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Conceptual Design and Turbine Selection for a Micro Hydropower System Using Multi-Criteria Analysis

B. Jimada-Ojuolape*, M. O. Balogun, L. M. Adesina

Department of Electrical and Computer Engineering, Kwara State University, Malete, Kwara State
*bilkisu.jimada@kwasu.edu.ng

Research Article

Abstract

Nigeria has grappled with a persistent electricity supply challenge characterized by surging demand, inadequate maintenance of power generation infrastructure, and a host of other issues. This ongoing predicament has given rise to frequent power outages, compelling citizens to resort to expensive alternatives like petrol and diesel generators. Moreover, a substantial number of Nigerian households rely on motorised boreholes for their water supply. Considering these circumstances, this study proposes an innovative solution in the form of a micro hydropower system that harnesses the existing tank-borehole setups within homes to generate electricity. The primary objective of this research is to define the specifications of the central subsystem, namely the turbine, by employing the multi-criteria analysis method, thereby facilitating the practical implementation of the proposed energy generation scheme. In particular, this study delves into an evaluation of two turbine options: Pelton and crossflow turbines. The results of the analysis revealed that the crossflow turbine emerges as the most suitable choice for this application, leading to the exclusion of other turbine alternatives such as the Francis and Turgo turbines.

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Keywords
Micro hydropower; Multi-criteria analysis; Power generation; Renewable energy; Turbine selection

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1. Introduction and background

Hydropower is the energy generated from the force of water in motion. Hydropower is the world's oldest and most underrated renewable energy resource. This means of power generation started over 2,000 years ago when the ancient Greeks used water wheels to grind grains. The first hydroelectric power plant was built on the Fox River in Appleton, WI, in 1882, and as of the end of 1999, hydropower provided 19% of the world's total output power (Breeze, 2019; Haidar, Senan, Noman, & Radman, 2012). Many more hydro plants were built in subsequent decades.

Hydroelectricity generation plants can be categorised according to their electrical power capacity (Haidar *et al.,* 2012). Large hydropower plants can generate above 100MW; small hydropower can generate below 30MW; mini-hydropower can generate from 100Kw to 1MW of electricity; micro hydropower plants can generate between 5KW to 100KW while pico hydropower plants can generate a maximum of 5Kw of electrical power (Yah, Oumer, & Idris, 2017).

Severe electricity shortage has plagued Nigeria for several years. An increasing population and consequently the demand for electricity and poor maintenance of the existing power supply network contributes this problem. The generation capacity, transmission and distribution networks have severely diminished because the entire structure, most established over 30 years ago, have not been adequately maintained. Nigeria's total installed capacity is about 12,954 MW, whereas the average available capacity is about 5755 MW (Ale & Adeyemi, 2022). This implies that only 44% of the installed capacity is currently realisable. The forecasted peak load demand stands at nearly 20,000 MW (Ezennaya, Isaac, Okolie, & Ezeanyim, 2014). When compared with the forecasted peak load demand, the average available capacity value is enough to warrant a severe energy crisis.

Given the incessant power outages and load shedding, it has become imperative that Nigeria starts seeking other cost-effective ways of providing power supply. As a result of these power shortages, a substantial number of citizens, estimated at about 40% of households in the country, have become dependent on emergency power generators fuelled by diesel fuel and petrol (Nnodim, 2022). Consequently, the affected households collectively spend about $14bn annually to fuel emergency power generators, according to the report (Nnodim, 2022).

Many homes own motorised boreholes, which are used for water consumption. Water is pumped from the borehole into a holding tank as frequently as needed and if electricity is supplied to power the machine (Kuta, Emigilati, Hassan, & Ibrahim, 2014). Since the primary electricity supply from the national grid is only deficient and not totally absent, this study proposes that the pre-existing borehole arrangement can be adapted as a micro hydropower system as a backup alternative.

This study proposes a system applicable to a household or rural neighbourhood comprising a few houses with a daily generation demand of about 12kw of electricity. However, this system can be modified to power other sources, such as larger neighbourhoods, hospitals, offices, and businesses with larger demand capacities. When examining small hydropower projects as opposed to larger ones, it is crucial to streamline the investigation process, making it efficient, cost-effective, and proportional to the project's scale, emphasising aligning the methodology with the project's size and purpose (Singal, Goel, Nautiyal, & Papantonis, 2023).

