Low-Cost Hydropower Turbines for Developing Countries

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Abstract

There are many hydropower turbines for low heads or low flows on a small scale. Many technologies are unsuitable for developing countries because equipment or materials are limited, high-tech machines are to expensive or spare parts are not readily available. This review combines currently available technologies with the requirements of developing countries in small, micro and pico hydropower. In small hydropower a propeller turbine from Thailand has a high efficiency of 70 to 80 percent at calculated production costs of around \$ 513 per kW. Pumps as turbines are suitable for developing countries in micro hydropower due to readily availability, low price and an large number of standard sizes. In pico-scale, a low-cost Turgo wheel can be made of spoons for \$ 48 and yields acceptable values in comparison to a 3D printed Pelton wheel for \$ 822. While the Turgo wheel is suitable for high heads, a homemade siphon turbine can be used for low heads. The siphon turbine generates up to 200 W, is made of materials that are available anywhere in the world, and costs less than \$ 50.

Keywords: hydropower, developing countries, low-cost, micro hydro, small hydro, pico hydro

1 Introduction

Hydropower is a major source of renewable energy. In 2019, the total global hydropower installed capacity increased by 15.6 GW and reached 1,308 GW. That corresponds to a rise of 1.2 percent. Nevertheless, this is below the required carbon reduction targets outlined at the Paris Agreement, which requires an estimated growth rate of 2.0 percent. For comparison, 21.8 GW were added in 2018 [1].

The construction of large and medium-sized dams is decreasing worldwide. Reasons for this are environmental protection, decreasing returns on investment, concerns about resettlement of residents and decreasing availability of suitable new locations. Conversely, small hydropower still has potential wordwide and does not have the cost and environmental problems associated with dams [2].

Basically, the kinetic and potential energy of the water is converted into mechanical energy by hydro turbines to rotate generators or other machinery for power generation [3]. In a nutshell, any hydroppower system´s output is based on equation 1. The decisive factors are head, flow and efficiency [4].

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot H \tag{1}$$

where

P:	mechanical power (W)
η:	hydraulic efficiency of the turbine
ρ:	density of water (kg/m^3)
g:	gravitational force (m/s^2)
Q:	volume flow rate (m^3/s)
H:	effective pressure head (m)

Hydropower plants can be differed based on several criteria, such as the power output, head or the type of turbine running. However, the classifications are not always uniform worldwide. Therefore, this paper uses the definition of the European Small Hydropower Association (ESHA) to classify the pressure head [4, 5]. Basically, pressure head is classified into ultra-low (<3 m), low (2 - 30 m), medium (30 - 100 m) and high head hydropower (>100 m) [6]. The subdivision of the hydropower potential is mostly country-dependent. Here the potential is divided into pico (<5 kW) , micro (<100 kW), mini (<1,000 kW), small (<10,000 kW) and large (>10,000 kW) hydropower [7].

Rural areas in developing countries with low population density need local and low cost electricity generation. Large hydropower plants are often not feasible as it requires high investments and a grid infrastructure [8] but there are still many potential locations for pico, micro, mini and small hydropower plants [2]. Those small-scale hydropower systems allow an economically viable electrification especially for small localities and remote areas [9].

Not all new technologies can be used in developing countries. Some are unsuitable due to the high development cost, operating costs or transport to the rural areas. This short review is intended to present examples of suitable solutions for developing countries in different performance classes.

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2 Components of Hydropower Plants

The main components of a hydropower scheme are listed below [8]:

- Intake structure: Water exits from a dam or comes from a river bypass to the turbine through a pipeline (penstock)
- Turbine: Energy is converted from the water into a rotary motion by the turbine blades.
- Generator: The rotary motion of the turbine is converted into electrical energy in the generator.
- Outflow: The water exiting the turbine is transported back into the river trough pipelines.

Another distinction of the hydropower plants is the type of water withdrawal. Water is taken directly from a river (run-of-river) or dammed up as a reservoir. In run-of-river schemes, a bypass flows to the turbine and back to the course of the river. This system is more flexible and more environmentally friendly. The main costs of the hydropower plant are the turbine and the piping framework (penstock) since the construction of a dam is not required. On the one hand, dams are cost-intensive large-scale projects, therefore seldom practicable in developing countries, and have a negative impact on the environment. On the other hand, reservoirs enable storage for dry periods and provide flood protection through regulation [8].

