Application of Crossflow Turbine in Off-Grid Pico Hydro Renewable Energy System

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Abstract:– This paper reviews small-scale hydro turbines and their applications at power production environment while focusing on the application of cross-flow turbine in pico hydro set-up, a run-of-river scheme which does not require dam or reservoir for water storage. The main criteria of the turbine are set to be cost effective, reliable, and environmentally friendly, which can be manufactured locally and capable of operating at wide range of flow rate. A cross-flow turbine has been considered, designed and fabricated based on data provided at site located within Universiti Kebangsaan Malaysia. The turbine is capable of producing up to100 W DC power at the head of 1.2 m and flow rate of 20 L/s. Cost of energy is at RM0.501 per kWh, which is reasonable compared to the lowest tariff set by the government at RM0.218. Cost of energy comparison between other power productions systems are done to find the feasibility of the system. The results show that pico hydro could play important role in providing the basic necessity to the off-grid rural folks.

Keywords: – cross-flow turbine, pico hydro, renewable energy, run-of-river, small-scale hydro

1 Introduction

The hydropower plant can be classified according to the size of electrical power it produces as shown in Table 1. High electricity demand for industry and household require the plant to produce as large power as possible to justify the capital it used. As a result most hydropower available around the world can be categorized as large hydro.

Table 1: Classification of hydropower

Power	Class
> 10 MW	Large
< 10 MW	Small
< 1 MW	Mini
< 100 kW	Micro
< 5 kW	Pico

This large reservoir or dam leads to environmental damages and remove people from their roots as experienced in the development of Three Gorges Dam in China. Furthermore the capacity of this large plant will be reduced after a number of years due to sedimentation built-up. This leads most experts to agree that hydropower of more than 1 MW cannot be considered as renewable.

While the capacity of micro and pico hydro may be small compared to other higher hydropower classes, they have made significant contribution in electrification program to remote and off-grid settlements. Currently power generation at these areas are provided using diesel or petrol generator, which operating hours are limited with high cost of fuel due to transportation cost and the scarcity of the fuel at these remote locations. This small-scale hydropower ensures the community is light-up at night, continuously. The system does not require dam, which is one of the advantages, meaning no environmental problem. It uses run-of-river application method through penstock to provide the necessary head and flow rate to the turbine.

A hydro system capable of producing the electricity up to 5 kW is categorized as a pico hydro. There will always be a tradeoff between head and the flow rate. If the stream is small, the flow rate is usually low, which will require high head to ensure the turbine to provide enough power as required, and vice-versa. This paper will focus on the pico hydro turbine, its status, the turbine technology, choice of turbine in low flow and low head environment and its application in renewable energy system set-up.

1.1 Status and Applications

Developing countries provide at least 70 percent economically feasible sites for hydropower plant [1]. This is referring to large-scale (mini to large classes) hydropower plant. In Malaysia there is 2400 MW Bakun project with several other mini hydro worth about 40 MW while technically seen to have another 29000 MW potential of hydropower [2]. However the capability of small-scale hydropower scheme is not included despite the availability of potential sites which could benefit the rural community tremendously.

Malaysia has many rivers, big and small, which are capable of producing electricity especially to off-grid settlements living nearby. Even sites with low head (less than 10 m) are worth looking at for their potential [3]. Due to seasonal variation of depth of these small rivers it is important to choose appropriate turbine for specific locations. Therefore selection criteria of the turbine need to be clarified to suit the head and the flow rate. Several renewable energy hybrid systems using small scale hydro were being tried at various locations. Among them is a project at Taratak Indonesia, which has been successfully in operation using a head of 5.5 m and discharge rate of 240 l/s [4]. Another in Cameroon, a water turbine of 5 kW capacity with available head of 10 m and flow rate of 92.6 l/s is used to provide 24 V DC system [5].

Some comparisons between pico hydro and solar powered systems have been made to evaluate the feasibility of the renewable energy resources by Maher et al. [6] in the off-grid electrification options in rural Kenya. Similar assessment was made by Nunes and Genta [7] at bigger micro hydro turbine (up to 100 kW) for off-grid electrification program in Uruguay. Both hydro systems are cost effective compared to using the solar panels when the settlements are located near river. Therefore small-scale hydro system should be considered, whenever available, due to cost and environmental concerns [8].

