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Design Optimization of a Run-Of-River Small Hydropower Plant: A Case Study of Mabula Kapi Site

Dean Lameck Musukwa[1], Dr. Edwin Luwaya[2]

[1, 2]Mechanical Engineering Department, School of Engineering, the University of Zambia, Lusaka, Zambia

ABSTRACT: Prior to construction, small or large hydropower plants undergo feasibility studies, which involve technical, economic, financial, social, and environmental aspects. Technical studies, particularly, include various engineering disciplines. This study sought to conduct a component of technical feasibility studies, focused on design optimization of the turbine-plant capacity size for a run-of-river case study called Mabula Kapi, on Kaombe River, Serenje, Zambia. The study method used computational modelling, simulation, and optimization techniques, and used secondary data from previous site. A prefeasibility study conducted earlier had underestimated the turbine-plant capacity owing to underestimated discharge data, owing to lack of site gauging station. A less accurate discharge estimation method involving transposition from a gauged similar catchment had been used. A later feasibility-level site hydrological study found improved discharge data. Riding on the improved discharge data, this study found the following optimised plant design parameters based on plant design discharge of 6.20 m^3/s: Installed capacity of 10.20 MW; Annual energy production of 42 GWh; Capacity factor of 47.1%; 3 x Pelton wheel of 272 rpm speed, 2.1 m diameter, 2-nozzles of diameter 0.16 m each, 21 buckets of 0.58m width each; and 3 x 4 MVA generators of 50Hz, 22-poles, and 11kV.

KEYWORDS: Gigawatt-hours, Installed Capacity, Modelling, Megawatt, Pelton Turbine, RETScreen, Run-of-river, Small Hydropower Plant

I. INTRODUCTION

A. *Background*

Zambia has many large and small rivers offering hydropower resource potential in excess of 6,000MW (Ministry of Energy, 2019). In 2023, Zambia was ranked fourth in Africa in hydropower-installed capacity having 3,153MW, trailing Ethiopia at 4,824MW, Angola at 3,836MW and South Africa at 3,600MW, out of 43 countries (International Hydropower Association, 2023). The figures include pumped hydro. Hydroelectricity dominates Zambia's generation mix, accounting for 80% of total electricity generated (Ministry of Energy, 2022). The remaining 20% is attributed to coal power, solar PV and heavy fuel oil plants. Wind power studies are at advanced stages, meant to widen the energy mix.

Efforts continue to increase electricity access to Zambians. Only about 70.6% of households in urban areas and about 8.1% of households in rural areas have access to electricity, translating into a national average of 32.5% (Ministry of Energy, 2022). The Zambian government's goal is to provide universal access to clean, reliable and affordable energy by 2030. Majority of the recent and ongoing projects are focused on large hydropower development, while small hydropower resources have remained largely untapped, despite their commensurate importance.

Development of small hydropower resources would help compliment the efforts of large renewable energy power projects. In 2019, with a view to contributing towards universal access to clean energy for Zambia, and global net-zero global targets, the Kafue Gorge Regional Training Centre decided to embark on the development of a grid connected Mabula Kapi Small Hydropower Project.

The Mabula Kapi study area is located on Kaombe River, Chieftainess Serenje's area, Serenje District, Central Province, Zambia, on latitude 13° 19' 28.02" and Longitude 30° 47' 14.02" in WGS84 coordinate system. The first study of the site was a prefeasibility study conducted in 2018 by the local power utility, ZESCO, which found a feasible run-of-river small hydropower plant potential of 7.4 MW utilizing a gross head of 203.38 m and a design discharge of 4.57 m^3/s. The prefeasibility study scope had included studies on topography, hydrology, geology, as well as layout options, and recommended the best scheme layout option. The study determined the scheme gross head, design discharge, and provided preliminary estimates of plant capacity, annual energy generation, capacity turbine-generator size, and construction costs. The plant capacity design at prefeasibility study stage was preliminary and the requirement was for a feasibility-level to be undertaken later, which is the focus of this study.

B. *Statement of the Problem*

The 2018 prefeasibility study conducted at Mabula Kapi found a potential of a 7.4 MW run-of-river small hydropower plant, with gross head of 203.38 m and design discharge of 4.7 m^3/s. However, the prefeasibility study had underestimated the plant and turbine capacity owing to use of underestimated discharge data. At the time there was no river gauging station, and so a less accurate method based on transposition of discharge data from a similar nearby catchment's gauged river, had been used instead. In 2019 a gauging station was installed at Mabula Kapi, and a feasibility-level site detailed hydrological study based on two-years river flow measurements was conducted, and resulted in more accurate and improved flow duration curve and discharge data. As a result, the design discharge improved from 4.57 m^3/s to 5.02 m^3/s at 30% flow-exceedance factor, and 6.20 m^3/s at 25% exceedance factor, while environmental flow improved from 0.2 m^3/s to 0.58 m^3/s Mabula Kapi (Mukuka, 2022). Utilizing the updated higher discharge data, this study, therefore, sought to improve upon the underestimated preliminary plant design by conducting a feasibility-level design optimization of turbine selection, number of units and configuration, plant capacity and turbine-generator size parameters for the Mabula Kapi site.

C. *Objectives*

This study had three specific objectives as follows:

(a) To analyze the applicable turbines' technical factors and select the most suitable type for the Mabula Kapi site conditions;

(b) To determine the optimal number of units, configuration, and plant output ratings; and

(c) To determine the optimal main dimensions of the turbine runner and generator unit size parameters.

D. *Scope of the Study*

This study's scope was limited to turbine selection, determination of the turbine shaft configuration and number of units, as well as plant power capacity, annual energy, capacity factor and turbine-generator size design optimization.

II. THEORETICAL BACKGROUND

A. *Design Optimization Concept for Hydropower*

Hydropower plant *design* refers to a multi-faceted analysis that is conducted to determine the facilities and the project feasibility with the ultimate goal of achieving the best design solution. Consequently, *design optimization*, implies a process and its result whose goal is to find the best technical idea and solution giving the best alternative or highest possible performance of the plant (Kalina, et al., 2021). This foregoing meaning of design optimization was adopted in this study.

According to (Alternate Hydro Energy Centre, 2012) the factors involved in determining optimum generating capacity to be installed and optimum number and size of units to be selected for a hydro project include the following:

a) Site characteristics and limitations
b) Maximum utilization of energy resource.
c) Optimum energy generation.
d) Minimum size of units for the available flow and net head to keep costs low.
e) Operating criteria including part-load or low-flow operation.
f) Worldwide and local experience.
g) Future needs provision.

B. *Theoretical Concepts, Formulas and Rules Of Thumb for Hydro Turbine-Plant Design Optimization*

1) Turbine Selection Charts and Preliminary Specific Speed:

Turbine selection charts and/or preliminary specific speed equations are used to select the most suitable turbine type for a particular site. Site characteristic data of net head and rated flow can be referenced on the turbine chart and the chart will show in which turbine operating envelope the site's suitable turbine lies (Adejumobi & Shobayo, 2015).

A typical turbine selection chart, showing common turbine operating range and the estimated expected plant power output is shown in Figure 1.

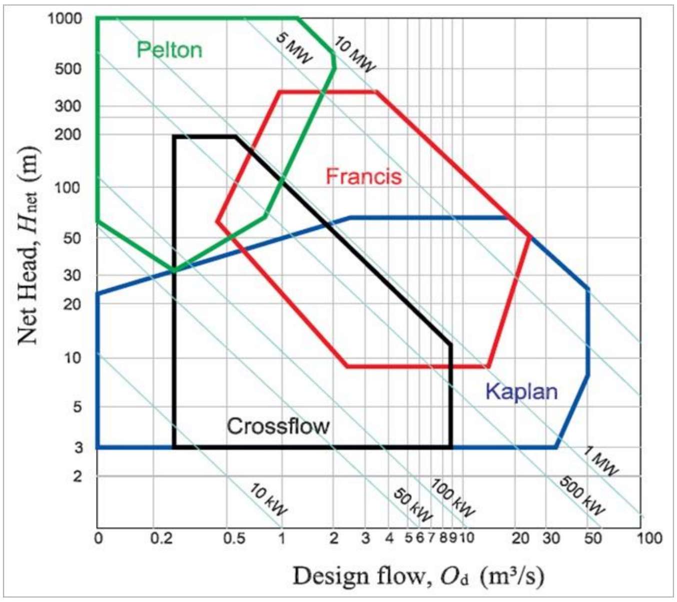

Figure 1: Turbine application chart based on net head and design flow

[**Source:** (Yildiz & Vrugt, 2019)]

Where more than one turbine is possible for a site available head and flow, other factors are considered to select the most suitable turbine, i.e. turbine power output; specific speed; turbine cost; turbine efficiency; minimum technical flow percent of maximum flow; site conditions, etc.

The preliminary specific speed is used in preliminary turbine type selection. Statistical studies on a large number of projects have established a correlation of the preliminary specific speed and net head for various turbines as outlined in Table 1.