There are two working principles for turbines. On the one hand, there are reaction turbines in which the rotor is completely immersed in the water in a closed pressure system. The profile of the runner blades creates pressure differences as well as lift forces thereupon form the rotary movement. On the other hand, there are impulse turbines that rotates under atmospheric pressure. The runner blades driven by a jet (or jets) operate in contact with the air [4] .

Generators convert the mechanical energy from the shaft to the electrical energy. Synchronous, asynchronous and permanent magnet generators are possible. Synchronous generators or alternators have a constant voltage, constant frequency, and supply active and reactive power. These are preferred in large and grid-connected systems. Induction generators are smaller size, lower cost and have a rugged construction with ease of maintenance as alternators. Permanent magnet systems with direct drive are often used for smaller projects [7].

The speed of the generator and hence output frequency can be regulated via the water input or the load. High-head systems with narrow penstock tubes can be easily control the water volume by mechanical governors. The electronic control, however, is more simple, less expensive, requires less maintance and responds faster at low heads [10]. Low speed turbines require low speed generators. These are bigger in size and costlier due to the higher number of poles [11].

3 Suitable Technologies for Developing Countries

There are many different types of turbines available for various situations. The selection of the most suitable turbine depends on the performance characteristics, power capacity, site conditions and cost of the turbine set. In addition, there are some difficulties in developing countries that should be taken into account [12].

The availability of high-tech equipment such as 3D printers or certain materials is limited, especially in rural areas. The delivery of new machines from other countries is sometimes not affordable or uneconomical. In addition, high-tech devices require the corresponding qualifications of people to operate and maintain the machines. Therefore, the construction of a plant should be simple in order to be able to exchange parts. Basically, low maintenance with low operating costs is required [5].

3.1 Small Hydropower

Axial blade machines are most suitable for low head and low flow conditions [13]. The best known types are Kaplan and propeller impeller turbines, which use the axial flow of water to rotate the runner blades. Both are reaction turbines that operates completely immersed in water. In contrast to the propeller impeller turbine, the Kaplan turbine can adjust the runner blades. Therefore, fluctuating water quantities can be optimally adjusted for a high degree of efficiency. In front of the impeller are the guide vanes that give the water a swirl. Guide vanes improves efficiency because the swirl is absorbed by the runner. With good adjustment, the emerging water only has a little residual angular momentum. Behind the impeller is the diffusor, also known as draft tube, through which the water discharges. The draft tube has a larger diameter and slows down the water velocity. This reduces the static pressure and increases the effective head of the turbine [4].

The manufacture of reaction turbines is demanding due to the complex blades and housing. Because of the manufacturing restrictions, these turbines are less common in developing countries [4]. The following example is different. There is a propeller turbine from Thailand, which is designed for a head range of 10 to 20 m. It´s power output is 160 kW by an SIEMENS induction motor with 1,000 rpm. Figure 1 shows the runner blade and guide vanes of the turbine.

The technical data are summarized in table 1. The production cost of this turbine are estimated at about

Fig. 1: Runner blade (top) and guide vane (bottom) of the small hydro propeller turbine [3]

$ 513 per kW. The estimate is based on a 1000 kW low head turbine (0-30 m) from Hydro Tasmania Company in Australia that costs approximately $ 900 per kW. Comparable turbines installed in Sri Lanka, Nepal, Peru, Zimbabwe, and Mozambique cost approximately $ 615 - 1,911 per kW [3]. A reason for the wide price range is unknown. Nevertheless, the turbine prices are from the year 2000 and are therefore out of date.

Tab. 1: Conditions and results of the axial propeller turbine [3]

Head range	10 - 20	m
Diameter	0.4	m
Guide vanes	12	pieces (0° - 90°)
Turbine blades	4	pieces (40° radial)
Generator	160	kW
Efficiency	70 - 80	%
Cost	$\sim$ 513	$/kW

The propeller impeller turbine from Thailand is a comparatively economical turbine in the micro hydropower, which is simply controlled via the guide vanes. Due to its low cost and easy operability, this turbine is suitable for use in developing countries. Nevertheless, there are areas that are dependent on self-sufficiency and need solutions on a smaller scale [3].