Therefore, the specific objective of this study is the selection of the most appropriate turbine to achieve the proposed layout using the multi-criteria analysis method. Two turbine options namely, Pelton and crossflow turbines are specifically studied. The rest of the paper is outlined as follows: section 2 describes the materials and methods used emphasising on the multi-criteria analysis procedure. In section 3, the system design is outlined while explaining the general concept and the system architecture. In section 4, the turbine selection analysis and results are discussed in detail, while the paper is concluded in section 5.

2. Materials and Methods

2.1 System Modelling

The proposed system is modelled using systems engineering Unified Modelling Language (UML). The UML is a graphical language initially built for information systems to enable the development and maintenance processes but has been broadened for use on other types of systems (Kleins, Merkuryev, Teilans, & Filonik, 2008). The UML models consist of diagrams representing partial aspects of the entire model and describing a system's structural and behavioural aspects. Types of diagrams in UML modelling include class, object, activity, and use case diagrams. In this study, the sequence diagram is used to visualise the operational concept of the proposed micro hydropower system. The sequence diagram is mostly used to depict interactions between items in the order in which those interactions take place. The sequence diagrams are drawn using the Sparx system engineering modelling tool.

2.2 Multi-criteria analysis

The turbine system forms the most important sub-system and thus must be studied intensely. Hydro turbines are generally categorised into two groups, reaction and impulse turbines. In reaction turbines, pressurized water goes in to push the rotating element (known as the runner) and the pressure of the water changes as it moves through thereby transferring its energy to the turbine which then generates mechanical energy (Date, Date, & Akbarzadeh, 2013; Thake, 2000). They convert the potential energy of pressurized water into mechanical energy. This principle of operation can be related to Newton's third law of motion which states that "for every action there is an equal and opposite reaction". Reaction turbines are enclosed in a pressurized water container or fully submerged in water for it to operate (Sangal, Garg, & Kumar, 2013). They are applicable in low and medium head generation plants and examples of reaction turbines include the Francis propeller and Kaplan turbines.

Whereas in impulse turbines, the pressurized water is passed through a nozzle and is converted into a high-speed jet of water that strikes the blades of the turbine and causes it to rotate to generate mechanical power. Unlike the reaction turbines, impulse turbines do not need to be submerged in water. However they are enclosed in a case which just serves as a splash guard and not as a water container (Sangal *et al.,* 2013). They are applicable mainly in medium and high head generation plants and examples include Pelton and Turgo turbines.

The case study is a 12kw micro hydropower system. Due to this small capacity, choosing a turbine for use in this system can be challenging, and so some typical solutions are either to use a pump as the turbine, to make a Pelton wheel locally, to use a mass-manufactured propeller system or to use a homemade impulse type turbine.

Therefore, picking a turbine is based on some criteria, which include the turbine speed, the head, and output power. These criteria are used with a turbine application range chart to finally select a turbine suitable for the system (Williamson, Stark, & Booker, 2011). The turbine selection process is carried out using the multi-criteria analysis, a tool adopted to make a comparative assessment between various options of an entity. In this case, the entity is the turbine for the system.

The turbine selection process involves specifying requirements, developing selection criteria, performing quantitative and qualitative analyses, assigning criteria weights, and making a final selection using a Pugh matrix based on performance and practical considerations. The method includes making a calculative analysis of the available turbine types and then narrowing it down to a final choice after the completion of the method (Catrinu-Renstrom et al., 2013; Eshra, Zobaa, & Abdel Aleem, 2021; Williamson et al., 2011). The steps involved in the method are summarised in

Figure 1 .