Table 1: Specific speed preliminary equations for different turbine types

Turbine Type	**n_{QE} Specific Speed Preliminary Formula**
Pelton (One nozzle)	$n_{QE} = \frac{0.0859}{H_n^{0.243}}$
Francis	$n_{QE} = \frac{1.924}{H_n^{0.512}}$
Kaplan	$n_{QE} = \frac{2.294}{H_n^{0.486}}$
Cross-flow (Banki)	$n_{QE} = \frac{1.107}{H_n^{0.2998}}$
Impeller	$n_{QE} = \frac{2.716}{H_n^{0.5}}$
Pipe	$n_{QE} = \frac{1.528}{H_n^{0.283}}$

[**Source:** (Vasic, et al., 2018)]

When presented with more than one option of applicable turbines, among other factors, selecting a turbine type with higher specific speed implies a smaller runner diameter and therefore a cheaper turbine cost (Vasic, et al., 2018)

2) Considerations for Number of Units: Depending on the extent of river flow variability in run-of-river schemes, a highly variable single turbine plant inflow compromises energy production. Thus, in highly variable flow conditions, multi turbine installations considerably enhance the range of workable flows, operational flexibility and energy production of a run-of-river plant (Yildiz & Vrugt, 2019). A single turbine is unable to extract all the available power of the plant flow when confronted with highly variable streamflow conditions, whereas two or more turbines in parallel increase the range of workable flows. In this way, multi turbines offer flexibility of operation and enhance production output for a run-of-river plant. Other factors affecting the decision on the number of units include the following requirements: (a) In order to facilitate optimal maintenance spare parts management, units with the same capacity shall be selected (United Nations Industrial Development Organisation, 2019); (b) Considering the reliability requirements of the power supply related to needs for maintenance outage, two or more units should be used (Temiz, 2013); (c) When selecting the unit capacity, engineers shall consider the convenience of manufacturing, transportation, and adequacy of utilization (European Small Hydropower Association, 2004).

3) Turbine Unit Shaft Configuration: Pelton turbines may be mounted horizontally or vertically. One or two jet Pelton turbines can have horizontal or vertical axis and three or more nozzles turbines are typically installed in vertical axis configuration. Low capacity units, such as in small hydropower are commonly installed in horizontal configuration, while large capacity units tend to be vertical installations (Alternate Hydro Energy Centre, 2012).

4) Design Discharge and Calculation of Installed Power: The installed power or installed capacity of a small hydropower plant shall be selected according to the evaluated "design discharge" provided by the hydrological study, and the "net head", derived from the site gross head less head losses (United Nations Industrial Development Organisation, 2019). Grid-connected run-of-river small hydropower plants normally optimizes at 30% flow exceedance factor, but depending on shape of the flow-duration curve design discharge could fall anywhere between 15% to 40% flow exceedance (US Army Corps of Engineers, 1985), (Natural Resources Canada, 2004), (Zhang, et al., 2013), (ZESCO, 2018) and (Mukuka, 2022). According to (Vasic, et al., 2018) power on the turbine shaft can be calculated by the following expression.

$$\mathrm{P}_t = \eta_t 9.81.Q_t.H_n\ (\mathrm{k}W) \qquad (1)$$

Where:

P_t = turbine shaft rated power in kilowatts
η_t= turbine efficiency
Q_t = design discharge through turbine (m^3/s)
$\mathrm{H_n}$ = Net head (Gross head H_g – hydraulic losses H_{hydr}) (m)

Equation *(1)***Error! Reference source not found.** can be modified to include the generator efficiency to obtain the turbine-generator unit output power. Using gross head and hydraulic losses, the turbine-generator power output equation for one machine is as follows (RETScreen International, 2005).

$$\mathrm{P}_{des} = 9.81.Q_{des}.\left(H_g - H_{hydr}\right).\eta_{t,des}.\eta_g(\mathrm{k}W) \qquad (2)$$

Where:

P_{des} = turbine-generator unit rated design capacity in kilowatts
$\eta_{t,des}$= turbine efficiency at design flow or discharge
η_g= generator efficiency
Q_t = design discharge through turbine (m^3/s)
H_{hydr} = hydraulic losses (m)
H_g = gross head (net head H_n + hydraulic losses H_{hydr}) (m)

Turbine efficiency is normally obtained from the manufacturer turbine specifications or the published standard turbine efficiency curves for different types of turbines. The generator efficiency, η_g, similarly, is provided by manufacturers, but in general it typically ranges from 93 to 97% (Adejumobi & Shobayo, 2015).

Many software applications exist on the market today, designed for modeling renewable energy projects with embedded calculation equations. One such example is RETScreen desktop application. The main input data that RETScreen requires to calculate the generated power, annual energy production and capacity factor include: project scheme type - whether dam or run-of-river, gross head, turbine design discharge, flow-duration curve data, percentage of time when the firm flow is available, residual (environmental) flow, hydraulic loss, generator efficiency, and selected turbine type. The software itself computes the net head. The turbine efficiency curve is based on standard manufacturer turbines imbedded in the application software. If so required, the turbine efficiency curve can be user defined.

To get the **plant installed capacity**, the power output of each turbine, as per Equation *(1)*,**Error! Reference source not found.** can be added using the following equation.

$$\begin{aligned}\mathrm{P}_{des(Plant)} = \text{Unit 1 } \mathrm{P}_{des} + \text{Unit 2 } \mathrm{P}_{des} + \ldots \\ + \text{Unit n } \mathrm{P}_{des}\ (\mathrm{k}W)\end{aligned} \qquad (3)$$

Where:

P_{des} = turbine-generator unit rated design capacity in kilowatts
$\mathrm{P}_{des(Plant)}$ = plant rated capacity in kilowatts

In the course of operating the plant, it must be noted that the power production will vary from the rated power depending on the actual flow through the turbine at any particular time.

Actual generated power P available from the small hydro plant at any given flow value Q is evaluated by taking into account the flow-dependent hydraulic losses and the tailrace reduction. Equation *(1)* is modified to obtain Equation *(4)*, which gives power as a function of actual flow *Q*, as follows (RETScreen International, 2005).

$$P = 9.81.Q.\left[H_g - \left(h_{hydr} + h_{tail}\right)\right].\eta_t.\eta_g(\mathrm{k}W) \qquad (4)$$

Where:

η_t = turbine efficiency at flow Q

η_g = generator efficiency
H_{hydr} = hydraulic losses (m)
H_{tail} = tailwater level effect losses (m)
H_g = gross head (m)

The power duration curve (PDC) or available power curve is derived from a flow-duration curve and both curves represent an annual cycle (Otuagoma, 2016). The PDC depicts the power output of the small hydropower plant's response to the annual variability of streamflow. Figure 2 shows an example of a power duration curve.

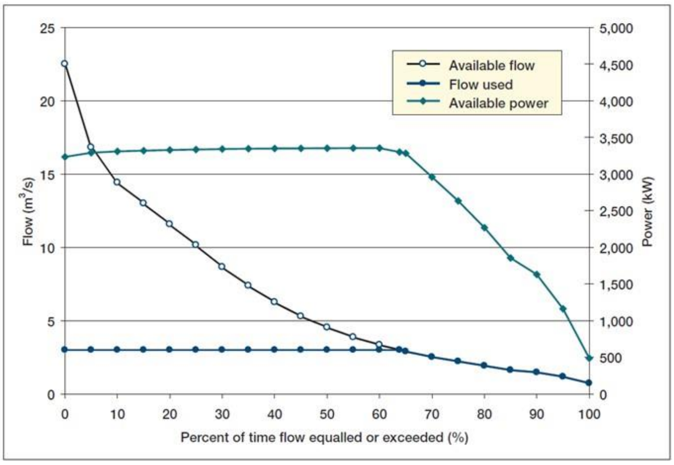

Figure 2: Example of power duration curve (integrated on flow- duration curve)

[**Source:** (RETScreen International, 2005)]

Consequently, annual renewable energy available from a plant is determined by calculating the area under the power duration curve (Adejumobi & Shobayo, 2015).

5) Calculation of Annual Energy Production: The annual energy production is calculated using the trapezoidal rule to evaluate the area under the power duration curve, discussed in the foregoing, by assuming a straight-line between adjacent calculated power output values. The area can be approximated by the following trapezoidal rule based mathematical expression (Adejumobi & Shobayo, 2015).

$$\int_a^b f(x)dx = \frac{h}{2}\sum_{z=0}^{n}\{f(x_z) + f(x_{z+1})\} \qquad (5)$$

Where h is the percentage spacing of intervals on the PDC (i.e. 5%), and n is the number of intervals of flow exceedance factor of the flow-duration curve, from which the power duration curve is derived. Therefore, if each trapezoidal area section on the flow-duration curve is broken up into 5% intervals, each interval is equivalent to 5% of 8,760 hours (number of hours per year). With incorporation of the plant availability, the available or the generated annual energy E (in kWh/yr.) can, therefore, be calculated based on **Error! Reference source not found.** *(5)* using the values P (in kW) from **Error! Reference source not found.** *(4)***Error! Reference source not found.**, as follows.

$$E = \sum_{k=1}^{20}\left(\frac{P_{5(k-1)} + P_{5k}}{2}\right)\frac{5}{100}A.t_y(kWh/year) \qquad (6)$$

In Equation *(6)*, "*E*" is the annual energy generated by the small hydropower plant in (kWh), "*P*" is the flow dependent power outputs from Equation *(4)***Error! Reference source not found.**. "*A"* is the plant's annual availability (typically a number picked from the range 85 – 98%). Most of the global hydropower industry use 90% availability (ZESCO, 2018) and (Mukuka, 2022). The factor t_y = 8760 is the approximated available maximum number of plant operational hours in a year (Adejumobi & Shobayo, 2015). The figure 5/100 (otherwise written as 5%) is the percentage spacing of intervals on the power duration curve. The spacing intervals can be detailed in different sizes, i.e. 1%, 10% or other, depending on user flow-duration curve desired intervals. RETScreen uses 5% intervals on the flow-duration curve and power duration curve (RETScreen International, 2005).