2 Methodology

2.1 Turbine Technology

Each potential site for small-scale hydropower scheme is considered unique since turbine selection is based mostly on the water head and the available flow rate. In most cases if the head is small the flow rate should be higher. The penstock and turbine should be increased proportionally to support the increment [9]. Due to the uniqueness of a specific location it is important that steps are taken to find successful approaches to provide standardized equipment, engineering designs and implementation methods specifically for a particular location [10].

The power produced by hydropower turbine can calculated using the following equations:

$$P = \eta \rho g H Q \quad (1)$$

$$H = h - h_f \quad (2)$$

$$h_f = f\frac{LV^2}{D2g} \tag{3}$$

$$\eta = \eta_{turbine} x \eta_{generator} \tag{4}$$

Or approximately:

$$P = 7.8HQ \tag{5}$$

P = power output
η = total efficiency
ρ = density
g = gravitational constant
H = net head
Q = flow rate
h_f = head friction loss
f = Darcy friction factor
L = pipe length
V = jet velocity
D = pipe diameter

There are two types of turbines to be considered, impulse and reaction turbines. In most cases impulse turbines are used for high head sites, and reaction turbines are used for low head sites. Impulse turbine is embedded in the fluid and powered from the pressure drop across the device. Pelton and Turgo turbines are suitable for high head, which is larger than 50 m, and medium head ranging between 10 and 50 m. Crossflow turbine is suitable for medium and low head, which is less than 10 m. Reaction turbines operate with the flow hits the turbine as a jet in an open environment, with the power deriving from the kinetic energy. Francis turbine is used in medium head scheme while propeller and Kaplan turbines are suitable for low head applications.

Pelton Wheels and propeller turbines could also be used for low head hydro systems, which is capable of producing power between 0.2 – 20 kW at head range of 2 – 40 m [11][12]. In hydro system with small head and modest flow rate, using turbines such Kaplan or Francis turbines, which has high initial capital cost, could lead to designing problem. Montanari [13] suggested that propeller turbines or Michell-Banki (crossflow) turbines due to their costs and potential power produced.

Fig. 1 [8] shows the range of suitability of various types of turbines based on the flow rate and net head. Propeller, Kaplan and crossflow turbines are suitable for low head low flow applications. Fig. 2 [14] shows the efficiency of typical small scale hydro turbines relative to turbine flow relative to their design flow. Crossflow turbine has significant advantages over other turbines if the flow rate varies a lot during seasonal variations.

Nunes and Genta [7] compared the cost of using axial flow and cross-flow turbines in small scale hydro system. They found out the cross-flow turbine costing per unit kW produced is less in all three categories involved. They are for power less 200 kW, for power more than 200 kW and grid connected applications. Williams [15] suggested the use of small centrifugal pump together with induction motor as turbines for low cost small-scale hydro power application.

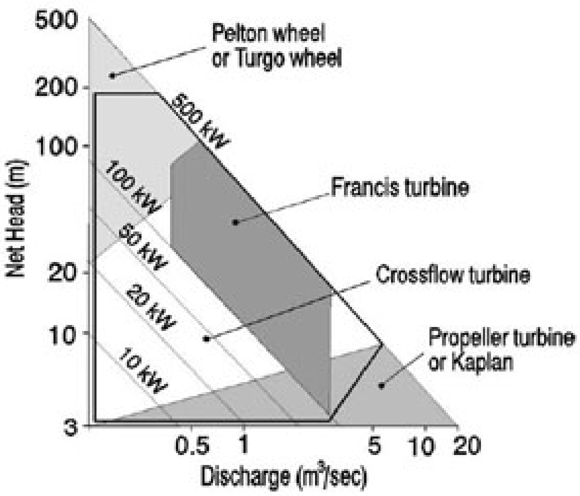

Fig. 1: Head-flow ranges of small hydro turbines [8]

