Operation, performance and economic analysis of low head micro-hydropower turbines for rural and remote areas: A review

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ABSTRACT

Electrical power is essential in commercial, economic and social investments especially in emergent countries. Hydropower energy has become one of the most suitable and efficient sources of renewable energy, though it has taken more than a century of experience to actually generate efficient electricity for supply. Nowadays, most rural areas in developed and developing countries use cheap and effective micro-hydropower plants for producing electricity. To achieve more efficiency, researchers are looking forward to using simple turbines for achieving good performance with minimum initial and running cost, for utilization especially in poor countries. This paper presents a review of low head micro-hydropower turbines; focusing on categories, performance, operation and cost.

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1. Introduction

Water is a clean, cheap and environment friendly source of energy generation which is of significant value for sustainable future [1]. Hydropower has been utilized for more than a hundred
years, and undeniably being the most efficient and confident source of renewable energy [2]. Hydropower contributes to 19% of total global output of electricity by the end of 1999, which produced 2650 Terawatt hour (TWh) [3]; later producing almost 3100 TWh in the beginning of 2009 and is expected to reach 3606 TWh in 2020 [4]. According to United Nations Development Program (UNDP), 1.4 billion people still remain without access to electricity [5], notably in poor areas in developing countries [6]. Generally, a large dam with high capital cost is required to produce sufficient power supply. Low head micro-hydropower stations present an attractive and efficient way for electricity generation in rural, remote and hilly areas because of the increment in the level of greenhouse gas emissions and fuel prices in these sites and they have become increasingly popular for application at small rivers [7–10]. Micro-hydropower schemes can be used to generate enough electrical power for home, farm, and plantation or for small village [11]. They can also be used in mechanical end-uses like agro-processing, textiles fabrication, ice cream production, cooling, and drying [12]. The main advantages of low head micro-power system are that it is predictable if enough water supply is available [13] and possesses positive environmental impacts [14]. Therefore, the system has become the main interest for future hydro-developments in Europe, where large-scale stations have indeed been utilized but in return giving negative effects to the environment [10,14]. Most low head micro-hydropower plants generate power less than 100 kW [15–18], but there are also other categories with classification below 500 kW [10] and < 10 m head [19]. The general formula for any hydropower system output is [16]

\[ P = \eta \rho g Q H \]  

where \( P \) is the mechanical power produced at the turbine shaft (watts), \( \eta \) is the hydraulic efficiency of the turbine, \( \rho \) is the density of water volume (kg/m³), \( g \) is the acceleration due to gravity (m/s²), \( Q \) is the flow rate passing through the turbine (m³/s) and \( H \) is the effective pressure head of water across the turbine (m).

Recent publications raise the importance of using simple turbines to achieve minimum cost to produce power [8]. Installation of large and mini hydropower plants with dams, huge reservoirs, large turbines, electrical equipments and controllers have been proven very expensive, uneconomical and negative environmental impact. Though intended as clean and cheap source of energy generation, many developing countries that are in need of rural electrification are instead exposed to economic problem when installing this costly hydro-equipment [20]. Using micro-hydropower with new design and arrangement of these equipments leading to, especially the turbines, can be the perfect solution to overcome the economical and operational problems and reduction of the total cost of hydropower plants. Hence, this study is aimed to review different types of hydropower turbines which can be used in micro-scale. This paper also presents several recommendations and solutions in terms of operation, performance and cost effective points of views. Micro-hydro-turbines have gained a rapid growth in the power generation field, especially in rural areas, as their power is needed to feed both base load and peak demand requirements of grid supply [21]. Micro-hydropower generation efficiency is generally in the range of 60–80% [10]. Micro-turbines generate very reliable power though with very simple designs and fabrications [22]. Nevertheless, the selection of micro-hydropower turbines for achieving the most efficient and best result is rather difficult, as most turbines are designed for higher systems; they may be modified applicable for low head micro-systems, but the operational principle often does not change [19].

2. Performance characteristics of turbines used for low head micro-hydropower

Hydropower turbines are categorized into two types, which are impulse and reaction turbines, each suitable for different types of water flows and heads. Fig. 1 shows the classifications of both types of hydropower turbines.

2.1. Impulse turbines

Impulse turbines have simple design and are inexpensive [18]. There are various types of impulse turbines, namely Turgo, Pelton and cross flow turbines. These types are commonly used as high and medium heads [19]. Recently, they have been applied for lower head micro-sites, and their proven effectiveness has made them becoming an accepted alternative practice in many countries [23].