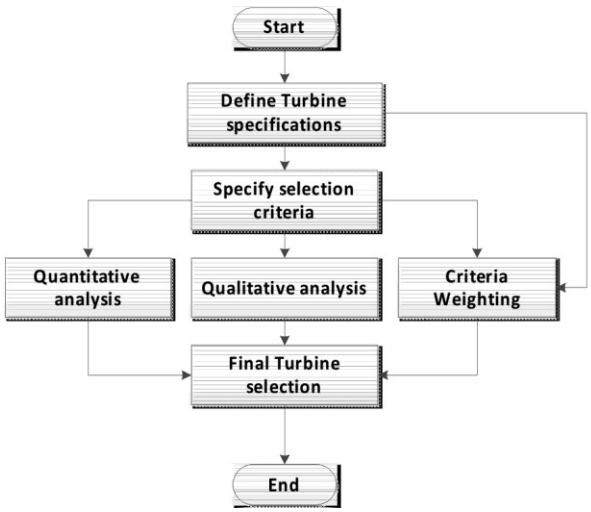


Figure 1: Multi-criteria analysis

2.2.1 Specification and selection criteria

There is a set of specifications and requirements for each turbine system. Location characteristics like head and flow rate as well as the necessary output power will be included. The turbine should require less maintenance and have a high level of reliability because it may be able to receive regular maintenance checks. A set of selection criteria can then be created using the requirements.

2.2.2 Quantitative analysis

Simple performance characteristics concerning the turbine choice are derived using simple fluid flow equations for the quantitative study. Hydropower generation is represented mathematically as Equation. (1).

$$P = \mu \times \rho \times g \times Q \times H_{gross} \quad (1)$$

where μ represents the machine's efficiency, ρ is the density of water, g is the acceleration due to gravity, Q represents the flow rate of the water, and H_{gross} is the gross head available.

A. Pelton turbine

Certain parameters need to be determined to select this type of turbine. They include the number of jets, jet diameter, Pitch Circle Diameter (PCD) of the runner, speed and gear ratios (Thake, 2000). The gross head under consideration is between the ranges of 0.5 – 12m. the flow rate is first calculated and then used to determine the jet diameter.
From Equation. (1),

$$Q = \frac{P}{\mu \times \rho \times g \times H_{gross}}$$

Considering the head values and 1 and 2 jet options, the jet and runner diameters are calculated as follows (Thake, 2000):

$$d_{jet} = \frac{17.2}{\sqrt{H_{gross}}} \times \sqrt{\frac{Q}{n_{jet}}}\ mm \quad (2)$$

$$Runner\ diameter = D \leq \frac{d_{jet}}{0.11}\ mm \quad (2)$$

where d_{jet} is the jet diameter and number of jets is n_{jet}.

B. Crossflow turbine

The parameters to be determined to check the viability of this turbine type include the corresponding values of the turbine runner diameter (Drunner) and the jet width (b0) (Harvey, Brown, Hettiarachi, & Inversin, 1993). These will be used to verify that they conform to available crossflow turbine specifications. These parameters are formulated as Equation. (4) and (5).

$$D_{runner} = \frac{41\sqrt{H}}{crossflow\ rpm}\ m \quad (3)$$

$$b_0 = \frac{Q_{max}}{0.9 \times \sqrt{H} \times D_{runner}}\ m \quad (4)$$

$$crossflow\ rpm = \frac{generator\ rpm}{gear\ ratio} = \frac{1500}{2} = 750\ rpm$$

where H represents the head while Q_{max} represents the maximum flow rate.

2.2.3 Qualitative criteria

Well-defined criteria are used in the qualitative analysis step of the turbine selection process to evaluate numerous qualitative features. Each criterion is defined precisely and clearly, and it is assessed using a scoring system that ranges from 1 (which denotes poor) to 5 (which denotes excellent). A distinctive score method is defined for each unique selection criterion. When a criterion covers several different features, sub-criteria are developed to fully specify each of these elements. Then, using either an arithmetic mean or a weighted mean approach, these sub-criteria are combined to produce a single score for the main criterion.

2.2.4 Criteria weighting and Final selection

The qualitative scores and the results from the quantitative analysis are normalised against the maximum value of 5. To determine a final score for each turbine solution, these weightings are compounded by the normalised values from the quantitative and qualitative studies. After analysing the results, a suitable solution can be selected using the Pugh matrix tool.
A conceptual technique known as a Pugh matrix examines and quantifies many design concepts with the aim of choosing an overall ideal configuration based on predetermined criteria (Motato, Mohammadpour, Theodossiades, Rahnejat, & Kelly, 2019). Pugh matrix has some benefits. First off, it enables designers to assess many options at the conceptual stage for either additional researchor testing and development. Additionally, it offers the advantage of acquiring alternate designs if the chosen design has certain flaws. Additionally, it has the potential to save time and money because the consequences of implementing an infeasible product would be unfavourable. This technique is shown in the flow chart in
Figure 2.