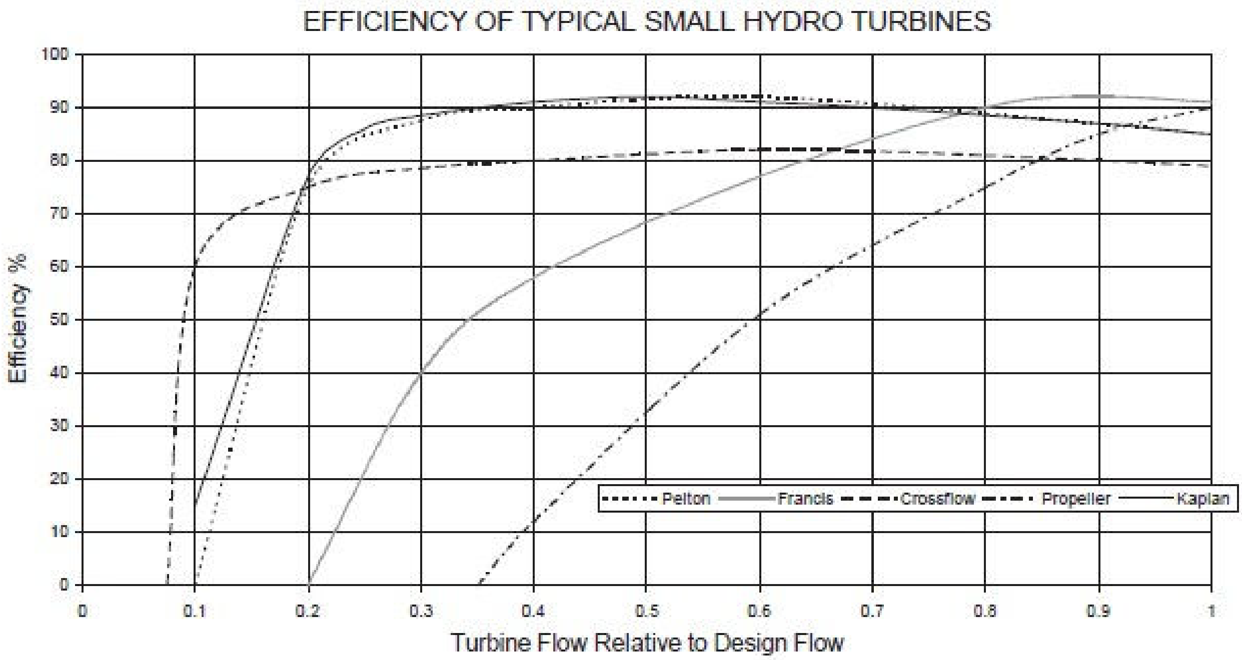

Fig. 2: Efficiency of small hydro turbines [14]

Specific speed of the turbine is another selection criterion to be considered. The specific speed is a determining factor for appropriate turbine speed. This is important to derive the correct gear ratio needed in producing the required generator speed for either charging the battery or providing directly to load. The correlation between specific speed and net head are given for the following turbines [16]:

Crossflow:

$$\eta_s = \frac{513.25}{H^{0.505}}. \tag{6}$$

Propeller:

$$\eta_s = \frac{2702}{H^{0.5}}. \tag{7}$$

Kaplan:

$$\eta_s = \frac{2283}{H^{0.486}}. \tag{8}$$

Investigation on the nozzle flow in a crossflow turbine shows no effect of changing the runner from 25 to 10 [17]. The diameter of the runner, D, for crossflow turbine can be calculated based on the turbine shaft speed, n, and net head, H, while the length of the runner, L, based on flow rate, Q, net head and jet thickness, t_j, which is usually between one tenth and one fifth of runner diameter [18].

$$D = 40\frac{\sqrt{H}}{n} \tag{9}$$

$$L = \frac{0.23Q}{t_j\sqrt{H}} \tag{10}$$

2.2 Test Site Location

A site within the Universiti Kebangsaan Malaysia campus (Fig. 3) at Bangi, Selangor has been selected for test study. A natural pond with continuous water flow is used as the source for water intake. Local weather data are used in consideration of turbine selection.

2.3 Pico Hydro System

The pico hydro system consists of a crossflow turbine, gear system, alternator, charge controller and a set of battery as storage, as shown Fig. 4. The crossflow runner diameter is 450 mm and the length of the blade is 300 mm. A fixed nozzle is built within the system to guide the flow of water through the turbine while hitting the blades twice, optimally at 10 and 5

ISSN: 1790-2769

ISBN: 978-960-474-150-2

o'clock. Several ratios of gear system, 12:50, 12:70 and 12:108, were used to find the optimum arrangement for charging the battery.

The initial capital cost for pico hydro turbine is RM2320 which include some civil works. The turbine is estimated to last the project lifetime at 25 years with little maintenance. The water flow rate is assumed to be constant all year at 20 L/s. The turbine has a nominal power of 0.1 kW.