Energy Systems & Design Ltd. [24] has produced a Turgo turbine which can be used for heads between 3 m and 150 m. In the previous researches, Williamson et al. [25,26] optimized Turgo turbine models in micro- and pico-projects, altering the location of low heads from 3.5 m down to 1 m to improve the turbine performance. Generally, the efficiency of the Turgo turbine depends on many factors, such as nozzle or jet inclination, cup design and speed ratio. The Turgo turbine efficiency for micro-hydro is very sensitive to jet position and jet inclined angle [25–27]. References [26,27] defined that the optimum jet inclination angle to achieve the peak efficiency of Turgo turbine for low head micro is approximately 20°. Koukouvinis et al. [28] performed a parametric study on Turgo turbine, related to the turbine inlet angle, by using smoothed particle hydrodynamics. Inappropriate nozzle angle may cause severe effects on the performance of Turgo turbines, as well as increasing the rate of erosion in the presence of silt particles [29]. Williamson et al. [25] presented new configurations of cups and jet inclination to improve Turgo turbine
efficiency at low heads, which was recorded efficiency up to 91% at 3.5 m head and 87% at 1.0 m head. Effectiveness in transmitting energy from the water jet to the generator of Turgo turbine depends on the shaft speed ratio. Regarding this, Cobb and Sharp [27] conducted a study and found that the peak efficiency can be achieved at a low speed ratio of approximately \( x = 0.53 \), in which they concluded that few degree misalignments can cause critical effects on Turgo turbine efficiency.

A Pelton turbine has one or multi-jets. Pelton wheels are suitable for large head and low flow sites [7,30–32]. Recently, Pelton turbines have been applied for small and micro-hydropower configurations, using a single jet [32,33]. Generally, a Pelton turbine has high efficiency rate of 70–90% [33]. A Pelton turbine performance is dynamic because of the unsteady flow in the rotating buckets in time and space. Xiao et al. [34] conducted dynamic performance prediction to define the dynamic efficiency of the bucket. In the following study, Xiao et al. [35] completed the unsteady numerical simulations by using a ANSYS Fluent 13 code and analyzed unsteady free surface flow patterns and various torque with the rotating bucket. Stamatelos et al. [36] studied performance characteristics of a micro-hydropower Pelton turbine model as a function of the buckets and injectors design and geometrical dimensions, in which the maximum efficiency of the prototype was around 86%, producing satisfactory performance for this micro-power range (80 kW). Anagnostopoulos and Papanotis [37] developed a numerical methodology to analyze the complex flow and energy conversion in Pelton hydro-turbines, where they applied the new micro-model to study the jet runner interaction and optimized the shape of bucket. Fu et al. [38] used the ANSYS software to demonstrate the stress on the bucket and improved their root; furthermore utilizing multi-nozzles to overcome the interference flows of jets problem. Solemnie and Dahlhaug [39] proposed a new design of Pelton turbine by using empirical data and NURBS; in addition, they included CFX and particle hydrodynamics (SPH) simulations in their study. In conclusion, the power output of a Pelton wheel can be controlled by regulating the flow within the nozzle; when the effective jet area is changed, the jet velocity and the nozzle efficiency will change accordingly [31]. Inaccurate calculation will cause the jet to be ineffective, thus tends to have insufficient discharging [34]. In their study, the theoretical peak efficiency for Pelton was indicated at a speed ratio of 0.50, but experimentally it occurred near to 0.41 [27].

A cross-flow turbine (CFT) is another significant impulse turbine. It is commonly applied in horizontal and vertical configurations. This type of turbine is usually used at higher flow rate and lower head than the Pelton and turgo turbines [7,40]. The average efficiency of CFT turbines is usually 80% for small and micro-power outputs; but can reach up to 86% in the case of medium and large units [40]. The operation effectiveness of CFT depends on geometrical parameters like the number of blades, runner diameter, nozzle entry arc and angle of attack. References [41–44] studied micro-CFT experimentally by manipulating different geometric parameters under flow/head variations. The maximum efficiency of the CFT was found to be increased when the nozzle entry arc was increased or when the aspect ratio of the runner was reduced [41]. They also found that efficiency improved with the increase in the number of blades [42,43]. They also suggested a method to get the optimum number of blades for maximum efficiency of the turbine and defined the specific speed of the CFT as a function of discharge flow rate and nozzle entry arc [41]. Reference [42] proved that the increase of the angle of attack to about 24° does not improve the maximum turbine efficiency. The inner and outer diameter ratios of a turbine also significantly affect turbine power characteristics, thus larger turbines are more efficient than small ones [43]. Nevertheless, CFTs do generate satisfactory electric power in varying flow in micro-hydro-stations [44].