Figure 2: Pugh Matrix technique

The method described above is demonstrated using the case study in the sections that follow.

3. System Design

3.1 Preliminary Concept

The concept is represented in a block diagram illustrated in Figure 3.

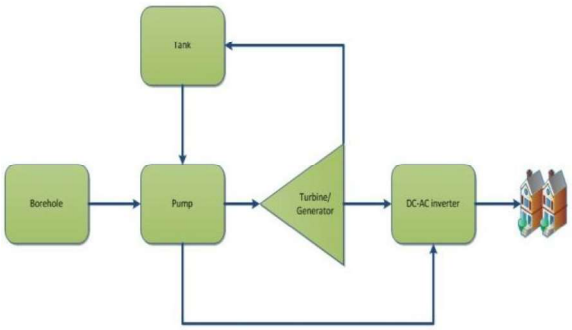


Figure 3: Block diagram of the preliminary concept

When the system is turned on, water from a borehole is pumped and pressurised into an overhead storage tank. When the overhead tank has attained a certain volume, water is cut off from the borehole via a cut-off valve, and the overhead tank feeds water into the turbine-generator system when it is to supply the house or community. Electricity is generated and transmitted into a DC-AC inverter, which will interface the generation system and the house. This layout is illustrated in Figure 4.

According to a rural household survey, rural areas in Nigeria have 2 different load profiles: areas that have access to electricity from the national grid and areas that do not. Essentially, the areas without access to electricity from the national grid consume about 1.583kw/day and areas with connections to the grid consume about 2.325kw/day (Adeoti, Oyewole, & Adegboyega, 2001). Factors contributing to a higher demand value in areas connected to the grid include more appliances, longer usage of their appliances and the use of appliances with higher power ratings (Adeoti *et al.,* 2001). Assuming there are 5 households to be fed by the system and using the profile of the rural area connected to the grid (2.324kw), total demand capacity will be a value of;

$$2.324 \times 5 = 11.5 \cong 12kw$$

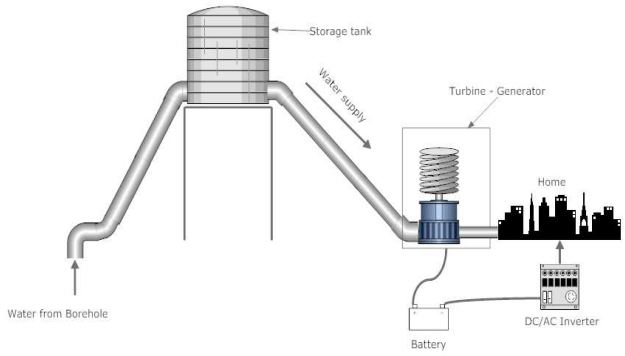


Figure 4: Layout of the proposed system

3.2 System Architecture

In this section the system architecture is described. This includes the baseline concept and the operational concept.

3.2.1 Baseline Concept

The UML metamodel in Figure 5 shows the structure of the system. The hydropower system is composed of 1 or more tanks, 1 pump, 1 turbine, 1 generator sub-system and a controller. The system depends on the borehole as the water source and is associated with the inverter, which is the interface between the system and the house.