Fig. 3: Test site at Universiti Kebangsaan Malaysia

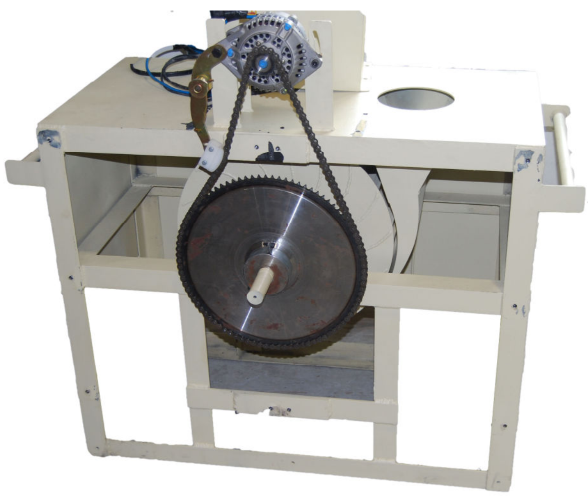

Fig. 4: Pico hydro turbine system

2.4 Loading

Loading used in the calculation is the typical off-grid community basic lighting needs as shown Fig. 5. The peak load happen at night at 0.1 kW. Adding hourly noise at 20% and daily noise at 15%, the total daily load is 1.67 kW.h with a peak of 193 W.

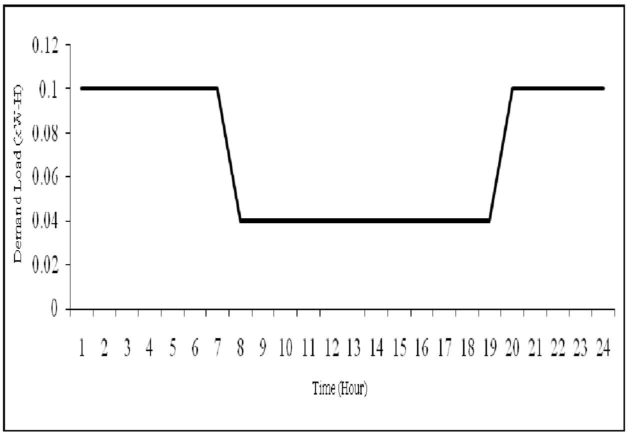

Fig. 5: Loading

2.5 Battery

The valve regulated lead acid battery is rated at 2 V and has a capacity 500 Ah. Only one battery is required, which is initially cost RM815. The operation and maintenance cost add further RM12 to the total cost annually.

2.6 Power Output

By charging the battery, the system is ready for sudden jump of load, especially at night, when the demand is at its peak. This procedure is to avoid having generator as back-up. The requirement is also depends on the amount of demand load being set. The system is producing a maximum of 69 W power. This is equivalent of 1.7 kW.h daily and about 47 kW.h monthly. This power is slightly more than 300 W peak output PV system, which will deliver about 42 kW.h per month.

3 Results and Discussions

Based on the experiment results as shown in Table 2, the gear ratio of 12:108 provides the best output with enough power to charge the battery. The alternator as a generator produces a maximum of 15.25 V in 12 V DC system. In order to charge the battery the system needs to produce at least 13 V for 12 V DC system. However the power produced by 12:70 gear ratio is enough to light-up the electrical load which is attached directly to the system. The maximum power is expected to reach 100 W when the head is at 1.2 m with flow rate of 20 L/s.

Table 2: Power generation by gear ratio

Ratio	Voltage (V)	Current (A)
12:50	**9.50**	**3.10**
12:70	**11.20**	**3.74**
12:108	**15.25**	**4.52**

Fig. 6 shows the simulated power output based on 1 m head with varying flow rate. The power output could reach up to 360 W for flow rate of 30 L/s. This is based on the gear ratio of 12:108. Increasing the head would definitely change the curve upward, resulting higher power produced at a particular flow rate.