The Darrieus-type hydro-turbine is of cross flow type but takes larger values of generated torque with higher efficiency on the upstream path as the Darrieus blades are designed to pass in one revolution. Furukawa et al. [45] presented guided design parameters of ducted Darrieus-type water cross flow turbine principle for high performance at low head hydro-power. From their experimental model results, they could determine the limiting effect of the casing clearance on the efficiency in case of slit intake. Shimokawa et al. [46] proposed more simplified runner casing by examining only the inlet nozzle and small upper-casing to improve turbine performance.

2.2. Reaction turbines

Compared to impulse turbines, reaction turbines have a better performance in low head and high flow sites [7,18]. At slow operating speed, the efficiency of reaction turbines is usually higher than that of impulse turbines [18].

Most reaction turbines are of axial flow type (propeller or Kaplan turbine) type. This type is indeed practical; indicating good efficiency, simplicity and is cost effective [47]. There are four types of propeller turbines, which are Bulb turbine, Straflo, Tube and Kaplan type [7,48,49]. Propeller turbines are more efficient for low water heads sites [31,50]. Toshiba Hydro-eKIDS proposed a new product for low head and micro-scale hydro-electric power plants [51], and had shown that the efficiency of the axial flow at low head micro-installations was recorded over 70% according to test rig unit in reference [22]; in addition, it is expected to increase with more iterative designs. The efficiency of propeller turbines can be improved with adjustment of the turbine blades and guide vanes angles [49]. Parker [52] predicted the performance of the axial flow turbine in micro-hydro-installation by simulating various guide vane angles and turbine blade angles, supported by using available experimental data. Singh and Nestmann [53] proposed geometrical modification of a propeller runner to optimize the runner performance, which was utilized in micro- and pico-hydropower with gross head from 1.5 to 2 m, and whose blades had been designed using the free vortex theory. The results showed that the efficiency recorded was very significant, rising from 55% to 74%. Meanwhile, Singh and Nestmann [54] proposed a holisitic theoretical prototype to get the internal performance parameters of the axial flow runner, and established a physical relationship between blade height and blade number. They found that manipulation on 3 runners showed increase in blade number, but the efficiency of the runner dropped dramatically. On the other hand, the blade height and overall runner loss coefficient were significantly reduced, but this could not increase turbine performance outcomes. Derakhshan and Kasaean [55] designed an axial hydro-turbine with low heads micro-potential flow at various flow rates and heads, ranging from 1 m to 5 m by optimizing their geometry and their model indicated improvement in efficiency by 3.5%. Ramos et al. [56] developed and studied a new reaction micro-hydro tubular propeller turbine with five blades, installed in a curved pipe without volute or guide vanes to overcome the shortage of energy in rural and isolated areas. This turbine has been shown to be suitable for constant flow conditions and more economical. Yassi and Hashem-loo [57] developed an Agnew turbine, which is an axial micro-hydro of Kaplan type, with its main shaft subtended to 45° to the line of horizon to operate sufficiently at low heads and limited flow. Test results showed that a turbine peak efficiency of 62% was achieved; in which the modified version of the Agnew turbine achieved 23% higher efficiency than the original design.

A Francis reaction turbine is the most commonly used type at hydropower stations [50]. This turbine can be used for micro-, medium or large hydro-stations, as the operating range of Francis
turbines is between 1 m and 900 m [58]. It has a radial or mixed radial/axial flow runner, which is most commonly mounted in a spiral casing with internal adjustable guide vanes [58]. Nevertheless, a Francis turbine’s effectiveness depends on the development of the helical vortex, or the so-called as vortex rope downstream the runner, in the draft tube cone. Ruprecht et al. [59] developed turbulence models to evaluate this type of turbine performance and inspected the power plant water passage to the exciting pressure oscillation caused by the vortex rope. Susan-Resiga et al. [60] proposed a new simple method to reduce the vortex rope by using a water jet supplied with high pressure from the spiral inlet. This had been shown to be able to eliminate the pressure fluctuations at partial load and increase the draft tube efficiency. In the following study, Resiga et al. [61] computed the circumferentially averaged flow field, induced by the processing vortex rope encountered in the draft tube cone of Francis turbines, worked at partial discharge by using an axisymmetric turbulent swirling flow model.