6) Calculation of Capacity Factor: The small hydropower plant annual capacity factor (C) is the ratio of the plant's estimated energy production to the plant's potential energy production if it had operated at rated output for the whole year (Nasir, 2021). A higher capacity factor plant is more dependable and a lower capacity factor vice versa. According to (Adejumobi & Shobayo, 2015) capacity factor can be calculated using the following equation.

$$C = \frac{E}{P_{des.}t_y} \qquad (7)$$

Where C is the plant capacity factor, E is the actual annual energy, based on Equation *(6)* and $P_{des.}t_y$ is the theoretical annual production of the plant as per machine nameplate based on Equation *(2)*. Capacity factors vary widely in hydropower. For example, average capacity factor for projects commissioned between 2010 and 2021 was 48% for large hydro projects and 50% for small hydro, with most projects in the range of 25% to 80% (International Renewable Energy Agency, 2022). This wide range of capacity factor is typical, owing to the high design flexibility of hydropower, which is site-dependent on inflows, head, environmental, and other site characteristics. It is also unique to hydropower, where low capacity factors are sometimes a design choice, for instance when designed to meet peak demand or provide other ancillary grid services (International Renewable Energy Agency, 2022)

7) Specific Speed and Turbine Runner Sizing: The specific speed of turbine is the speed of a geometrically similar turbine that would generate 1 kW under 1 m head (Rajput, 2015). Consequently, all geometrically similar turbines, whatever their size, all have the same specific speed. According to (European Small Hydropower Association, 2004), as well as (Temiz, 2013) and (Vasic, et al., 2018), the IEC60193 and IEC60041 standards state the dimensionless specific speed formula for a hydro turbine as follows.

$$n_{QE} = \frac{n_t.\sqrt{Q}}{E^{3/4}} \qquad (8)$$

Where:

Q = discharge or flow through turbine (m^3/s)
$E = H_n.g$ = specific hydraulic energy of machine (J/Kg)
n_t = rotational speed of turbine (revs/s)

n_{QE} is dimensionless specific speed

The specific speed n_{QE} and its parameters characterize any turbine. Selection of a high specific speed for a given head will result in a smaller turbine and generator, with savings in capital cost, while lower specific speed would entail a larger turbine runner diameter. (Alternate Hydro Energy Centre, 2012). However, additional factors must be considered. For instance, if a reaction turbine is found to be smaller and cheaper option over impulse turbine, the reaction turbine will have to be placed lower as a submerged runner, for which the cost of excavation may offset the turbine savings. Site conditions could also prevent the application of a certain turbine type. Typically, additional factors such as annual energy output, capacity factor, and others enter into the selection of the most optimal turbine.

It is common in small hydropower projects for the manufacturer to specify a standard turbine whose size and operational characteristics best fit the site conditions. This avoids costly designs of unique turbines as practiced in large hydropower projects. Turbine sizing design is an iterative process, which is dependent on various principles involving rotational speed, specific speed, economic runner diameter, and other factors dependent on particular turbine type, such as cavitation (European Small Hydropower Association, 2004). This means that a design engineer analyses a number of alternative options and picks optimum size. Once the specific speed is known, then the fundamental dimensions of the turbine can be roughly estimated (Temiz, 2013).

For all turbine types, the first step is to choose a standard rotational speed to calculate the specific speed. The common approach, alternatively, is to begin by picking the maximum specific speed, which in turn leads to calculating the smallest runner size (ZESCO, 2018). If the required design parameters are not all satisfied at the maximum specific speed, then one has to iterate to a lower speed (or increase number of nozzles for Pelton) until the speed and size that optimally satisfy all design boundaries is reached. For detailed turbine dimension calculations, the following typical specific speed ranges of common turbines shown in Table 2 are applicable as guidance.

Table 2: Range of specific speed for common hydro turbines

Turbine Type	**n_{QE} Specific Speed Range**
Pelton (One nozzle)	$0.005 \leq n_{QE} \leq 0.025$
Pelton (n nozzles)	$0.005\,.n^{0.5} \leq n_{QE} \leq 0.025\,.n^{0.5}$
Francis	$0.05 \leq n_{QE} \leq 0.33$
Kaplan, Propeller, Bulb	$0.19 \leq n_{QE} \leq 1.55$

[**Source:** “ (Temiz, 2013)”]

Equations for determining feasibility study stage dimensioning of size parameters of common turbines are shown in Figure 3.

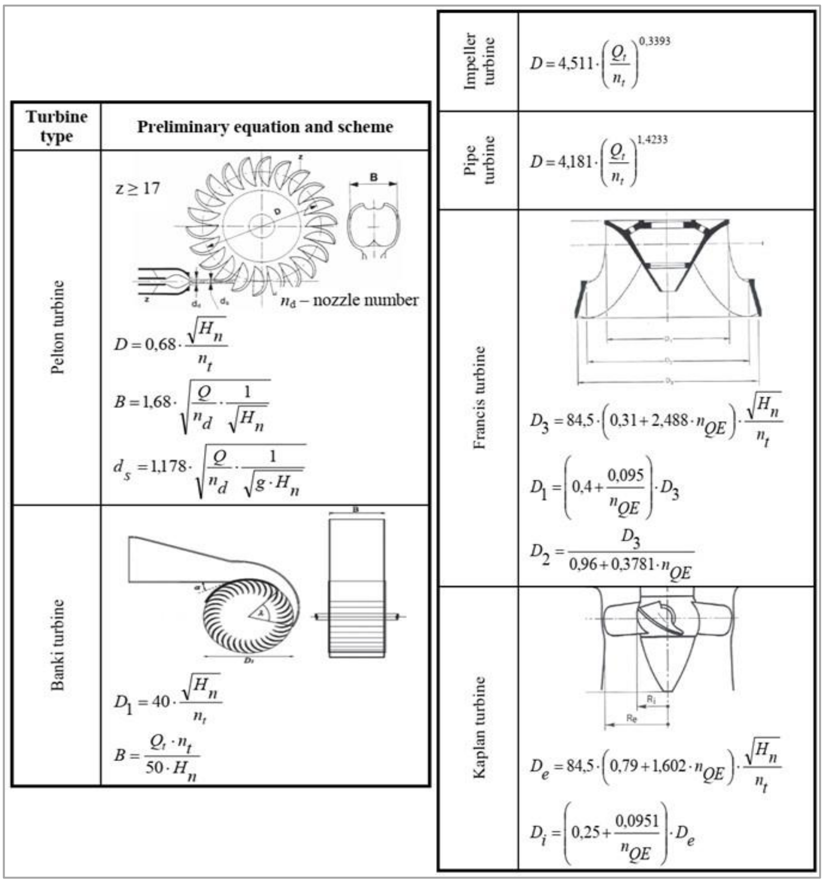

Figure 3. Preliminary equations for basic dimensioning of common turbines

[**Source:** (Vasic, et al., 2018)]

8) Pelton Wheel Optimal Sizing Rules for Runner, Nozzles and Buckets: In feasibility study stage Pelton wheel sizing, the typical component dimensions of interest are the runner diameter, bucket width, number of nozzles and diameter of nozzle (Vasic, et al., 2018). A number of optimal design requirements are required to be fulfilled in harmony with these Pelton turbine size parameters. Pelton turbines have a bit more number of parameters that require sizing than other common turbines. As shown in **Error! Reference source not found.**, *D* is the Pelton pitch circle diameter describing the buckets centerline, *Z* is the number of buckets, *B* is the bucket width, and d_s is the jet diameter. The runner diameter, bucket width, and nozzle diameter can be determined from the following equations (Vasic, et al., 2018).

$$D = 0.68\,\frac{\sqrt{H_n}}{n_t} \qquad (9)$$

$$B = 1.68\sqrt{\frac{Q}{n_d\,.\,\sqrt{H_n}}} \qquad (10)$$

$$d_s = 1.178\sqrt{\frac{Q}{n_d\,.\,\sqrt{g.H_n}}} \qquad (11)$$

Where, H_n is the net head for the site applicable to the turbine; Q is the turbine rated flow or maximum flow; n_t is the turbine rotational speed in rev/s and n_d is the number of nozzles, and g is acceleration due to gravity.

As a rule of thumb, the ratio D/B must always be greater than 2.7 for optimum design performance (Nasir, 2014) and (European Small Hydropower Association, 2004). If not achieved in the early iterations of sizing, a new calculation with a lower rotational speed or more nozzles has to be carried out until the requirement is achieved.

Further, the ratio of pitch circle diameter of Pelton wheel to the jet diameter is known as jet ratio, represented by m. It is one of the size parameters of a Pelton turbine. According to (Rajput, 2015) the jet ratio can be evaluated using the following expression.

$$m = \frac{D}{d_s} \qquad (12)$$

For maximum hydraulic efficiency, the jet ratio must lie between 11 and 15 (Zaw Oo, et al., 2019). A smaller value of m results in either too close bucket spacing or too few buckets leading to poor jet utilization. A larger value of m results in a more bulky installation.

The number of buckets for a Pelton wheel should be such that the jet is always completely intercepted by the buckets so that volumetric efficiency of the turbine is very close to unity (Rajput, 2015). Through empirical observation it has been determined that the number of buckets should always be greater than 17 (Vasic, et al., 2018). Consequently, empirical formulae have been developed for determining the number of buckets, and according to (Zaw Oo, et al., 2019) a widely used formula for calculating the number of buckets, Z, is:

$$Z = 0.5m + 15 \qquad (13)$$

The approximate number of buckets determined from wide industry experience is given in Table 3.

Table 3: Approximate number of Buckets for a Pelton turbine

Jet Ratio	6	8	10	15	20	25
Number of Buckets	17-21	18-22	19-24	22-27	24-30	26-33

[**Source:** (Zaw Oo, et al., 2019)]

Further, in a Pelton turbine sizing design the ratio of the bucket width to the jet diameter is one of the important parameters to consider. The standard formula are often superseded by industry rule of thumb, which further optimize turbine runner size parameters. One such parameter is the optimum ratio of the size of the bucket and the nozzle, which is given by the following industry rule of thumb (Acharya, 2019).

$$3.1 > \frac{B}{d_s} \geq 3.4 \qquad (14)$$

Where:

$$B = 3.1\,d_s \quad \text{for 1 Nozzle} \qquad (15)$$

$$B = 3.2\,d_s \quad \text{for 2 Nozzles} \qquad (16)$$

$$B = 3.3\,d_s \quad \text{for } 4-5 \text{ Nozzle} \qquad (17)$$

$$B > 3.3\,d_s \quad \text{for 6 Nozzle} \qquad (18)$$

If the bucket width is too small in relation to jet diameter, work done by the fluid is poor because of poor deflection, turbulence and considerable efficiency drop (Zaw Oo, et al., 2019). On the other hand, if the buckets are disproportionately large, friction on the bucket surfaces becomes unnecessarily high.

