelton wheel with two nozzles
80 to 120	Francis turbine, slow speed runner
120 to 220	Francis turbine, normal speed runner
220 to 350	Francis turbine, high speed runner

350 to 430	Francis turbine, express
300 to 1000	Propeller and Kaplan

3.3 Install Capacity and Energy Output

The mechanical power at the turbine shaft of the plant is derived from the following formula:

$$P = \eta \, g \, \rho \, Q \, Hn \qquad (2)$$

Where P is the mechanical power produced at the turbine shaft (kW); η is the efficiency of the electromechanical equipment (%); g is the acceleration due to gravity (m/s^2); ρ is the density of water (kg/m^3); Q is the volume flow rate passing through the turbine (m^3/s) and Hn is the effective net head of water (m).

Meanwhile, the energy output is a function of available daily flow with subtraction of ecological flow; available of the net head; electromechanical equipment efficiency; and the loss in the interconnection system. The energy output varies depend on the available flow in the river [20].

4. Result and Discussion

Twelve scenarios varying installed capacity of the schemes and its respective design flow has been simulated with the consideration where the intake structure located at the same location and having the same gross head of 262.5 m. The head loss was assumed to be fix at 6% which produced net head about 246.75m. Furthermore, the energy output and plant factor were calculated based on the variation of the installed capacity in range of 4MW to 7.5MW. The detail parameters for each scenario are presented in the Table 2. The installed capacity of 4MW to 7.5MW requires design flow about 1.872 m^3/s to 3.510 m^3/s, respectively.

Table 2. Installed capacity and its parameters for each scenario

Description	Installed Capacity											
	4.0MW	4.1MW	4.2MW	4.3MW	4.4MW	4.5MW	5MW	5.5MW	6MW	6.5MW	7MW	7.5MW
Design flow, Q_d	1.872	1.918	1.965	2.015	2.060	2.106	2.340	2.574	2.808	3.042	3.276	3.510
Prob. of Exceed.	29.2%	27.9%	26.7%	25.3%	24.4%	23.5%	19.2%	16.2%	13.9%	11.8%	9.9%	8.9%
Gross head, Hg	262.50	262.50	262.50	262.50	262.50	262.50	262.50	262.50	262.50	262.50	262.50	262.50
Head Loss	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%
Net head, Hn	246.75	246.75	246.75	246.75	246.75	246.75	246.75	246.75	246.75	246.75	246.75	246.75

The relationship between the intended installed capacity and the probability of the flow exceeds or equal to the design flow is presented in Figure 3. Based on the figure, the increased of installed capacity will decrease the probability of the flow exceeds or equal to the design flow. This would affect the running of the plant at the full load and could lead to the decreasing of the electromechanical equipment efficiency. In addition, it shows that the best fit of the relationship is in form of polynomial function ordo 4. The coefficient of the correlation (R2) is close to 1 which indicates very strong correlation between these two parameters.

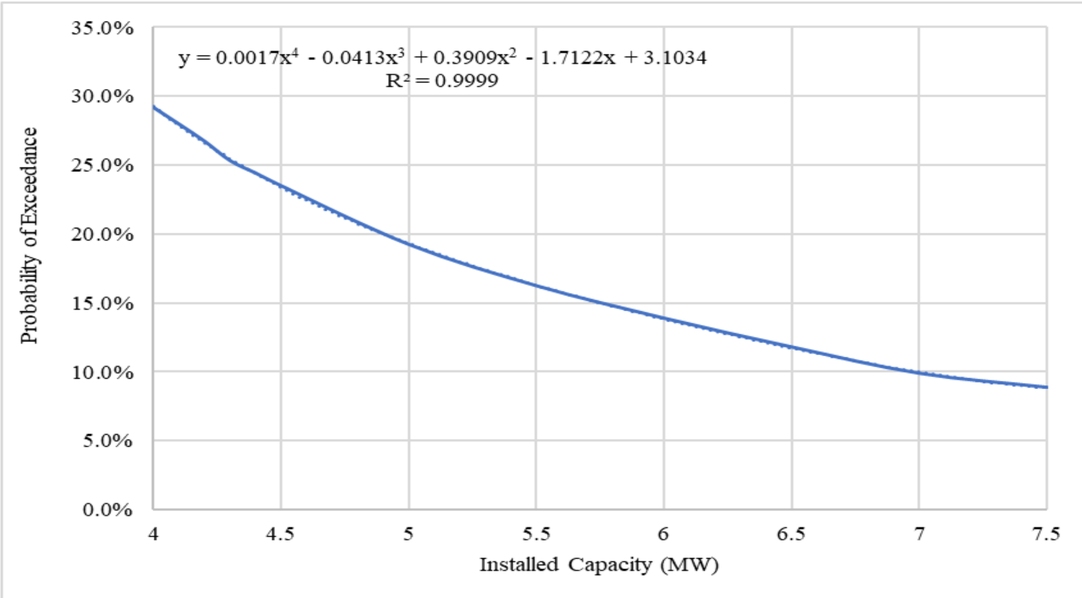

Fig 3. Relationship between the capacity and the probability of flow exceeds or equals to the design flow