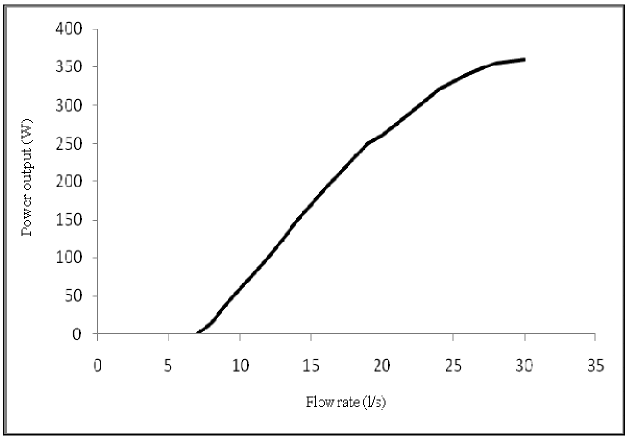

Fig. 6: Power output at 1 m head

3.1 Pico Hydro Turbine Energy Cost

The breakdown of cost of power production for pico hydro turbine is as shown in Table 3. The critical value is cost of energy (COE) is RM0.501/kWh, which can be compared to the tariff set by the government with the minimum at RM0.218/kWh and maximum at RM0.460/kWh.

Table 3: Cost and energy production for pico hydro turbine

Item	Value
Initial cost	RM3220
Total annualized per year	RM305
Total net present cost	RM3898
Total annual energy production	920 kW.h
Total load served	609 kW.h
Excess electricity	311 kW.h (34%)
Cost of energy	RM0.501/kWh

3.2 PV Energy Cost

The PV panels with a capacity of 300W are incapable of providing for the daily load of 1.67 kW.hr. The number of PV panels has to be increased to produce power of 0.7 kW and the battery quantity is increased to 5 leading to the substantial cost rise. The breakdown of the cost of power production for PV panels is as shown in Table 4. The COE is too high at RM2.633/kWh.

Table 4: Cost and energy production for PV panels

Item	Value
Initial cost	RM15600
Total annualized per year	RM1603
Total net present cost	RM20463
Total annual energy production	1069 kW.h
Total load served	609 kW.h
Excess electricity	460 kW.h (43%)
Cost of energy	RM2.633/kWh

3.3 Generator Energy Cost

In order to provide for the daily load of 1.67 kW.hr a generator system with a capacity of 0.2 kW is required. Most generators of this capacity have a lifetime operating hours of 15000. Since it is operating continuously, the generator will be replaced at least once. The breakdown of cost of power production for generator is as shown in Table 5. The COE is reasonable enough at RM1.716/kWh. The initial cost is quite misleading since the generator uses diesel or petrol to produce power. The fuel cost varies from time to time but mostly in upward trend.

Table 5: Cost and energy production for generator

Item	Value
Initial cost	RM200
Total annualized per year	RM1045
Total net present cost	RM13354
Total annual energy production	701 kW.h
Total load served	609 kW.h
Excess electricity	92 kW.h (13%)
Cost of energy	RM1.716/kWh

Since the derivation of COE is based on the amount of total load served, COE can be further reduced by minimizing the excess energy [19]. If the total power produced is fully utilized, COE for pico hydro system, PV panels and generator will be decreased to RM0.332, RM1.500 and RM1.491 respectively.

Those are reductions of 34%, 43% and 13%. The COE number produced by pico hydro system is worth to look into.

4 Conclusion

One of the main reasons the crossflow turbine is selected in this research project is due to it can be fabricated locally. The maintenance and repair can be done by the local people, meaning the actual total cost will be kept relatively low. Imported turbine will be subjected to taxes, cost of maintenance and non existence technology transfer.

Each site is unique as it derives the power potential of the location and the selection of suitable turbine which is based on the head and flow rate of the water. Crossflow turbine is suitable for low head application and most preferable when there is large variation of flow rate due to seasonal change.

Comparing pico hydro turbine system with other alternative power-producing systems at off-grid community, where water flow is available, leads to a COE low enough to be accepted as alternative to grid connected tariff. Currently used generator set will cost three times as much if operated continuously.

Correct sizing of components is important since oversizing means overproducing the required power. High excess energy leads to high COE. Steps need to be taken to minimize the excess energy while optimizing the system. Using a single component usually leads to oversizing. A hybrid system, which requires optimization, could reduce the probability of having high excess energy.

As shown in Fig. 3, works currently are undertaken to incorporate the pico hydro, PV panels and wind charger as a hybrid renewable energy system, and generator as a back-up to charge the battery. Instead of using the battery as storage, it is used to supply DC current to provide electricity to off-grid community. All three renewable components and generator are designed to charge the battery set to provide enough power to meet the demand load. Based on the loading optimum sizing of each of the hybrid components and suitable operation strategy for each optimum combination will be decided.

Acknowledgment

The authors would like to thank the Universiti Kebangsaan Malaysia and Ministry of Higher Education of Malaysia for financial assistance on this research project.

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