Determination of optimum number of nozzles involves a range of factors such as technical design conditions, rules of thumb and specific site conditions. For instance sandy waters. Horizontal shaft Pelton turbines tend to be smaller capacity units with one-nozzle and two-nozzle installations, while vertical units are large capacity with multi-nozzle turbines (Alternate Hydro Energy Centre, 2012). For the same rated head and flow conditions, increasing the number of jets results in a smaller runner and a higher operating speed. Therefore, whether vertical or horizontal shaft, multi-jet turbines tend to be less costly for comparable outputs because the cost of the runner represents up to 20% of the cost of the entire turbine (Alternate Hydro Energy Centre, 2012)

9) Generator Type and Number: There are two main types of generators that are used for the hydropower production: synchronous or asynchronous generators (Zhamalovich, et al., 2013). Synchronous generators are the most commonly used type in large and small hydropower because of their high efficiency and their constant speed operation. In general, when the power exceeds IMW or MVA a synchronous generator is installed (European Small Hydropower Association, 2004). Further, synchronous generators are able to supply the reactive energy required by the power system when the generator is connected to the grid.

Alternatively, synchronous generators can power an isolated grid since their excitation is not grid-dependent, rather they have self-excited. Asynchronous generators, conversely, cannot generate when disconnected from the grid because they are incapable of providing their own excitation. Nevertheless, they are used in very small stand-alone applications as a cheap solution when the required quality of the electricity supply is not very high (European Small Hydropower Association, 2004).

A hydropower electrical generator is typically directly coupled to a turbine to form a turbine generator unit. Therefore, the number of generators would normally correspond to the number of turbines. For maximum efficiency, hydraulic turbines should correspond to the generator speed compatible to an even number of generator poles (Alternate Hydro Energy Centre, 2012).

10) Frequency, Number of Poles and Synchronous Speed: In small hydropower projects, standard generators based on standardized synchronous rotational speed (in RPM) are installed (Zaw Oo, et al., 2019). Standard generators are chosen to avoid conducting a completely new design whose manufacture is very expensive because that design may not be used again on another project. The generators are either directly coupled or through a speed increaser in order to attain the synchronous speed. According to (Zaw Oo, et al., 2019) the number of poles, P_o, for synchronous speed generator is always even and it is expressed by:

$$P_o = \frac{120f}{N} \qquad (19)$$

Where, f is frequency, which is 50 Hz in Zambia, and N is the generator number of revolutions per minute. Small hydropower generators designs are standard and are based on wide choice of synchronous speed as illustrated in Table 4.

Table 4: Standard Generator synchronization speed

Rated Power (kW)	**Best Efficiency**
10	0.91
50	0.94
100	0.95
250	0.955
500	0.96
100	0.97

[**Source:** (European Small Hydropower Association, 2004)]

Table 5: Typical efficiencies of small generators

Number of Poles (P_o)	**Frequency & RPM**		**Number of Poles (P_o)**	**Frequency & RPM**	
	50Hz	60Hz		50Hz	60Hz
2	3000	3600	16	375	450
4	1500	1800	18	333	400
6	1000	1200	20	300	360
8	750	900	22	272	327
10	600	720	24	250	300
12	500	600	26	231	277
14	428	540	28	214	257

[**Source:** (Zaw Oo, et al., 2019)]

Generally, the generator with higher number of poles is more costly than the one with lower number of poles, meaning that a high rotational speed is economically preferable (Temiz, 2013). Therefore, when presented with options, the highest possible speed option is usually preferred for lower cost reasons.

11) Generator kW, kVA and Voltage Rating: When it comes to generator sizing, equation *(2)* is applicable for determining the generator real power capacity rating in kilowatts (kW), because generator rating is fixed by the turbine rated output and consideration of generator efficiency. Subsequently, generator KVA or MVA rating is determined by incorporating power factor. In general, the generator is rated for its turbine output at rated head (Alternate Hydro Energy Centre, 2012). According to (ZESCO, 2018) the generator apparent power rating in KVA capacity can be determined from the following formula:

$$P_g\ (kVA) = \frac{9.81.H.Q.\eta_t.\eta_g}{pf} \qquad (20)$$

Where:

P_g = generator capacity (kVA)
H = net head
Q = turbine rated discharge (m^3/s)
η_t = turbine efficiency
η_g = generator efficiency
pf = power factor

The generator efficiency, η_g, is provided by manufacturers, but in small hydropower in general, it typically ranges from 93 to 97% (Adejumobi & Shobayo, 2015). The power factor, *pf*, is specified based on the power system requirements and is generally between 0.8 and 1.0 depending on the reactive power requirements (Alternate Hydro Energy Centre, 2012). The Mabula Kapi prefeasibility study adopted power factor of 0.85 and generator efficiency of 0.97 (ZESCO, 2018). As for generator efficiency, typical best efficiencies for small hydropower are shown in [Source: (European Small Hydropower Association, 2004)]

Table 5.

The International Electro Technical Commission IEC-60034-1 standard states that generator terminal voltage should be as high as economically feasible (Alternate Hydro Energy Centre, 2012). The economical terminal voltages for small hydro generators recommended according to IEC-60034-1 are as shown in Table 6.

Table 6: IEC standards for generator terminal voltage

IEC – 60034-1 (Minimum)	
Voltage	**Generator Power**
3.3kV	Above 150kW (or kVA)
6.6kV	Above 800 kW (or kVA)
11kV	Above 2500 kW (or kVA)

[**Source:** (ZESCO, 2018)]

III.METHOD

A. Research Type and Adopted Modelling Techniques

This study sought to conduct a technical component of feasibility-level studies focusing on selecting the suitable hydro turbine type, determining the optimal number of turbine units and their configuration, whether vertical or horizontal, main turbine dimensional parameters, as well as determining the optimized design parameters of plant power and energy output and capacity factor rating for the proposed run-of-river Mabula Kapi small hydropower site.

The research utilized applied research methods of Computational Modelling and Simulation, and Optimization Techniques. It is typical in hydropower plant design processes, to use simulation or modelling software to analyse power and energy output of different turbine options and output of alternative number of turbine units to determine the optimal design solution. RETScreen energy modelling software was used for modelling and simulation, while excel was used for calculation formulas. RETSCreen's ability to conduct site-specific energy and power assessments makes it suitable for small hydropower projects (Zhang, et al., 2013).

B. Research Data and Mabula Kapi Turbine Plant Sizing Design and Optimisation Process

The data used in this study was secondary data from previous site studies, namely, the prefeasibility study and feasibility-level hydrological study conducted at site prior. The secondary data type used included the following.

(i) Scheme type
(ii) Site gross head and net head
(iii) Site flow-duration curve
(iv) Design discharge (a second optional design discharge was analysed and included to that proposed in earlier study)
(v) Environmental flow

To conduct the installed size options analysis, based on design discharge alternatives, the installed cost in US$ per kW was evaluated for Mabula Kapi. This study adopted a figure of US$3,500 per kW of installed cost for analyzing the installed cost versus the installed power and annual energy production options at 15%, 20%, 25%, 30%, 35% and 40% flow-duration curve exceedance, a region where run-of-river scheme optimize the design discharge. The selected installed cost was guided by a detailed study on hydropower total installed cost that found that the weighted average cost for projects of 0 – 50 MW, installed between 2000 and 2021, was US$3,563 (International Renewable Energy Agency, 2022). .

The research method for carrying out the design optimisation analysis of the Mabula Kapi run-of-river small hydropower plant involved the following components.

(i) Collection of secondary data from previous site studies conducted at Mabula Kapi;
(ii) Analysis of optimal design discharge following standard rules based on flow-duration curve data, with a view to having two optional design discharge values for optimization simulation scenarios;