Pump as turbine (PAT) is the utilization of pump rotating in reverse direction [62]. The efficiency of PAT can reach up to 85% [48]. The research on using PAT started around 1930, and the main challenge in using PAT for small and micro-hydro-schemes was the selection of a suitable PAT [8]. Nowadays, pump as turbine (PAT) remains an attractive and significant alternative low head and micro-sites, because it has both practical and running cost saving over other types of turbines in rural and remote areas [62–69]. PAT was discovered accidentally in 1931 when Thoma and Kittredge were performing experiments on pumps, where they found that pumps could be operated very efficiently in turbine mode [67]. Pumps are easily available in most developing countries [8]. The main problem of using a pump as turbine is still the difficulty of predicting accurately the turbine performance, since pump manufacturers do not normally provide the characteristic curves of their pumps working as turbines [8,62]. Thus, the estimations on the operating performance of PAT based on the data for pump performance to achieve best efficiency often produce wide range of results. Burton and Mulugut [15] used the extended area ratio method proposed by Burton and Williams (1991) [70] to show that simple ratios of KH and KQ can be used in determining the head and flow ratios for pump and turbine operation. Williams [63] used and compared eight methods to analyze the effects of turbine prediction on the operation of a pump as turbine at typical micro-hydro-sites. Furthermore, Williams [64] proved that pumps as turbines can be used efficiently in the same range of multi-jet Pelton turbines, cross flow turbines and small Francis turbines. Derakhshan and Nourbakhsh [8] tested many centrifugal pumps that worked as turbines; where they used experimental data with some relations derivatives to find the peak efficiency point of a pump working as a micro-hydro-turbine, with regard to pump hydraulic characteristics. The efficiency of PAT was improved when geometrical modifications in the impeller were carried out. Derakhshan et al. [65] optimized the impeller geometry of a pump and changed the shape of blades by using a gradient based optimization algorithm, coupled by a 3D Navier–Stokes flow solver. The results showed that the efficiency was improved when the impeller was modified. The efficiency of the optimized impeller was increased by 2.9% and the efficiency of the modified turbine reached to 75%. Yang et al. [66] investigated various specific speeds of PATs with different blade wrap angles by building micro-hydropower rig. They then compared their results with numerical results, where the optimum blade wrap angle was found having tendency to increase in efficiency. The specific speed was increased when the blade angle was decreased, while the pressure head and hydraulic loss were reduced, which means that the flow rate versus pressure head (Q–H) curve was reduced with decreasing blade angle. Bozorgi et al. [67] simulated an industrial axial pump to be used as a turbine by computational fluid dynamics (CFD), which was then validated using experimental test rig. The results showed that the tested axial pump gave a good performance, indicating that it can be a good alternative to produce electricity from varying low-heads. Meanwhile, Motwani et al. [68] carried out a cost analysis of 3 kW capacity pico-hydropower plant by considering PAT and Francis turbine as a prime mover to improve the performance characteristics, intended to be compatible with economical way.

Archimedes screw turbine has become more attractive for lower head sites, as its heads can be set as low as 1 m, moreover specially suited to sites with large flows [69]. Western renewable energy [71] and Landinustries [72] have developed the Archimedean screw as a relatively novel method to generate electrical energy from a low-head source. The highly efficient Archimedean screw is able to generate electricity all year round 24 h/day, whilst maintaining the natural flow of the river; in fact being one of a few systems that are able to maintain or even improve the wildlife in and around the river [7,72]. Stergiopoulou et al. [73] presented a series of modern Archimedean low head hydropower turbines, plans and proved that Archimedean screw is indeed a good alternative solution for clean environment and sustainable development. Raza et al. [74] proposed an analytical prototype of low head Archimedes screw, where they found that the screw efficiency depended basically on the flow rate and the inclination angle. They also found that the capacity of water increased and efficiency decreased with few inclined angle and vice versa, while the maximum model efficiency recorded was 86%.

Barker’s mill turbine was the first reaction turbine, which was invented in 1740. Most analyses observed that such machines were inefficient at low speeds. It was also usually noted that centrifugal induction in pressure would increase in the arms as they rotated, tending to increase in flow rate [75]. Date et al. [75] explored in more detail the changes in efficiency, flow rate, torque and power which occurred with the increment of the rotational speed of an ideal frictionless Barker’s mill.