3.2 Micro Hydropower

Standard pumps as turbines are a attractive option for micro hydropower in developing countries. Centrifugal pumps running in reverse acts as a turbine. As it´s mass-produced, it is readily available an generally cheaper than turbines. Here are some advantages compared with purpose-made turbines [14]:

- Available for a wide range of head and flows
- Available in a number of standard sizes
- Low cost
- Spare parts such as seals and bearings are easy available
- Easy installation - uses standard pipe fittings

The testing of several pump types has shown that end-suction centrifugal pumps are most suitable. Other types of centrifugal pumps such as in-line or double suction centrifugal pumps are less efficient. It is important that the pump has a spiral volute, as a simple round casing with an angled outlet pipe is inefficient as a turbine. Centrifugal pumps are generally the most easily available and cheapest type. Alternatively, dry-motor submersible pumps are also possible, in which the pumped water flows through a casing and thus cools the motor. On the other hand, dry-motor submersible pumps with fin-cooling are useless because they will overheat. Furthermore, all positive displacement pumps are unsuitable [14].

It is particularly important in less industrialized countries to check the quality of a pump. Pumps from large manufacturers are often copied with poor quality in small workshops. This has a bad impact on performance and lifetime. The parts to be checked are Impeller eye clearance, casting quality, impeller material, shaft material and bearing quality [14].

Background: A pump has a specific performance curve and a best efficiency point. The best efficiency point depends on head and flow. These data are usually available from the pump manufacturer [14].

A suitable pump is selected based on the specific head and minimal available flow conditions of a site. (The head is the vertical head difference between the intake of the stream and the turbine outlet minus the loss from the penstock.) However, the best efficiency point (of head and flow) of a pump should be as close as possible to the site conditions in order to select the most suitable pump [14].

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3.3 Pico Hydropower

Spoon-Based Turgo Turbine

In high head and low flow conditions, a Pelton turbine is likely more efficient but not more expensive than a pump [14]. On the outside of a Pelton wheel, split buckets are arranged around one behind the other. The jet of high speed water hits the middle and splits into both buckets. The halved jets turn and deflect back almost through 180° in the bucket. Therefore nearly all of the energy goes into the rotation of the wheel.[5][4]

The Turgo turbine works on a similar principle. It differs mainly in the shape of the bucket and the direction of the incoming jet. Instead of two curved structures (Pelton) the buckets of a Turgo turbine consists of only one curved structure.[15] In addition, the jet hits at an angle of (typically) 20 °. Therefor the jet enters on one side and exits the other. The advantage is that the reflected water does not interfere with the jet, which reduces the flow rate. Consequently the Turgo turbine can be smaller than the Pelton turbine with equivalent power.[4]

In an experiment, a low-cost Turgo wheel was compared with a 3D printed Pelton wheel. Figure 2 shows the Turgo and Pelton Turbie that were tested. The bucket structure of the Turgo wheel is formed by spoons. The spoons are shortened and welded onto a steel plate that is wrapped around a wooden runner. The geometry of the Turgo wheel depends on the jet velocity and nozzle diameter. For example, the optimal ratio of wheel diameter to jet diameter is 11-16.

Fig. 2: Spoon-Based Turgo wheel (left) and 3D printed Pelton wheel (right) [15]

The main advantages of the Spoon-Based Turgo Turbine are easy availability and low cost. Spoons are easy to get in developing countries, unlike 3D printers, which are very rare and expansive. The low construction costs of $ 42 are suitable for rural areas with a low-income population. The experiment has proven that the Turgo turbine provides acceptable performance and efficiency in pico scale. Tabular 2 shows the most important results of the comparison between Turgo and Pelton wheel [15].

Tab. 2: Comparison of a low cost spoon-based Turgo wheel and a 3D printed Pelton wheel [15]

	Pelton	Turgo	
Flow rate	2.40	2.37	l/s
Hydraulic power	117.72	116.25	W
Generated power	30.42	32.80	W
Mechanical efficiency	26	28	%
Investment cost	822	48	$

Homemade Siphon Turbine

There are in the pico hydropower many approaches to build hydropower plants with simple objects, such as the Spoon-Based Turgo turbine. Many hobbyists explain their self-made turbines in videos and upload them to media platforms. These have not been tested under laboratory conditions, documented and published, so this does not represent a good scientific source. The functionality is often based on established techniques that are tested and applied on a larger scale. The difference are mainly the objects used for the construction, which are adopted from other applications. For example, Daniel Connell designed a 200 watt siphon turbine that costs around $ 50 and can be replicated anywhere in the world [16].