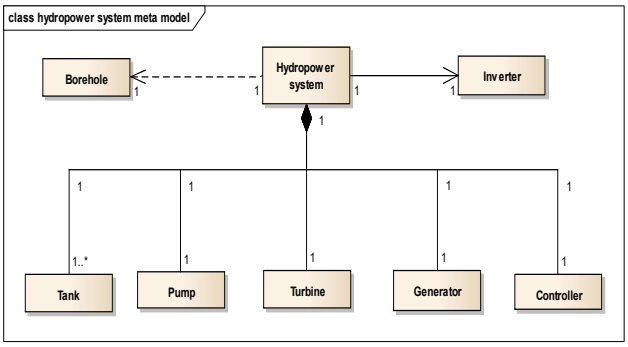


Figure 5: Meta model of the baseline concept

3.2.2 Operational Concept

A. Initial starting

The operator (can be any unskilled/ semiskilled/ skilled individual, perhaps the owner of the house or any authorised person) turns the system on, and the controller conducts a self-check to know the status of the sub-systems. The controller then constantly checks the volume status of the holding tank, which will be 0 m3 initially (i.e., empty), and because this is so, the controller then switches on the pumping system to pump water from the borehole into the turbine system. The turbine generates power, which is transmitted to the inverter system that serves as the interface between the generation system and the house. A sequence diagram representing the sequence of events during its initial starting operation is illustrated in Figure 6.

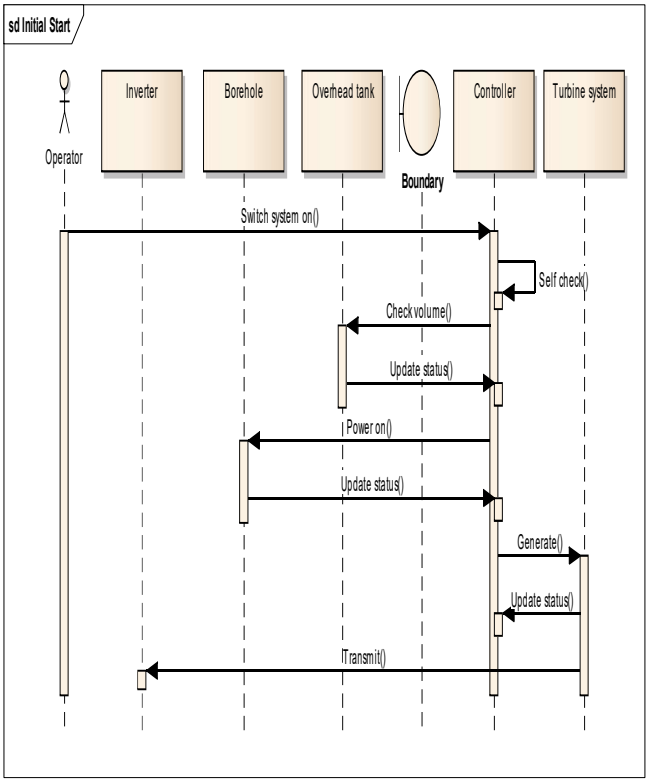


Figure 6: Sequence diagram illustrating the initial starting of the system

B. Continuous operation

Following the system initialization, after some time, the tank would have stored an equivalent of the water required to power the system, so the flow sensor in the tank, sends a message to the controller updating the status of the tank volume. The controller then switches off the borehole and opens the valves on the tank to allow the flow of water, thereby recycling the water in the tank and using it to generate the power. A diagram describing the sequence of events is shown in Figure 7.

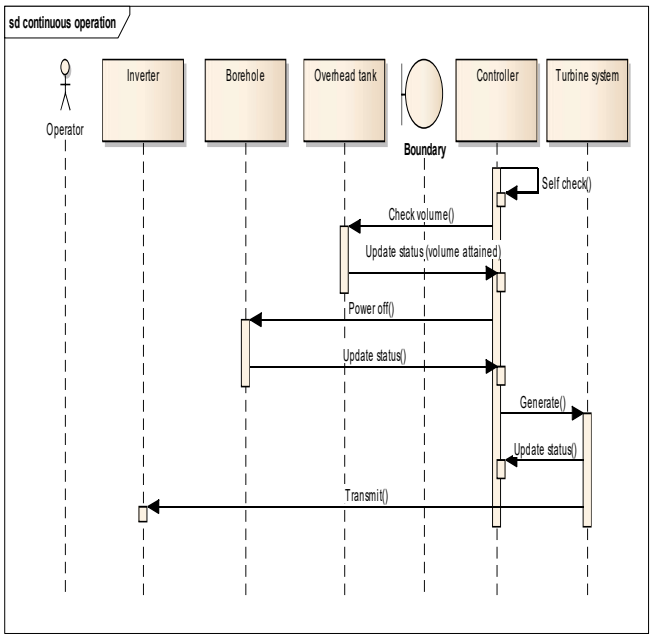


Figure 7: Sequence diagram illustrating the continuous operation of the system

4. Analysis and Results

4.1 Turbine specification

The specification for the turbine based on the case study capacity of 12kw are highlighted in Table 1.