Another type of turbine is the split pipe reaction turbine, manufactured by cutting a plastic pipe into two halves, and then off-set the centers and join the top and bottom plates. The idea of split pipe reaction turbine is influenced by the savonius wind rotor [1]. References [1,76] presented the performance properties of a simple split reaction hydro-turbine for power generation.

3. Effectiveness criteria of low head micro-hydropower turbines selection

The selection range of the turbines generally depends on many criteria, such as various ranges of the head, flow rate, shaft speed and specific speed (see Table 1) [2]. There are also other factors that need to be taken into account when selecting turbines, including the depth at which the turbine should be positioned, its performance and cost effectiveness [7]. Williamson et al. [2] proposed a method to select the most efficient turbine for a

<table>
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<tr>
<th>Quantitative criteria</th>
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<tr>
<td>Rated flow/head efficiency</td>
<td>Environmental – weather – location</td>
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<tr>
<td>Part flow/head efficiency</td>
<td>Required civil works</td>
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<tr>
<td>Cost</td>
<td>Portability</td>
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<tr>
<td>Turbine rotational speed</td>
<td>Maintenance</td>
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<td>Power for given site</td>
<td>Reliability</td>
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<tr>
<td>Size of system</td>
<td>Ease of manufacture</td>
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<td>Design modularity</td>
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low-head hydro-specification by using quantitative and qualitative analyses.

Head is a criterion for classification of hydropower turbines, which are either classified as high-head, medium-head, or low-head, as shown in Table 2. The turbine selected for micro-head hydropower systems should be < 10 m. However, large hydropower turbines can still be used for micro-hydropower systems after some modifications of these turbines for suitability [19].

Currently, pumps-as turbines (PATs) are used for medium head projects. Turgo turbines are also a vital solution in this range [27].

Turbine effectiveness is determined based on head and flow. Figs. 2 and 3 show the operating range of varying turbines for a given head and flow, whereas Fig. 4 shows different ranges of

<table>
<thead>
<tr>
<th>Turbine types</th>
<th>Head classification</th>
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<tr>
<td></td>
<td>High &gt; 50 m</td>
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<tr>
<td>Impulse</td>
<td>Pelton</td>
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<td></td>
<td>Turgo</td>
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<td>Multi-jet Pelton</td>
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<td>Reaction</td>
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Fig. 2. The range of selection of small and micro-hydro-turbines with heads and flow rates variations [77].

Fig. 3. The various turbines in terms of head and flow rate [78].

Fig. 4. Head and power capacity for various types of turbines [48].

Fig. 5. Efficiency variation over different head ranges from 0.5 to 3.5 m [2].
turbines that can be selected depending on head and power capacity. These figures can also be used as a reference for selecting the most suitable micro-hydropower turbine type if a certain power output is required.

A significant factor which indicates the suitability of micro-hydro-turbine type is the relative efficiencies both at their design point, head and at various flows [78]. Each turbine typology has its characteristic efficiency at different head and partial flow, as shown in Fig. 5 [2] and Fig. 6 [78], respectively.

Operation of a turbine also depends on the ‘specific speed’, which determines its performance. The specific speed relates the output power of the turbine to its running speed and the head across it, as in the following equation [10]

$$N_S = \frac{n P^{0.5}}{H^{0.75}}$$

(2)

where $n$ is the turbine speed (r/min), $P$ is the shaft power (kW) and $H$ is the pressure head across the turbine (m).

The site selection should be quite typical to exploit the maximum potential of the site conditions for selecting micro-turbines. Adhau et al. [79] carried out extensive study at two potential sites, and studied the hydrological data of one site for possible development of mini/micro-hydro-power plant. He concluded that irrigation projects are economically and technically viable for micro-power generation. It was found that the installation of mini/micro-hydropower plants in an irrigation canal with higher head is more interesting and has more potential than with larger flow rates [80]. Meanwhile, Chattha et al. [81] designed cross flow turbine for micro-hydro-installation which depends on the available site conditions.