The energy yield and plant factor for each scenario are presented in the Figure 4. Based on the Figure 4, it shows that as the energy yield increased in respect to each installed capacity, the plant factor is significantly decreased. The energy yield for the 4MW plant is about 23 589 MWhr and 7.5MW is about 28 636 MWhr. Meanwhile, the plant factor for the 4MW plant was about 67.32% and 7.5MW was about 43.59%. It was found that by increased of installed capacity about 87.5%, the energy yield increased only about 17.6%. In addition, the plant factor decreased about 35.2%. Based on the figure, the optimum installed capacity was at 5MW as indicated by the energy yield and plant factor crossed at the installed capacity of 5MW. Furthermore, based on the power output in range of 4MW to 7MW and available net head of 246.75m, it was found that the pelton turbine would be the most suitable for the scheme. In addition, the synchronous generator would be used to generate the power. In this study, the efficiency of the combination of pelton turbine and generator equipment about 0.88 has been used in the energy calculation.

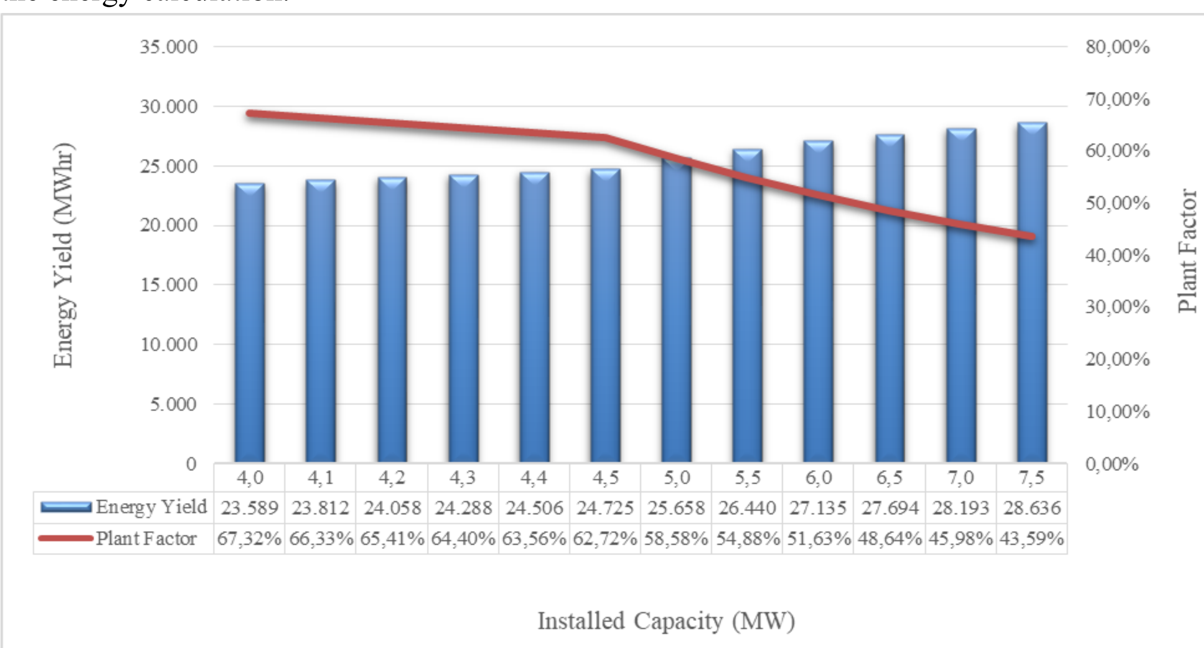

Fig 4. Relationship between the installed capacity, energy yield and plant factor

5. Conclusion

The small run-of-river hydropower scheme would be a potential choice in hydro-power energy development in less developed and developed countries. The scheme configuration should be designed based on good engineering practices considering relevant guidelines and regulations to minimize the environmental impact, risk, energy output, and cost-effectiveness. The optimum design of the hydraulic parameters and its facilities of the plant would play a major role in successfully developing the small run-of-river hydropower plant. Hence, in this study twelve scenarios of the plant capacity in range of 4MW to 7.5MW have been studied for the optimization of the plant capacity. Considering the fixed available head and at the same site location, the designed flow for the plant would be in range of 1.872 m^3/s to 3.510 m^3/s with the probability of the flow exceeds or equal is about 29.2% to 8.90%, respectively. In respect to the install capacity, energy output and plant factor, it concluded that the optimum plant capacity would be at 5MW plant.

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