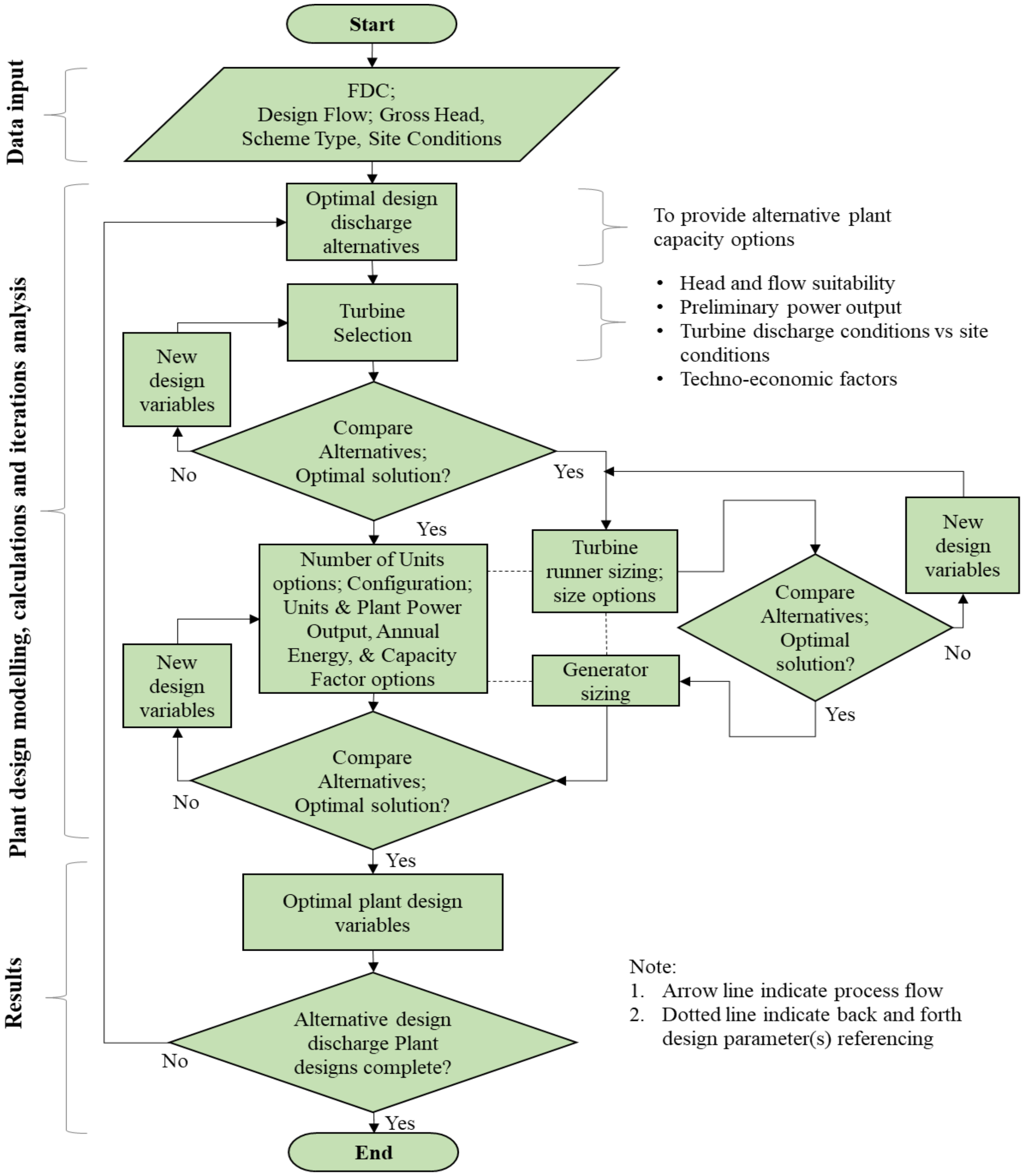

Figure 4. Flow chart of Mabula Kapi Run-of-River Turbine Plant Sizing Design and Optimization Process

IV. RESULTS ANALYSIS AND DISCUSSION FOR MABULA KAPI PLANT DESIGN OPTIMIZATION

A. Discharge Analysis for Mabula Kapi Design

The Mabula plant installed cost analysis was in RETScreen software by inputting all secondary data of plant gross head, flow duration curve and inputting different variables for design discharge. Preliminarily a Pelton turbine was used in this stage of analysis, in keeping with earlier study pre-recommendation, and the standard installed cost figure used was US$3,500 per kW.

The analysis in Figure 5 indicate the following graphically plotted installed capital expenditure (CAPEX) and energy output result.

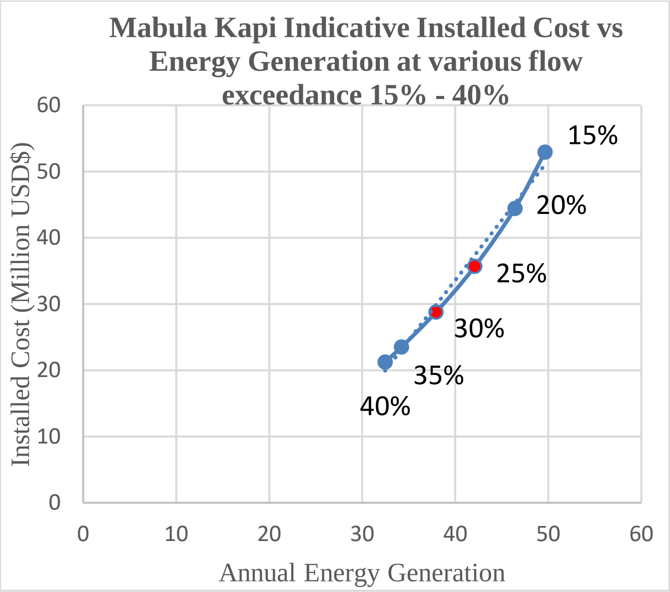

Figure 5. Installed cost vs energy output analysis of design discharge

An analysis of the cost-energy plot and the best-fit line revealed that beyond the 25% flow exceedance point the cost-energy curve gradient started increasing significantly, and drifting to the left side of the best-fit curve. This shift meant that the energy generated began to drop with increasing installed cost. Therefore, flows at exceedance factors of 30% ($5.02m^3/s$) and 25% ($6.20m^3/s$) were adopted as that which optimized the plant design and energy production versus investment cost. The two flows, $5.02m^3/s$ and $6.20m^3/s$, were thus adopted as design discharge (Q_{design}) alternatives for the analysis of two plant size options for the Mabula Kapi site.

B. Turbine Selection

The Pelton, Francis, Turgo and Cross-flow (Michell-Banki) common turbines turbine types were found were all applicable for the site net head of 195.24m and design discharge options of $5.02m^3/s$ and $6.20m^3/s$, after checking their application range information. The Kaplan and Propeller were not applicable.

A RETScreen analysis of installed power results for each applicable turbine type found the following results shown in Table 7.

Table 7. RETScreen modelling results of power output per type turbine for Mabula Kapi site

S/N	**Turbine Type**	**Installed Power Capacity (MW)** [Design flow = $5.02m^3/s$]	**Installed Power Capacity (MW)** [Design flow = $6.20m^3/s$]	**Installed Power Rank**
1	Francis	8.355	10.33	1
2	1-Nozzle Pelton	8.284	10.27	2
3	2-Nozzle Pelton	8.221	10.2	3
4	1-Nozzle Turgo	8.010	9.94	4
5	2-Nozzle Turgo	7.95	9.86	5
6	Cross-flow	7.368	9.1	6

The Francis turbine provided the highest installed power capacity of 10.33 MW at design discharge of $6.20m^3/s$, but was not adopted because of site conditions that were not permitting at Mabula Kapi. The Mabula Kapi site layout was such that plant abstracts intake water from the perennial Kaombe River and discharges the turbine flow into a powerhouse and tailrace located on the adjacent seasonal Kalamabwe stream, which further downstream is a tributary of Kaombe River.

The requirement for a reaction turbines, in this case the Francis, to be fully submerged at start-up and while in operation poses a challenge, particularly at start-up for the Mabula Kapi site because the Kalamabwe stream, where the tailrace is situated, dries up in the dry season. Machine start-up is not achievable in the dry season due to lack of tailwater needed to submerge the Francis reaction turbine. Therefore, the Francis, being a reaction turbine type, was not applicable for the operating conditions of the Mabula Kapi scheme.

For impulse turbines, on the contrast, a free water jet operates the runner, and these do not require submerging during start-up or in operation and are therefore, installed above the tailwater level. Hence, the lack of Kalamabwe Stream flow in the dry season at the tailrace of the Mabula Kapi plant does not affect the normal operation of an impulse turbine installation. Impulse turbines, therefore, were applicable at Mabula Kapi, and particularly the Pelton, which gave the second highest installed power at 10.27 MW at equivalent design discharge of $6.20m^3/s$ was determined as the suitable and optimal choice for the Mabula Kapi site, with respect to the site-specific operational conditions.

C. Number of Units Determination

To determine the number of installed units, the one-nozzle and two-nozzle Pelton turbines were analyzed in RETScreen software for annual energy production versus number of units. One-nozzle and two-nozzle where the typical Pelton turbines in small hydropower. Table 8 shows the analysis.

Table 8. RETScreen analysis of annual energy output vs number of Pelton turbine units

Pelton Turbines Energy Output								
Design Flow	**Plant Capacity**	**Annual Energy Production**						**Nozzles**
		1 x Pelton	**2 x Pelton**	**3 x Pelton**	**4 x Pelton**	**5 x Pelton**	**6 x Pelton**	
m^3/s	**MW**	**GWh**	**GWh**	**GWh**	**GWh**	**GWh**	**GWh**	
5.02	8.284	37.69	38.27	38.33	38.29	38.26	38.31	1
5.02	8.221	37.36	37.88	37.94	37.90	37.88	37.92	2
6.20	10.27	41.44	42.36	42.55	42.44	42.84	42.52	1
6.20	10.20	41.11	41.95	42.11	42.03	42.06	42.09	2

For the Mabula Kapi site, RETScreen energy modelling indicated that plant installation with three-Pelton turbine units produced the highest energy output for both one-nozzle and two-nozzle installation, for both alternative design flows of 5.02 m^3/s and 6.20 m^3/s. Further analysis of Pelton turbine ability to handle low flows in the dry season for run-of-river schemes was considered for the Mabula Kapi flow-duration curve and the three-Pelton installation was established to have at least one turbine running at the lowest possible flows at 90% (P90) flows probability exceedance, which is the least expected operational flow. The selected three-Pelton installation for Mabula Kapi, also provides the advantage of allowing for annual shutdown maintenance in the low flow season, when only one or two runners will be in operation.

Apart from lower power output, the one-Pelton or two-Pelton installation would have larger turbines that would pose potential shut down during dry-season low flows, due to plant flows falling below turbine technical minimum allowable.

D. Mabula Kapi Plant Installed Power, Annual Energy and Capacity Factor Analysis

Installed power, annual energy production, and capacity factor were analyzed using RETScreen energy modelling software, based on embedded standard formulas, listed in Chapter II of this paper. Using gross head of 203.38m, plant design discharge of 5.02 m^3/s (Alternative 1) and 6.20 m^3/s (Alternative 2), environmental flow of 0.58 m^3/s, maximum hydraulic losses of 4% recommended by the RETScreen energy modeling manual, and using generator efficiency 0.97, and plant availability of 90%, the RETScreen plant sizing analysis gave the results shown in

Table **9** and
Table **10**.

