Improving the Efficiencies of Pelton Wheel in Micro-Hydro Power Plants

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Abstract

Most Micro Hydro Power Systems (MHPS) in developing countries, are not delivering their best possible power output due to sub-optimal design and construction of their various components. For existing MHP plants the turbine is much more adaptable to retrofit than any other part of the MHP while keeping the overall project cost per kilowatt produced within acceptable range. Therefore this becomes a feasible cost effective strategy to improve the efficiency of a hydro- turbine with the effect of improving the overall efficiency of the system. This research showed that the main factors that affect efficiency of Pelton wheel turbines, which are commonly used in Southern Africa, are the fabrication processes; material used; the control of the water jet movement and flow rate. The fabrication process and the material used determine the roughness of the turbine produced. The roughness determines the friction which in turn affects the efficiency of a turbine. Current fabrication processes were compared to other processes such as laser and electron beam cutting and welding, pressure die casting, investment casting and milling. These processes and use of stainless steel resulted in the least rough finish. This gave an overall increase of 20 – 25% on the turbine efficiencies.

Keywords
Hydro-Power, Pelton, Turbine, Efficiency, Micro Hydro Power System (MHPS)

1. Introduction
In Southern Africa, rural areas are not connected to grid electricity. In such areas perennial rivers Micro-Hydro Power Plants (MHPP) are an attractive option for providing electricity. In the construction of micro-hydro power plants in developing countries, Pelton and Cross-flow turbines are predominantly used. This is because these turbines are cheaper to construct and require less specialisation compared to other types of turbines. A Non-Governmental Organisation based in Zimbabwe is currently working on the development of ten micro hydro power plants for different rural communities in Zimbabwe, Mozambique and Malawi. For the construction of these micro-hydro schemes, the organisation designs and fabricates Pelton wheel turbines whose efficiency is estimated to be 60%. At this percentage turbine efficiency micro-hydro schemes seem to be underutilising resources hence engineers working on these micro hydro schemes have suggested that these turbine efficiencies can be improved while the micro-hydro projects remains financially viable. It is known that in a micro hydro scheme the turbine has the lowest efficiency, compared to other components. Therefore, improving turbine efficiency has the best chances of improving the overall efficiency of the whole micro-hydro system.

2. Literature Review

2.1 Introduction to Micro-Hydro Power Systems
Hydro power is the harnessing of energy from falling water, such as water falling through steep mountain rivers. The energy in flowing water is converted into useful mechanical power by means of a water wheel or a turbine. The mechanical power from the turbine can be converted into electricity using an alternator or a generator. A hydro power system is classified as micro when it generates power less than 100kW. MHPS are relatively small

power sources that may be used directly to run machines in a workshop or that may be fed into an electricity distribution network and may supply power to a small group of users or communities, who are independent of the general electricity supply grid.

A micro-hydropower system (MHPS) has the following components:

- A water turbine that converts the energy of flowing or falling water into mechanical energy. This drives an alternator, which then generates electrical power. This is the heart of the MHPS.
- A control mechanism in the form of electronic load controller to provide stable electrical power.
- Electrical distribution lines
- Each generation site is different, but generally, to develop an MHS the following features are needed:
- An intake or weir to divert stream flow from the water course;
- A headrace, the canal or pipeline to carry the water to the forebay from the intake;
- A forebay tank and trash rack (gravel trap) to filter debris and prevent it from being drawn into the turbine at the penstock pipe intake;
- A penstock (pipe) to transport the water to the powerhouse. This may be set up above the ground surface or underground depending on the topography of the site. At rocky sites, penstocks are supported above ground on concrete blocks called Anchors or Saddle (Pier) supports. The saddle supports are provided along the straight   length at regular intervals and anchors are provided at horizontal and vertical   bends along the alignment of the penstock. These are designed to carry the   thickness and the diameter of the penstock   (Indian   Institute   of Technology, 2008);
- A powerhouse, being the building that accommodates and protects the electro-mechanical equipment, (turbine and generator), that convert the power of the water into electricity;
- A tailrace through which the water is released back to the river or stream without causing erosion;

To determine the actual power output from an MHPS the following equation is used:

$$P_{actual} = \rho_{water} \times Q \times g \times h_{gross} \times \eta_{total}$$

where P_{actual} is the actual power produced (kW)

ρ_{water} is the density of water (kg/m^3)

Q is the flow in the penstock pipe (m^3/s)

g is the acceleration due to gravity (9.81m/s^2)

h_{gross} is the total vertical drop from intake to turbine (m)

$$\eta_{total} = \eta_{canal} \times \eta_{penstock} \times \eta_{manifold} \times \eta_{turbine} \times \eta_{drive} \times \eta_{generator}$$

Typical system component efficiencies are shown in Table 1:

Table 1: Typical System Component Efficiencies (Harvey, 1993)

System Component	Efficiency
Canal	95%
Penstock	90%
Turbine	60 -80%
Generator	85%
Step-up and down transformers	96%
Transmission	90%

The turbine efficiency is typically the lowest of the component efficiencies. Hence it has the highest chances of being improved and once this has been done, the overall system may be improved.