Table 1: Turbine specification

Power	12kw
Head	ranges from 0.5m to 12m
Portability	should have the ability to be transported easily to different locations with limited transport infrastructure
Reliability	High reliability for low-maintenance operations
Frequency	50Hz output frequency from the generator
Maintenance	servicing and maintenance carried out with unskilled labour
Flow rate	Varying flow rate
Modularity	Easy fault identification and system component replacement
Civil works	very minimal civil work. Hardly any concrete

4.2 Selection criteria

The selection criteria considered for the quantitative and qualitative analysis are shown in Table 2 and Table 3.

Table 2: Quantitative criteria

Efficiency	efficiency of the unit at rated and part flow/head
Power	power of the unit must be 12kw
Head	options of 0.5m – 12m
Flow rate	Varying flow rates

Table 3: Qualitative criteria

Portability	easy to transport between different locations
Civil work	hardly any concrete
Modularity	The unit must be highly modular so the components can be easily taken apart and reassembled for maintenance, replacement and easy transportation.
Serviceability	The unit must be easy to service and maintain with unskilled labour
Cost	The unit must be as economical as possible, i.e., the cheapest option.

4.3 Quantitative analysis

The appropriate turbines that can be used for this system are the crossflow, Francis and Kaplan turbines from Figure 8 (Penche, 1998). However, from Table 4, it can also be seen that the turgo, multi-jet Pelton and pump-as-turbine (PAT) options are also possible (Paish, 2002). In this subsection, each of the possible turbine types are justified quantitatively.

Table 4: Turbine classifications per Head

Turbine type	Head classification		
	High (>50 m)	Medium (10-50 m)	Low (<10 m)
Impulse	Pelton Turgo Multi-jet Pelton	Crossflow Turgo Multi-jet Pelton	
Reaction		Francis (spiral case)	Francis (open-flume) Propeller Kaplan

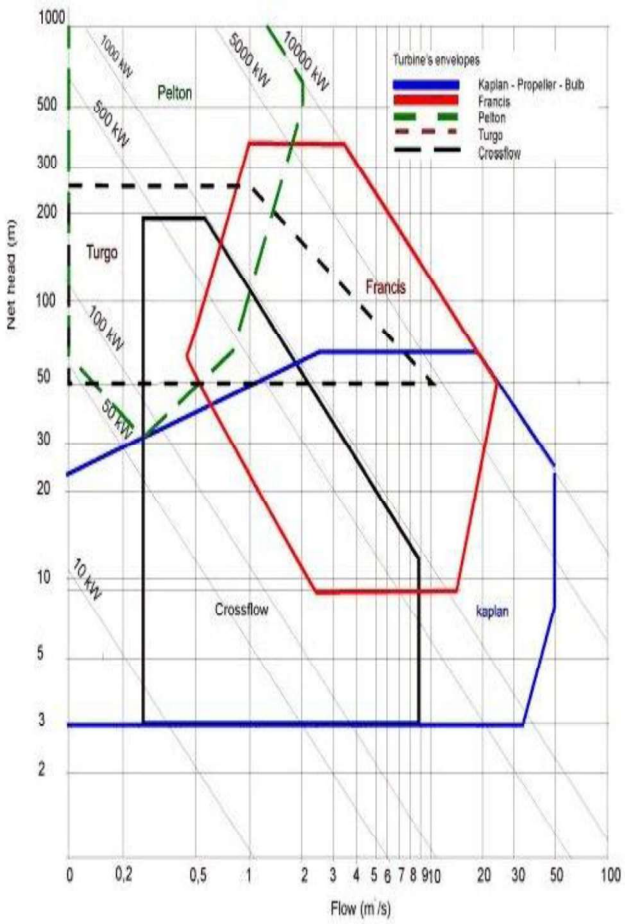


Figure 8: Turbine application range chart

4.4 Pump-as-turbine

In the pump-as-turbine option, it is difficult to find the correct turbine operation curves compared to regular turbines that are available; they generally have lower efficiencies, do not permit variable flow rates, and their processes are not as well documented as the regular turbines (Teuteberg, 2010).