Table 9. Analysis of Mabula Kapi plant power rating, annual energy production and capacity factor for Alternative 1 design discharge

Alternative 1: Design Discharge = 5.02 m^3/s						
Number of Turbines Installation Option	**One-Nozzle Pelton**			**Two-Nozzle Pelton**		
	Power (MW)	**Energy (GWh)**	**C.F. (%)**	**Power (MW)**	**Energy (GWh)**	**C.F. (%)**
1 x Pelton	8.284	37.69	51.9	8.221	37.36	51.9
2 x Pelton	8.284	38.27	52.7	8.221	37.88	52.6
3 x Pelton	8.284	38.33	52.8	8.221	37.94	52.7
4 x Pelton	8.284	38.29	52.7	8.221	37.90	52.6
5 x Pelton	8.284	38.26	52.7	8.221	37.88	52.6
6 x Pelton	8.284	38.31	52.8	8.221	37.92	52.7

Table 10. Analysis of Mabula Kapi power rating, annual energy production and capacity factor for Alternative 2 design discharge

Alternative 2: Design Discharge = 6.20 m^3/s						
Number of Turbines Installation Option	**One-Nozzle Pelton**			**Two-Nozzle Pelton**		
	Power (MW)	**Energy (GWh)**	**C.F. (%)**	**Power (MW)**	**Energy (GWh)**	**C.F. (%)**
1 x Pelton	10.27	41.44	46	10.20	41.11	46
2 x Pelton	10.27	42.36	47.1	10.20	41.95	47
3 x Pelton	10.27	42.55	47.3	10.20	42.11	47.1
4 x Pelton	10.27	42.44	47.2	10.20	42.03	47.1
5 x Pelton	10.27	42.84	47.2	10.20	42.06	47.1
6 x Pelton	10.27	42.52	47.2	10.20	42.09	47.1

As illustrated earlier in the section on number of units determination, and further in this section (

Table 9 and
Table **10**) using RETScreen energy modeling, the three-turbine Pelton installation was conformed as the choice that

maximizes plant power capacity, annual energy production and capacity factor for Mabula Kapi. The Plant size rating design two alternative results are further explained as follows.

- **Plant Size Alternative 1:** Using design discharge of 5.02 m^3/s the plant capacity was found as 8.282 MW for one-nozzle Pelton turbines installation, and 8.221 MW for two-nozzle Pelton turbines installation. Further, results indicated that a three-turbine plant arrangement gave the highest energy output: 38.33 GWh for one-nozzle Pelton plant and 37.94 GWh for two-nozzle Pelton plant. The capacity factors were 52.8% and 52.7%, respectively.
- **Plant Size Alternative 2:** Using design discharge of 6.20 m^3/s the plant capacity was found as 10.27 MW for one-nozzle Pelton turbines installation, and 10.20 MW for two-nozzle Pelton turbines installation. Further, results indicated that a three-turbine plant arrangement gave the highest energy output: 42.55 GWh for one-nozzle Pelton plant and 42.11 GWh for two-nozzle Pelton plant. The capacity factors were 47.3% and 47.1%, respectively.

Finalization of the final design of the Mabula Kapi plant installed power, annual energy, and capacity factor, could not be achieved at this stage until an analysis on optimal number of Pelton runner nozzles was conducted, whether a one-nozzle or two-nozzle Pelton installation. This was so because the number of nozzles had an effect on installed power and energy output.

The next section outlines the analysis of the optimal parameters for the turbine runner and generator, together with runner speed, runner diameter, number and diameter of nozzles, number and width of buckets, generator power and voltage rating, and number of poles.

E. Turbine Sizing Design and Optimization of Runner and Generator

1) Speed and Size of Runner, Size and Number of Nozzles and Buckets: As per standard practice, specific speed, net head and turbine design flow were used for the determination of the turbine speed, dimensions of the Pelton wheel, buckets and number of nozzles for optimal installation at the Mabula Kapi, based on standard formulas and rules of thumb outlined in Chapter II of this paper.

Using net head of 195.245 m, plant design discharge alternatives of 5.02 m^3/s and 6.20 m^3/s, equally shared by the three installed turbines at turbine design flow of 1.6733 m^3/s and 2.067 m^3/s, respectively, the turbine sizing and optimization calculations were carried out. Design calculations and iterations were conducted by inserting the relevant equations in Microsoft Excel to find runner and nozzle diameters, and number and width of buckets, based on number of nozzles.

As per standard practice, the iteration for sizing turbine runner parameters started with selecting the highest specific speed based on the number of nozzles, and ensuring that all the design rules and boundaries are satisfied. When not achieved, a higher number of nozzles and related specific speed, or lower rotational speed was chosen, and calculations repeated until the requirement was achieved as outlined in

Table **11** as follows.

Table 11. Alternative 1 Pelton runner size design iterations based on number of nozzles and plant design discharge option 1

S/N	**Alternative 1 Mabula Kapi Plant Turbine Sizing: Number of Turbine Units = 03: For Plant Design Discharge of 5.02 m3/s and each Turbine’s Design Discharge $Q_{t\text{-}design}$ = 1.6733 m^3/s**						
	No. of Nozzles	**1**	**1**	**2**	**3**	**4**	**Equation/Reference**
1	Max specific speed n_{QE}	0.0250	0.0250	0.0354	0.0433	0.0500	Table 2
2	Corresponding Turbine Speed n_t(Rev/s)	5.60	5.60	7.91	9.69	11.19	Equation (8)
3	Corresponding Turbine Speed (RPM)	335.73	335.73	474.79	581.50	671.45	Rev/s to rpm
4	Applicable Synchronous Speed (RPM)	333	231	333	375	428	Table 4
5	Applicable Synchronous Speed n_t (Rev/s)	5.55	3.85	5.55	6.25	7.13	Equation (8)
6	Corresponding specific speed n_{QE} for Applicable Synchronous Speed	0.0248	0.0172	0.0248	0.0279	0.0319	Rpm to rev/s
7	Runner Diameter D (m)	1.71	2.47	1.71	1.52	1.33	Equation (9)
8	Bucket Width B (m)	0.58	0.58	0.41	0.34	0.29	Equation (10) **Error! Reference source not found.**
9	Optimized Bucket Width B (m): B=3.1ds for 1 nozzle; B=3.2ds for 2 and 3 nozzles; B=3.3ds for 4-5 nozzles (Rule of thumb supersedes standard equation for optimisation of ratio of bucket width to nozzle diameter (Acharya, 2019))	0.71	0.71	0.52	0.43	0.38	Rule of thumb equations (14)(15)(16)(17)

S/N	**Alternative 1 Mabula Kapi Plant Turbine Sizing: Number of Turbine Units = 03: For Plant Design Discharge of 5.02 m3/s and each Turbine's Design Discharge $Q_{t\text{-}design}$ = 1.6733 m^3/s**						
	No. of Nozzles	**1**	**1**	**2**	**3**	**4**	**Equation/Reference**
10	Required D/B > 2.7: D/B must always be greater than 2.7. If not, a new calculation with a lower rotational speed or more nozzles has to be carried out	2.4	3.5	3.3	3.6	3.5	Rule of thumb (European Small Hydropower Association, 2004)
11	Nozzle Diameter d_s (m)	0.23	0.23	0.16	0.13	0.12	Equation (11)
12	Jet Ratio (m) [required to be between 11-15 for Max Hydraulic Efficiency]	7	11	11	11	12	Equation (12)
13	Is jet Ratio (m) between 11-15?	No	Yes	Yes	Yes	Yes	Rule of thumb (Zaw Oo, et al., 2019)
14	Number of Buckets [req. volumetric efficiency (Rajput, 2015)]	19	20	20	21	21	Equation (13)
15	Is No. of Buckets>17?	Yes	Yes	Yes	Yes	Yes	Rule of thumb (Vasic, et al., 2018)

As shown in the tabulated results for Alternative 1 with plant design discharge of 5.02 m^3/s and turbine design discharge of 1.6733 m^3/s, the one-nozzle option Pelton wheel that met the design requirements had a diameter of 2.47 m, whereas the two-nozzle option Pelton wheel had a diameter of 1.71 m.

The two-nozzle Pelton had a lower diameter, which implied a lower equipment cost, and therefore, presented a potential recommendation as optimal installation for Mabula Kapi. The three-nozzle and four-nozzle turbine installation would have been the more preferred because of their smaller runner diameter and consequent lower equipment cost, but these were not typically applicable for horizontal shaft configuration. It was earlier determined in this section that the horizontal shaft Pelton was the optimal configuration for Mabula Kapi.

In small hydropower plants, low capacity units are commonly installed in horizontal configuration, while large capacity units in larger hydro plants tend to be vertical. Consequently, the double-nozzle Pelton was chosen to be the optimal installation at Mabula Kapi.

Similarly as in Alternative 1, runner sizing iterations were performed for Alternative 2 plant discharge. The results for Alternative 2 are outlined in Table 12 as follows.