4. Economic analysis of low head micro-hydropower turbines schemes

The budget for rural and hilly areas electrification within grid connection is very expensive, especially in poor developing countries. Thus, cost is the most important aspect for low head micro-hydropower installations. The implementation of micro-hydropower has been recommended by many international organizations such as United Nations Industrial Development and World Bank. According to studies by World Bank, the startup cost of micro-hydropower consumes about 6 cent/h, while the estimated initial costs of wind and solar power plants are 7 cents/h and 10 cents/h, respectively; defining the initial cost of a micro-hydropower plant is around half of that of solar energy plant, as shown in Fig. 7 [82]. Hence, micro-hydropower source is significantly cost effective in socio-economic development of isolated hilly and mountain areas. In addition, low head micro-hydropower can reduce the poverty level in these areas, considering the cost per person to pass above the poverty line [83]. However, most governments favor solar and wind schemes over micro-hydropower installation [23,82].

The cost of the establishment of a micro-hydro-power station can be divided into four parts: the civil work which represents about 40% of the total cost, turbine and generator set (30%), control equipment (22%) and management cost (8%), respectively, as shown in Fig. 8 [20]. References [84,85] proposed micro-hydropower projects with the total budget varying from $1500 to $2500 per kilowatt of power capacity.

The cost of turbines plays a vital role in the total budget of low head micro-hydropower plants, where the cost depends on the type of turbine, which may also vary from one site to another. The power capacity and turbine diameter of the plant are the most significant factors to determine the cost of the turbine set [86]. Some correlations are developed beforehand for this purpose, by using regression analysis based on the head and capacity of the required power. Singal [87], and Singal and Saini [88] proposed correlations for cost by estimating the independent net head and power capacity, as given below.

Cost per kilowatt of turbines with governing system is

$$Cost = 63,346P^{-0.1913}H^{-0.2171}$$

(3)

Fig. 9 shows the relation between micro-hydropower project cost and power capacities at various site heads. This figure shows that turbines cost per kilowatt produced by low head micro-plants decreases with the increase of head and power capacity. Ogayar and Vidal [89] proposed formulas to determine the cost of micro-hydropower turbines from basic parameters such as
power and head. The typology of the micro-hydro-turbines was included in the methodology of this study. Developed equations of every type of micro-hydro-turbines had been validated with those from different small/micro-hydro-power stations companies. The correlation for cost was obtained for each type of impulse and reaction turbine, as described below:

- Pelton turbine
\[
\text{Cost} = 17,693 P^{-0.3644725} H^{-0.281735} \quad (\text{€/kW}).
\]  
(4)

- Francis turbine
\[
\text{Cost} = 25,698 P^{-0.3644725} H^{-0.127241} \quad (\text{€/kW}).
\]  
(5)

- Kaplan turbine
\[
\text{Cost} = 33,236 P^{-0.58338} H^{-0.113901} \quad (\text{€/kW}).
\]  
(6)

The comparison between the various types of low head micro-hydrowater impulse and reaction turbines is shown in Fig. 10. The cost increases from low power scales, in which the Pelton turbine has the lowest cost over the other two types of turbines (Francis and Kaplan) for high head. Reaction turbines like Francis turbines are the most suitable turbine for lower head level based on cost survey, as shown in Fig. 11, which illustrates the relation between turbine cost and net head at 100 kW of power. The cost analyses as shown in Figs. 10 and 11 indicate that the impulse turbine (Pelton) is more preferable for micro-hydrowater system compared with reaction turbines (Francis and Kaplan). Nevertheless, reaction turbines have a major advantage of being the most suitable for low-head applications.

5. Technical discussions, recommendations, solutions and case study

5.1. Technical advantages and disadvantages

**Impulse turbines** such as the Turgo, Pelton and cross flow turbines have many advantages. They have higher efficiency especially at part flow condition, which can deliver more than 90% effectiveness. The efficiency is also predictable even with different working conditions. In addition, they are easy to maintain and fabricate, the shafts do not require any pressure seals, having greater tolerance to sand and other particles in water, with little effect on the turbines performance. In addition, the Pelton and Turgo turbine have simple designs and are cost effective in micro-hydrowater scales.

Installing Pelton and Turgo turbine impulse turbine at low head sites is not effective, when taking into account their performance characteristics and cost analysis, contrary to the cross flow turbine which is more proper for low head applications because its efficiency depends on the flow rate than the other two types of impulse turbines. Impulse turbines also have lower specific speed, which would be required in speed-increasing drive system. The flow in the Pelton and Turgo turbines is also unsteady in the rotating buckets.

The significant advantages of the **reaction turbines** are that they are mostly suitable for low-head sites because of their higher specific speeds, since the turbines are connected directly to the alternator without needing the transmission system. Consequently, the cost of removing the drive system is significantly low. These turbines also can be used at different heads; the Francis turbine is suitable for medium and high heads, while the propeller and PAT are more suitable for lower heads.