4.5 Pelton turbine

Pelton turbines have runner PCDs between 100mm and 400mm for micro hydropower applications (Thake, 2000). The jet and runner diameters are calculated based on Equation (2) and (3) and the results are presented in Table 5. From the analysis of Table 5, the Pelton turbine has unreasonably high runner PCD values based on the calculated jet and runner diameters. These high values resulted from the medium and low head range, i.e., 0.5 – 12m. Increasing the head will mean that the costs will increase because it will cost more to mount the tank in a higher position.

Table 5: Pelton turbine analysis

Pelton		d_{jet} (mm)		D (mm)	
H (m)	Q (m^3/s)	n_{jet} = 1	n_{jet} = 2	n_{jet} = 1	n_{jet} = 2
0.5	4.897959	1431.5	1012.23	13013.64	9202.091
1	2.44898	851.18	601.88	7738	5471.636
3	0.816327	373.33	263.98	3393.909	2399.818
6	0.408163	221.98	156.97	2018	1427
9	0.272109	163.77	115.81	1488.818	1052.818
12	0.204082	131.99	93.33	1199.909	848.4545

4.5 Crossflow turbine

The crossflow turbine has specifications of Drunner = 300 mm (0.3m) and b0 = 324 mm (0.324m) (Harvey et al., 1993) and so the closest match to these values is the 12m head option. So, considering this scheme, the values from Table 6 can be modified to meet the standard values using eqn. (3) as follows:

$$New\ crossflow\ rpm = \frac{41\sqrt{H}}{D_{runner}} = \frac{41\ \times\ \sqrt{12}}{0.3}$$
$$= 473\ rpm$$
$$New\ gear\ ratio = \frac{1500}{473} = 3.17$$

And finally, referring to eqn. (4), the new jet width is:

$$b_0 = \frac{0.2}{0.9\ \times\ \sqrt{12}\ \times 0.3} = 0.214\ mm$$

These calculated values are applicable to this particular 12m head, 12kw capacity hydropower scheme. This value can be recalculated and applied to any other required scheme. A standard gear ratio of 2 is appropriate since the required generator speed is 1500 rpm to generate at 50 Hz.

Table 6. Crossflow turbine analysis

H (m)	Q (m3/s)	D runner (m)	b0 (m)
0.5	4.897959	0.038655171	199.104032
1	2.44898	0.054666667	49.776008
3	0.816327	0.094685444	5.53066755
6	0.408163	0.133905439	1.38266689
9	0.272109	0.164	0.61451862
12	0.204082	0.189370888	0.34566672

4.7 Qualitative Analysis

The qualitative criteria include cost, portability, maintenance, modularity and civil works.

i. Cost: This is the price of the turbine. From the range of costs in

Table **7**, the cheapest options are the crossflow and the multi-jet Pelton turbines.

ii. Portability: This is the capability that the turbine can easily move from point to point. This is a criterion because the system will need to have this capability because it must be moved to its point of sale and place of use.

iii. Maintenance: This refers to how easily maintainable the turbine unit is. It is closely related to the modularity.

iv. Modularity: This refers to how easy it is to disassemble the unit when it needs maintenance or parts replacement.

Table 7: Costs of turbines in units of $1000 (Harvey *et al.*, 1993)

Shaft Power (kW)	Cross flow	Francis	Single-jet Pelton	Multi-jet Pelton	Turgo	Propeller
2	1 – 2	4 – 6	1 – 4	1 – 3	2 – 4	4 – 6
5	2 – 6	8 – 10	2 – 8	2 – 6	5 – 8	8 – 10
10	2 – 10	15– 20	2 – 15	2– 10	8– 14	15– 20
20	3 – 14	20– 30	3 – 20	3– 15	12– 20	20– 30
50	5 – 30	25– 70	5 – 50	5– 30	35–50	25– 70
100	30– 50	40–100	40– 80	15– 60	55– 80	40– 100
150	50– 80	60–120	60– 100	30 – 80	80 – 100	60– 120

4.8 Criteria Weighting

The criteria weightings are used as a guide during the final turbine selection process when populating the Pugh matrix. The criteria considered and the respective weightings, as well as the reasoning behind the weightings, are shown in Table 8.