Table 12. Alternative 2 Pelton runner size design iterations based on number of nozzles for plant design discharge option 2

S/N	**Alternative 2 Mabula Kapi Plant Turbine Sizing: Number of Turbine Units= 03: For Plant Design Discharge of 6.20 m^3/s and each Turbine's Design Discharge $Q_{t\text{-}design}$ = 2.0667 m^3/s**						
	No. of Nozzles	**1**	**1**	**2**	**3**	**4**	**Equation/Reference**
1	Max specific speed n_{QE}	0.0250	0.0250	0.0354	0.0433	0.0500	Table 2
2	Corresponding Turbine Speed n_t(Rev/s)	5.03	5.03	7.12	8.72	10.07	Equation (8)
3	Corresponding Turbine Speed (RPM)	302.09	302.09	427.23	523.24	604.19	Rev/s to rpm
4	Applicable Synchronous Speed (RPM)	333	214	272	333	375	Table 4
5	Applicable Synchronous Speed n_t (Rev/s)	5.55	3.57	4.53	5.55	6.25	Equation (8)
6	Corresponding specific speed n_{QE} for Applicable Synchronous Speed	0.0276	0.0177	0.0225	0.0276	0.0310	Rpm to rev/s
7	Runner Diameter *D* (m)	1.71	2.66	2.10	1.71	1.52	Equation (9)
8	Bucket Width *B* (m)	0.65	0.65	0.46	0.37	0.32	Equation (10) **Error! Reference source not found.**
9	Optimized Bucket Width *B* (m): B=3.1ds for 1 nozzle; B=3.2ds for 2 and 3 nozzles; B=3.3ds for 4-5 nozzles (Rule of thumb supersedes standard equation for optimisation of ratio of bucket width to nozzle diameter (Acharya, 2019))	0.79	0.79	0.58	0.47	0.42	Rule of thumb equations (14)(15)(16)(17)
10	Required D/B > 2.7: D/B must always be greater than 2.7. If not, a new calculation	3.35	3.36	3.62	3.62	3.60	Rule of thumb (European Small

	with a lower rotational speed or more nozzles has to be carried out						Hydropower Association, 2004)
11	Nozzle Diameter d_s (m)	0.26	0.26	0.18	0.15	0.13	Equation (11)
12	Jet Ratio (m) [required to be between 11-15 for Max Hydraulic Efficiency]	7	10	12	12	12	Equation (12)
13	Is jet Ratio (m) between 11-15?	No	No	Yes	Yes	Yes	Rule of thumb (Zaw Oo, et al., 2019)
14	Number of Buckets [req. volumetric efficiency (Rajput, 2015)]	19	20	21	21	21	Equation (13)
15	Is No. of Buckets>17?	Yes	Yes	Yes	Yes	Yes	Rule of thumb (Vasic, et al., 2018)

The Alternative 2 with plant design discharge of 6.20 m^3/s and turbine design discharge of 2.0667 m^3/s, the one-nozzle option Pelton wheel did not meet the recommended jet ratio for hydraulic efficiency, whereas the two-nozzle option Pelton wheel met all the design requirements and had a runner diameter of 2.1 m. Therefore, the two-nozzle option presented a potential recommendation.

As for the three-nozzle and four-nozzle runners, they were not applicable for the horizontal shaft installation at Mabula Kapi, given that three-nozzle and four-nozzle Pelton wheel are typically for larger hydro plants with vertical shaft configuration.

Consequently, the double-nozzle Pelton was chosen to be the optimal installation at Mabula Kapi, for Alternative 2 design discharge conditions. The two sizing results for turbine runner for Alternative 1 and Alternative 2 are summarized Table 13 below.

Table 13. Summary of calculated size parameters of turbine runner for Mabula Kapi small hydropower site

S/N	**Pelton Design Parameters**	**Alternative 1:** Plant design discharge = 5.02 m^3/s; Turbine design discharge = 1.6733 m^3/s	**Alternative 2:** Plant design discharge = 6.20 m^3/s; Turbine design discharge = 2.0667 m^3/s
1	Number of Pelton Units	3	3
2	Design Discharge (m^3/s)	1.6733	2.0667
3	Runner Speed (rpm)	333	272
4	Specific Speed (n_{QE})	0.0248	0.0225
5	Runner Diameter (m)	1.71	2.10
6	Bucket Width (m)	0.52	0.58
7	Number of Nozzles	2	2
8	Nozzle Diameter (m)	0.16	0.18
9	Number of Buckets	20	21

2) Generator Type, Speed, Number of Poles, MVA and Terminal Voltage: In practice, the speed of the generator is established by the turbine speed, and for small hydropower the turbine and generator speed are determined by standard generator synchronous speeds.

For maximum efficiency, hydraulic turbines should determine the generator speed corresponding to an even number of generator poles (Alternate Hydro Energy Centre, 2012).

Using a turbine efficiency at design flow of 88.2% (Alternative 1) and 88.5% (Alternative 2), both defined by RETScreen in the Mabula Kapi small hydropower plant modelling for three Pelton turbine installation, generator efficiency 0.97, and using power factor of 0.85, net head of 195.245 m that was calculated using RETScreen recommended 4% maximum hydraulic losses on gross head of 203.38 m, and using turbine design discharge of 1.6733 m^3/s (Alternative 1) and design discharge of 2.0667 m^3/s (Alternative 2) for each of the three turbines units, and a grid frequency of 50Hz, the calculation results for generator apparent power (MVA) capacity, number of poles and terminal voltage for each of the three required generators were found to be as shown in

Table **14**.

Table 14. Synchronous generator size parameters for Mabula Kapi small hydropower plant for turbine discharge of 1.6733 m^3/s (Alternative 1) and 2.0667 m^3/s (Alternative 2)

S/N	**Generator Parameter**	**Alternative 1:** Plant design discharge = 5.02 m^3/s; Turbine design discharge = 1.6733 m^3/s	**Alternative 2:** Plant design discharge = 6.20 m^3/s; Turbine design discharge = 2.0667 m^3/s	**Equation / Reference**
1	Number of Generators	3	3	Same as turbines

S/N	**Generator Parameter**	**Alternative 1:** Plant design discharge = 5.02 m^3/s; Turbine design discharge = 1.6733 m^3/s	**Alternative 2:** Plant design discharge = 6.20 m^3/s; Turbine design discharge = 2.0667 m^3/s	**Equation / Reference**
2	Frequency (Hz)	50	50	(Standard)
3	Synchronous Speed (rpm)	333	272	Same as Turbine; Table 4
4	Number of Poles	18	22	Equation (19)
5	Capacity (MVA)	3.2	4.0	Equation (20)
6	Terminal Voltage (kV)	11	11	IEC-60034-1 Standard; Table 6

F. *Summary of the Alternatives of the Optimized Plant Design Main Parameters and the Recommended Option for the Mabula Kapi Site*

As part of arriving at the decision for the recommended Mabula Kapi plant design option, the summary of the optimized design results involving turbine selection, turbine configuration, number of units, plant power, energy and capacity factor rating, as well as the turbine and generator size parameters, were summarized as shown in

Table **15** below.

Table 15. Summary of optimized design main parameters of Mabula Kapi run-of-river small hydropower plant based on two design discharge options

S/N	**Item**	**Alternative 1** [Design discharge of 5.02 m^3/s]	**Alternative 2** [Design discharge of 6.20 m^3/s] ***(Recommended Option)***
1	Installed Plant Capacity (MW)	8.22	10.20
2	Unit Rated Capacity (MW)	2.74	3.4
3	Annual Energy Production (GWh)	37.94	42.11
4	Capacity Factor (%)	52.7	47.1
5	Turbine Type	Pelton	Pelton
6	Number of Turbines	3	3
7	Unit Configuration	Horizontal	Horizontal
8	Design Discharge (m^3/s)	1.6733	2.0667
9	Turbine Speed (rpm)	333	272
10	Turbine Diameter (m)	1.71	2.10
11	Number of Nozzles	2	2
12	Nozzle dimeter (m)	0.16	0.18
13	Number of Buckets	20	20
14	Width of Bucket	0.52	0.58
15	Generator Type	Synchronous	Synchronous
16	Number of Generators	3	3
17	Generator Capacity (MVA)	3.2	4.0
18	Generator Terminal Voltage (kV)	11	11
19	Synchronous Speed (rpm)	333	272
20	Frequency (Hz)	50	50
14	Number of Generator Poles	18	22

Based on the technical analysis of this study, **Alternative 2 with installed capacity of 10.20 MW, annual energy generation of 42.11 GWh and capacity factor 47.1%, and based on design flow of 6.20 m^3/s at 25% exceedance probability, was recommended as the more optimal installed capacity for the Mabula Kapi small hydropower plant**.

The recommendation of Alternative 2 was because it had higher installed power and annual energy production than Alternative 1. Although the turbine size in Alternative 2 was higher (at 2.1 m) than in alterative 1 (at 1.71m), which implied that the turbine installation cost was higher in Alternative 2, the higher energy output of Alternative 2 provides the opportunity for higher income from higher production which should far offset the slightly higher turbine installed cost.

Notwithstanding, both Alternative 1 and 2 were presented as alternative techno-economic design options to enable future studies that would further analyze and compare detailed economic and financial evaluation and lead to a final decision on the best investment option between the two options.

G. *Comparison of Previous Studies and Current Study Results*

The related previous studies at Mabula Kapi were compared to the current study results and the current study’s improvements were outlined. The comparison indicated an improvement in the plant output and turbine wheel sizing and design optimization, as shown in Table 16.