On the other side, the implementation of reaction turbines is more complicated than that in impulse turbines because they require the use of profiled blades with special casing and guide vanes designs. This can cause increment in the cost of startup budget of the reaction turbines. Hence, the use of reaction turbines in the micro-hydrowater schemes is less attractive, especially in poor areas. Furthermore, reaction turbines have lower performance properties for part flow condition. However, PAT and propeller turbines nowadays have been innovated to be utilized in micro-hydrowater-installations but with condition that the sites have regular head and flow rate.
5.2. Solutions and case study

The main problem in rural and remote sites is that the electrification by conventional way in these sites is very costly; moreover, they already have financial burden. Micro-hydropower is the best alternative in economic terms. The runway cost of micro-plants is low, but the startup budget may be relatively high [64]. Hence, the reduction in any terms of the micro-schemes cost can make the micro-hydro-projects more profitable. There are a number of solutions regarding this matter, such as low cost penstock, micro-hydro-power turbines development and induction generator, to eliminate the total cost of the micro-schemes and make them more accessible in the remote and hilly areas applications. This research paper is useful as a reference for the development of the micro-hydro-turbines performance and cost. Reducing the cost of the turbine is the most effective way to reduce the initial budget of micro-projects because turbine is the most costly part in the system.

A number of turbine configuration options have been proposed to reduce the cost of micro-turbines set. Developed pump as turbine (PAT), propeller turbine and cross flow turbine (CFT) can be used as suitable alternatives for rural and hilly areas micro-hydropower installations.

5.2.1. Pump as turbine (PAT)

Many researchers presented that the centrifugal pump as turbine (PAT) is an ideally cost effective choice for micro-hydropower scale, with regard to the following advantages:

- **Low cost**: the PAT cost is low as it is a mass product (integral pump) [13,64,90,91]. The cost of PAT is 50% less than the cost of corresponding turbines [92].
- **Availability and wide range of operation**: PAT is available for various ranges of flow and heads, and it is available locally and abroad with a wide range of standard sizes [13,64,90].
- **Simple design and ease of installation** [13,64,90].
- **Spare parts are easily available** [13,64,90].
- **Long life term**: it can be operated continuously for over 25 years [91,92].

The suitable head range of PATs varies from 13 to 75 m (40–250 ft) and PATs are available from 1.7 kW to 160 kW. The cost per kilowatt of PATs decreases with higher head [92]. Measuring and predicting the PATs performance characteristics are very difficult because there are no actual characteristic curves of their pumps available compared to turbines [8,62]. The efficiency of PATs is very poor at partial flow, hence they need sites with regular head and flow rate [92]. Using PAT in high capacity applications is not economical [93]. Many studies have been conducted to predict the performance of PATs, which has been discussed in Section 2.2.

5.2.2. Propeller turbines

Propeller turbine is the most suitable option which can be considered for low head hydropower schemes [53]. Williamson et al. [2] proposed quantitative and qualitative selection criteria to determine suitable turbines for particular micro-/pico-sites. They concluded that propeller turbine is suitable to be applied in low head remote site. Propeller turbines are most efficient in the range of 0.5–1.5 m of gross head, and the power varies from 200 W to 20 kW [2]. Guilherme et al. [94] analyzed the power generation feasibility of an experimental propeller turbine, and they reached to a conclusion that propeller turbine is a very promising solution for low head hydro-power.

5.2.3. Case study of cross flow turbine (CFT) for zero head application

One of the most attractive turbines is cross flow turbine (CFT), known as Banki and Ossberger turbines. This type of turbine is more practical, easy to fabricate and of low cost [95]. These turbines are also familiar for installation in higher and medium flow rate and low head [7,40], whereby the average efficiency of CFT turbines is 60–80% for micro-power [40]. The cross flow turbine is more proper for run-of-river applications because its efficiency is lower compared to others, depending on the flow rate than other types of impulse turbines [95]. Kim et al. [96] proposed a new configuration of cross flow turbine for harnessing tidal energy by utilizing a larger area of the channel. Prasad et al. [97] also implemented cross flow turbine as drive turbine for wave energy production field. In this case study, the authors proposed cross flow turbine to harness the current power in micro-channels. This turbine is applied in zero-head microscheme, as shown in Fig. 12, which can be used in rural areas especially in territories with little or no head. The studied CF runner is shown in Fig. 13. Numerical investigations had been performed using a finite volume RANSE code Ansys CFX to investigate the performance of the cross flow turbines. The inlet velocity and water depth at the inlet boundary of the model channel in this research were set at 1 m/s and 0.25 m, respectively. The velocity also had normal direction to the water model channel inlet, in which the boundary conditions were constructed as a wall (no slip condition).