Table 8. Criteria weightings

S/N	Criteria	Weightings	Reasoning
	Power Capacity	0.18	These criteria represent the quantitative aspects and hence have been scored higher than the others, with 'power capacity' being the highest because it is the most important.
	Efficiency	0.14	
	Head	0.14	
	flow rate	0.14	

	Cost	0.12	Cost is also important, so it scored higher than the other qualitative criteria.
	Maintenance	0.07	These are the qualitative criteria and scored lower than the quantitative ones.
	Portability	0.07	
	Modularity	0.07	
	Civil works	0.07	

4.9 Final Turbine Selection

The Pugh matrix illustrates the final decision-making process to choose a suitable turbine. The crossflow turbine has been chosen as the baseline concept because it showed the best results for this scheme based on the analysis in the previous sub-section; other options are considered against the crossflow turbine for final selection.

Table 9: Pugh matrix analysis for turbines

Criteria	Scores	Crossflow	Francis	Kaplan	Turgo	Multi-jet Pelton	PAT
Power	0.18	12	12	12	12	12	Less for scheme
Efficiency	0.14	70	80	85	75	75	50
Head	0.14	Adequate	Adequate	Varying	No varying	Needs high head	No varying
flow rate	0.14	Adequate	No varying	No varying	No varying	Needs low flow	No varying
Cost	0.12	3 to 14	20 to 30	20 to 30	12 to 20	3 to 15	-
Maintenance	0.07	Easy to maintain	Hard to maintain	Easy to maintain	Hard to maintain	Easy to maintain	Easy to maintain
Portability	0.07	Portable	Not Portable	Not Portable	Portable	Portable	Portable
Modularity	0.07	High	low	High	low	High	High
Civil works	0.07	Not much needed	Needs concrete	Needs concrete	Not much needed	Not much needed	Not needed

It is observed from Table 9 that the only option better than the baseline for this scheme is the pump-as-turbine option. The PAT option has the negatives for the quantitative criteria. As stated previously and referring to Table 8 the quantitative criteria have more weightings, so where the PAT lacks power, efficiency and flow rate, the crossflow automatically has more significance. The best turbine option is therefore the Crossflow turbine. Table 10 shows the full analysis.

Table 10: Pugh matrix for final turbine selection

Criteria	Crossflow	Francis	Kaplan	Turgo	Multi-jet Pelton	PAT
Power capacity	S	S	S	S	S	-
Efficiency	S	+	+	+	+	-
Head	S	+	S	-	-	S
flow rate	S	-	-	-	-	-
Cost	S	-	-	-	S	+
Maintenance	S	-	S	-	S	S
Portability	S	-	-	+	S	+
Modularity	S	-	+	-	S	+
Civil works	S	-	-	S	S	+
Total +	0	2	2	2	1	4
Total -	0	6	4	5	2	3
Total score	0	-4	-2	-3	-1	1

5. Conclusion

This study has proposed a concept for possible decentralization of the power supply chain from a central grid and easily delivering power to individual homes or rural areas by designing a portable micro hydropower system. The focus of this paper is the determination of a suitable turbine type for the scheme. A simple layout is suggested that includes a water tank and a compact generator-turbine unit. The pelton and crossflow turbine types were analysed using the multi-criteria analysis method and compared with other turbine types such as the PAT, Francis, Kaplan and Turgo turbines. It was found that PATS generally have lower efficiencies and do not permit variable flow rates. The results show that the Pelton turbine has unreasonably high runner PCD values which makes the turbine heavier and more expensive for the application. Thus, the Crossflow turbine proves to be the ideal choice for this system because of its portability, high adaptability,

and cost-effectiveness in comparison to the alternatives, which were carefully evaluated. This study can serve as a guide for any system designer willing to undertake the realisation of this type of scheme.

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