Table 16. Comparison of previous Mabula Kapi studies to current study results

S/N	Description	Previous Results (Prefeasibility study) [Source: (ZESCO, 2018)]	Previous Results (Hydrological Study) [Source: (Mukuka, 2022)]	Current Study Result: Alternative 1	Current Study Result: Alternative 2 *(Recommended Option)*	Results Comparison
INPUT DATA						
1	Gross head	203.38 m	203.38 m	203.38 m	203.38 m	Data input
2	Net Head[1]	195.24 m	195.24 m	195.24 m	195.24 m	Calculated from gross head
3	Residual (e) flow	0.20 m^3/s (5% of mean flow)	0.58 m^3/s (10% of mean flow)	0.58 m^3/s (10% of mean flow)	0.58 m^3/s (10% of mean flow)	Data input
4	Firm flow probability exceedance	90%	90%	90%	90%	User input
5	Plant Design Discharge	**4.57 m^3/s** (30% Probability of exceedance)	**5.02 m^3/s** (30% Probability of exceedance)	**5.02 m^3/s** (30% Probability of exceedance)	**6.20 m^3/s** (25% Probability of exceedance)	Optimized optional input in Alternative 2
6	Maximum hydraulic losses	4%	4%	4%	4%	Data input
7	Plant availability	90%	90%	90%	90%	Data input
8	Generator efficiency	97%	97%	97%	97%	Data input
PLANT DESIGN RESULTS						
1	Turbine type	**Pelton**	**Pelton**	**Pelton**	**Pelton**	No change; Optimal
2	Number of turbines	**3**	**3**	**3**	**3**	No change; Optimal; Maximizes energy output
3	Configuration	**Horizontal**	**N/A**	**Horizontal**	**Horizontal**	No change; Optimal
4	Turbine efficiency at design flow[2]	88%	88%	88.2%	88.5%	Defined by RETScreen. Improved through use of RETScreen Expert
5	Turbine peak efficiency[3]	89.5	89.7	89.7%	90.1%	Defined by RETScreen; Improved
6	Firm flow	0.33 m^3/s	0.85 m^3/s	0.85 m^3/s	0.85 m^3/s	Defined by RETScreen
7	Runner speed	**428 rpm**	**N/A**	**333 rpm**	**272 rpm**	Optimized; Prefeasibility

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[1] Based on subtracting 4% of gross head as maximum hydraulic losses **Invalid source specified.**.

[2] This study used RETScreen Expert software version, which had embedded Pelton turbines that had higher turbine peak efficiency and higher turbine efficiency at design discharge. Whereas, the earlier studies by (ZESCO, 2018) and (Mukuka, 2022) had used RETScreen version 4, which had slightly lower Pelton peak efficiency and lower design discharge efficiency.

[3] This study used RETScreen Expert software version, which had embedded Pelton turbines with higher turbine peak efficiency and higher turbine efficiency at design flow. The earlier studies by (ZESCO, 2018) and (Mukuka, 2022) had used RETScreen version 4, which had slightly lower Pelton peak efficiency

S/N	Description	Previous Results (Prefeasibility study) [Source: (ZESCO, 2018)]	Previous Results (Hydrological Study) [Source: (Mukuka, 2022)]	Current Study Result: Alternative 1	Current Study Result: Alternative 2 *(Recommended Option)*	Results Comparison
						study did not optimize for jet ratio
8	Specific speed (nQE)	0.03	N/A	0.0248	0.0225	Optimized
9	Runner diameter, *D*	**1.33 m**	**N/A**	**1.71 m**	**2.10 m**	Optimized; Prefeasibility study did not optimize for jet ratio
10	Bucket Width, *B*[4]	0.39 m	N/A	0.52 m	0.58 m	Optimized
11	Number of Buckets[5]	Did not analyse	N/A	20	21	New Inclusion; Optimized
12	Number of Nozzles	2	N/A	2	2	Optimized; No change
13	Nozzle diameter, d_s	0.15 m	N/A	0.16 m	0.18 m	Optimized; Prefeasibility study undersized nozzle diameter
14	Jet ratio, m=*D/ds* (Req. 11-15[6])	8.8	N/A	11	12	Improved and optimized; Prefeasibility study undersized the jet ratio
15	*D/B* (Req. >2.7[7])	3.4	N/A	3.3	3.62	Optimized
16	Generator number of poles	**14**	**N/A**	**18**	**22**	Optimized
17	Generator Rating	**2.957 MVA**	N/A	**3.2 MVA**	**4.0 MVA**	Optimized and improved
18	Plant installed capacity[8]	**7.4 MW**	**8.20 MW**	**8.22 MW**	**10.20 MW**	Alternative 1 improved; Alternative 2 new inclusion and provides improvement
19	Unit installed capacity	2.47 MW	2.73 MW	2.74 MW	3.4 MW	Alternative 1 Improved; Alternative 2 new inclusion and provides improvement

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[4] Rule of thumb supersedes standard equation for optimization of ratio of bucket width to nozzle diameter (Acharya, 2019)

[5] Jet must always be intercepted by buckets for high turbine volumetric efficiency (Rajput, 2015)

[6] Requirement for maximum hydraulic efficiency (Zaw Oo, et al., 2019)

[7] D/B must always be greater than 2.7 for optimum design performance (Nasir, 2014) and (European Small Hydropower Association, 2004)

[8] This study used RETScreen Expert software version, which had embedded Pelton turbines that had higher turbine peak efficiency and higher turbine efficiency at design discharge. Whereas, the earlier studies by (ZESCO, 2018) and (Mukuka, 2022) had used RETScreen version 4, which had slightly lower Pelton peak efficiency and lower design discharge efficiency. This resulted in slightly higher installed power in this study.

S/N	Description	Previous Results (Prefeasibility study) [Source: (ZESCO, 2018)]	Previous Results (Hydrological Study) [Source: (Mukuka, 2022)]	Current Study Result: Alternative 1	Current Study Result: Alternative 2 *(Recommended Option)*	Results Comparison
20	Plant Annual Energy	**34 GWh**	**38 GWh**	**38 GWh**	**42 GW**	Alternative 2 new inclusion and provides improvement
21	Capacity Factor	**52%**	**52.7%**	**52.7%**	**47.1%**	Alternative 2 new inclusion; Optimized

CONCLUSIONS

This study had set out to conduct design optimization of plant capacity and turbine-generator size parameters for the Mabula Kapi run-of-river small hydropower potential site. The study had set three specific objectives, which together with their respective study findings are outlined as follows.

Objective 1: To analyze the applicable turbines' technical factors and select the most suitable type for the Mabula Kapi site conditions.

The study found that the impulse turbines were the only suitable turbine type, and, particularly, the Pelton turbine was found to be the most suitable and optimal turbine for the Mabula Kapi site characteristics and conditions.

Objective 2: To determine the optimal number of units, configuration, and plant output ratings.

The study found an optimal plant design of three installed Pelton turbines of horizontal configuration for Mabula Kapi. The design proposed two alternative plant sizes whose installed parameters are summarized as follows.

a) Alternative 1 (Based on plant design discharge of 5.02 m^3/s at 30% flow exceedance factor):
  - 3 x Pelton Turbines of 2.74 MW each; Horizontal installation configuration; Plant installed capacity of 8.22 MW, annual energy generation of 38 GWh, and capacity factor of 52.7%.

b) Alternative 2 ([**Recommended Option**] Based on plant design discharge of 6.20 m^3/s at 25% flow exceedance factor):
  - 3 x Pelton of 3.4 MW each; Horizontal installation; Plant installed capacity of 10.20 MW, annual energy production of 42 GWh; and capacity factor of 47.1%.

Objective 3: To determine the optimal main dimensions of the turbine runner and generator unit size parameters.

a) Alternative 1 (Based on plant design flow of 5.02 m^3/s at 30% flow exceedance factor; Installed capacity of 8.2 MW):
  - 3 x Pelton runner with speed of 333 rpm, runner diameter of 1.71 m, with 2 nozzles of diameter 0.16 m each, and 20 number of buckets with bucket width of 0.52 m each.
  - 3 x Synchronous 3.2 MVA generator with speed of 333 rpm, 50 Hz, 18 poles, and terminal voltage of 11kV.

b) Alternative 2 ([**Recommended Option**] Based on plant design discharge of 6.20 m^3/s at 25% flow exceedance factor):
  - 3 x Pelton runner with speed of 272 rpm, runner diameter of 2.10 m, with 2 nozzles of diameter 0.16 m each, and 21 number of buckets with bucket width of 0.58 m each.
  - 3 x Synchronous 4.0 MVA generator with speed of 272 rpm, 50 Hz, 22 poles, and terminal voltage of 11kV.

Each of the turbine-generator units had direct shaft coupling and so the turbine and generator had the same speed rating.

Alternative 2 was recommended as the more optimal technical design because of its higher plant installed capacity and higher annual energy output, which maximized energy export to the grid for the grid-connected Mabula Kapi plant. However, both plant size options were proposed for further future studies on economic and financial evaluation to aid the final decision on the better investment option.

The study results improved on the plant design rating compared to previous studies and optimized the Mabula Kapi plant capacity and turbine-generator size parameters. This study was a feasibility-level plant design rating work and its results can be used in downstream decisions for tender specifications for the proposed installed power, turbine and generator specifications for Mabula Kapi.

RECOMMENDATIONS

This design optimization study proposed two installed capacity alternatives, 8.22 MW and 10.20 MW, for the run-of-river Mabula Kapi small hydropower plant, with the 10.20 MW installation being the recommended option. However, the conducted study is only one of a series of multidisciplinary studies needed for full feasibility studies for a small hydropower site. Among the range of buildup studies needed for the Mabula Kapi site is the economic and financial analysis, and assessment of GHG emissions reduction contribution by the small hydro project. In this vein, the researcher of this current study recommends the following two future studies, with the stated purpose.

- Economic and financial analysis to evaluate the capital cost, cost-benefit ratio, pay-back period, cash flows, internal rate of return (IRR), net present value (NPV), levelized cost of electricity, and other parameters, for each alternative installed capacity, and in conjunction with other Mabula Kapi feasibility studies, such as geological study, hydraulic conduits design, environmental and social impact studies, etc. The economic and financial analysis study would help the project developer comprehensively determine the best investment solution from the two proposed alternative plant capacities.
- Greenhouse gas (GHG) emissions reductions achievable by each of the alternative installed capacity at Mabula Kapi. The GHG emissions reduction study would determine to what extent the small hydro plant would offset GHG emissions and mitigation of climate change and would offer an opportunity for carbon credit trading.

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