This current case study indicated that the jet flow region was presented beside the two main stages of the cross flow turbines to increase the energy absorbed by the turbines. It was found that the maximum power output recorded as 37.5 W; consequently, the power coefficient was nearly 0.5 at TSR=0.55, as shown in Fig. 14. The coefficients of power are lower than those of other most comparable hydro-turbines like Pelton, Turgo, Francis and Kaplan. However, this system is defined as cost effective hydrokinetic solution. Conventional micro-hydropower scheme needs the penstock to divert the water from the supply to the turbines. The penstock is one of the most costly parts in the micro-hydropower budget; it can even reach as much as 40% of the total cost in some cases [16]. The system also utilizes the CFT runner, only without the special casing, inlet nozzles and guide vanes. Consequently, the cost of removing penstock and other parts can be saved. According to hydrokinetic turbines performance, this configuration presents adequate and high efficiency in comparison with conventional current turbines. Furthermore, the effectiveness of the current CFT can be developed by some modifications and improvements on the turbine runner, as described in Section 2.1. Another advantage of the current configuration is that it can be employed in the rainy and irrigation channels, especially in irrigation projects which are viable economically and technically for micro-power generation [79].

5.3. Recommendations and limitations

Selecting suitable turbines to be used in the low head micro-hydropower plants can be determined by comparing the performance characteristics, power capacity, site conditions and cost of the turbines set required to supply energy in rural and electrification
areas. As referred from the current study, the following guidelines are provided:

- Micro-hydropower turbines are divided into two categories, which are impulse turbines (Turgo, Pelton and cross flow turbines) and reaction turbines (PAT, Francis, Kaplan or propeller turbines).
- Impulse turbines generally are more suitable for high and medium head. Recently, they have been used for lower head micro-sites.
- Turgo turbine with single jet is able to work efficiently in low head micro-hydro remote sites. Moreover, it can work at various ranges of head and flow, but it is most efficient in the range of 1.5–3.5 m of head in case of low head micro-scale.
- Pelton turbine is more preferable in micro-hydropower scales compared with other turbines, based on its performance and cost. It can also work sufficiently at partial flow.
- Impulse turbines, especially Pelton turbines, have poor efficiency in low head applications and they are very costly. However, they can be used in low heads if low speed and runner size do not cause any performance problems.
- Cross flow turbine is the most suitable option for micro-low head applications, since it can be familiarized with higher flow rate and lower head compared to the Pelton and Turgo turbines. Consequently, it is more proper for low head schemes. In addition, it can be used as a hydrokinetic solution, as described in Section 5.2.3.
- Installation of reaction turbines (PAT, Francis, Kaplan or Propeller) in low head site is the most suitable way to increase system efficiency and reduce cost.
- PAT is more practical, easy to construct and cost effective for use at low head sites. In contrast, it is inadequate with partial flow and higher capacities.
- Francis and Kaplan turbines have moderate efficiency at low head applications. Also, they have lower cost in low head applications, according to the current cost analysis. These types of turbines have complicated design and arrangements, which are expensive for micro-hydropower scales. Hence, it is not recommended to utilize these turbines in micro-power schemes in remotes and rural areas.
- The cost of propeller turbine is significantly lower for installation at low head micro-hydropower stations and its efficiency is very satisfactory. It can be proposed as the best solution for remote sites micro-scales.

6. Conclusions

The low head and micro-hydropower is the most secured alternative solution to overcome the problem of lack of electric power supply and financial problem in rural and poor areas, in ensuring better future for the population. A great connection is necessary between renewable hydropower energy and sustainable development. It is also essential to promote innovative researches concerning this power scale. Therefore, this article focuses on various types of low head micro-hydropower turbines; covering general descriptions of micro-hydropower turbines systems and their various categories, operation, performance and cost. This current study includes analyses on the effectiveness features of each typology of these turbines, which are explained in detail, as well as the significant factors that can affect the operation and performance of the turbines. This study provides a guideline for selecting the most suitable turbine system for use in different low head and micro-hydropower projects.

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References