A siphon turbine has the advantage in small-scale hydropower that it can be retrofitted in existing structures. For example, suitable places are non-powered dams, irrigation canals, water diversion structures, water distribution systems, water or wastewater treatment plants and others. The siphon conveys the water from the upper reservoir over the dam into the lower reservoir [17].

Conell´s pico hydropower plant consists of the following materials:

- Penstock: PVC pipes and fittings (diameter: 125 mm and 160 mm)
- Turbine wheel: computer power supply plastic fan (diameter: 120 mm)
- Alternator: hoverboard wheel or motorcycle alternator
- Accessories: glue, nuts, bolts and washers

The U-shaped penstock consists of PVC pipes, PVC elbows and an PVC Y-piece. The PVC Y-piece is the upper part of the drop side. The water flows in through the side inlet and out on the straight side downwards in regular flow direction. The inlet on the straight side is closed airtight by a lid. A plastic fan serves as an impeller, which is centrally positioned at the outlet of the PVC Y-piece (Fig 3).

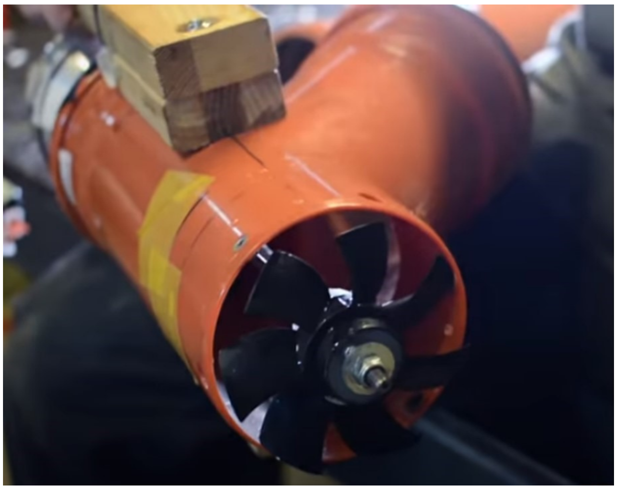

Fig. 3: Computer power supply PVC plastic fan as impeller [16]

The alternator is positioned centrally on the outside above the lid (Fig 4). Impeller and alternator are directly connected via a threaded rod through the lid. Behind the impeller, the diameter increases from 125 mm to 160 mm. The outlet can be extended as required to the lower reservoir by pieces of pipe. The pipes must end below the water surface, so no air enters from below and interrupts the siphon effect.

Fig. 4: Hoverboard wheel used as alternator [16]

A hoverboard wheel is available in western countries in secound hand or online shops for low budget. Alternatively, a motorcycle alternator can be used, which are widely used and available in developing countries.

The performance of the Pico hydropower plant was measured in a workshop with an ammeter and a voltmeter. The data are listed in Table 3.

Tab. 3: Conditions and results of the siphon turbine [16]

Head range	~ 2.5	m
Flow rate	~ 35	l/s
Power generated	~ 192	W
Investment cost	~ 50	$

4 Conclusion

The selection of the most suitable type of turbine for a site depends on various parameters. In addition, there are difficulties in developing countries. For example, equipment or materials are limited, high-tech machines are to expensive or spare parts are not readily available. Rural electrification requires a robust, low cost solution.

In small hydropower (> 10,000 kW) a propeller turbine manufactured in Thailand is a suitable solution in head range 10 to 20 m. This turbine operates with a simple propeller and adjustable guide vanes, is low-priced at around $ 513 per KW compared to other manufacturers and has a high efficiency of 70 to 80 %.

Standard pumps running in reverse act as turbines. This is usable in micro hydropower (> 100 kW) due to readily availability, lower price than turbines and a large number of standard sizes as pumps are mass-produced.

In pico-scale (> 5 kW), a low cost spoon-based Turgo turbine yields an acceptable value of mechanical of power and efficiency in comparison to a 3D printed Pelton wheel. The Turbine wheel can easily be copied and is suitable for developing countries in high head and low flow conditions. A homemade siphon turbine is a suitable solution for low head and high flow. This generates up to 200 W, is made from materials that are available anywhere in the world, and costs less than $ 50.

These are just a few selected examples of the many possibilities that were presented due to their efficiency, low cost or simple construction. Further reviews could describe the installation of the presented technologies, problems occurring in operation and solutions for these.

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