2.2 Turbines

Turbines convert energy in the form of falling water into rotating shaft power. They basically consist of the following components:

- intake shaft - a tube that connects to the piping or penstock which brings the water into the turbine
- water nozzle - a nozzle which shoots a jet of water (Impulse type of turbines only)
- runner - a wheel which catches the water as it flows in causing the wheel to turn (spin)
- generator shaft - a shaft that connects the runner to the generator
- generator - a unit that creates the electricity
- exit valve - a tube or shute that returns the water to the stream from where it came
- powerhouse - a small shed or enclosure to protect the water turbine and generator from the elements

The selection of the best turbine for any particular hydro site depends on the site characteristics, the dominant factors being the head available, the flowrate and the power required. This selection also depends on the speed at which the turbine is desired to run the generator or other device loading the turbine. Other considerations, such as whether or not the turbine will be expected to produce power under part-flow conditions, also play an important part in the selection. All turbines have a power-speed characteristic and an efficiency-speed characteristic. For a particular head they will tend to run most efficiently at a particular speed, and require a particular flow rate.

2.3 Pelton Wheel Turbine

A Pelton turbine (Figure 1) consists of a series of buckets or cups mounted around the periphery of a circular disc (i.e. the runner). The shaft of the Pelton turbine may have a horizontal or vertical orientation. The turbine is not immersed in water but operates in air with the wheel driven by jets of high pressure water which hit the buckets or cups. The kinetic energy of the water jets is transferred to the turbine as the water jet is deflected back. The principle of the Pelton turbine is to convert the kinetic energy of a jet of water into angular rotation of the buckets as the jet strikes. The high-velocity jet of water emerging from a nozzle impinges on the buckets (Figure 2) and sets the wheel (runner) in motion. The speed of rotation is determined by the flow rate and the velocity of water and these are controlled by the spear valve. In order to do this at the best efficiency, the water leaving the buckets after striking should have little remaining kinetic energy, having transferred most of its energy. Hence the water must have just enough speed to move out from between the buckets and fall away under gravity from the wheel.
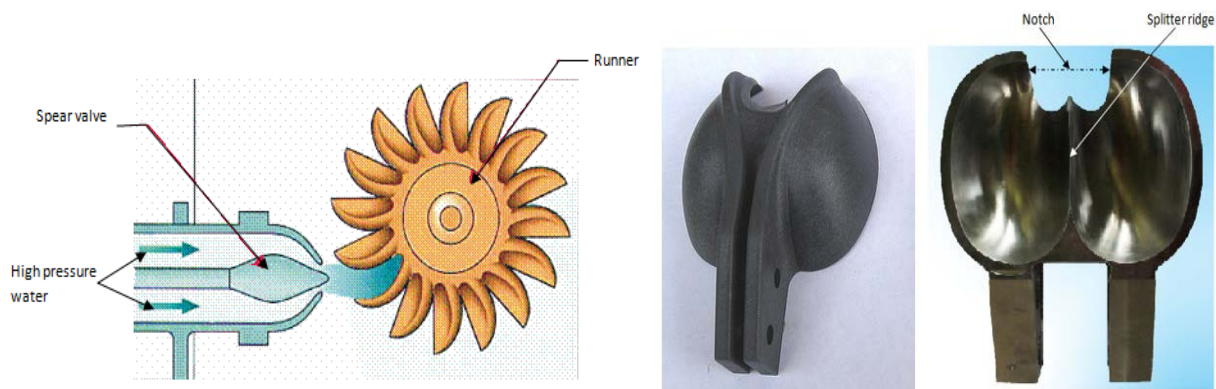

Figure 1: Pelton turbine. (HK RE Net, 2011) and a single bucket (Balino, 2011).

2.4 Characteristics Of Individual Pelton Wheel Bucket Which Affect Turbine Efficiency

Individual Pelton wheel buckets are designed to maximise the efficiency of the turbine. The central part of each bucket has a splitter ridge (Figure 9). This is the part that the water jet hits first. This splitter ridge should be sharp and smooth, so that it cleanly splits the jet into two halves. The force on the bucket comes from it catching the water and taking out as much of the water's momentum as it can. The more the water's momentum absorbed by each bucket, the better the turbine efficiency. Getting a good torque (turning force) from this force requires the force to act at as large a radius as possible. To achieve this, the position of the end point of the splitter ridge is important. The optimum position will have most of the water hitting the bucket when it is nearly at right angles

to the jet. The angle of the splitter ridge is set so that it is approximately at right angles to the jet when the full cross-section of the jet is hitting it. The rest of the internal shape is designed to allow water to flow freely round, and out at the edges. The water should emerge at as favourable an angle as possible, to give maximum moment from the momentum change. To achieve this, and hence achieve maximum efficiency, the surfaces must be smoothly curved, with a reasonably large radius. The end of the bucket, between the end of the splitter and the outside edge, is cut away to form a notch as shown in Figure 9. This shape is important as it allows the bucket to straddle the jet before the water starts to flow in it. This means that the bucket is at a much better angle to the jet when the water hits it, giving a good flow pattern and a greater force on it. If there were no notch, the jet would initially hit the outside lip of the bucket and flow straight in towards the hub, where it has no adequate escape route. This significantly reduces the power of the runner. The jet should always strike the surface between the splitter ridge first and never at the edges of the bucket (Thake, 2000).

Ideally the bucket should take the water around a complete 'U', removing all the energy from the jet, and leaving the water stationary in air and then have it fall under its own weight into the tailrace. In reality this is not achievable because the next bucket would hit the water left hanging in mid-air. The edges of the bucket are consequently angled outwards; just enough to make sure that the water clears the next bucket. The design is such that the jet is deflected back through 165^0 (the maximum angle possible at which the return jet does not interfere with the next bucket, see Figure 9).

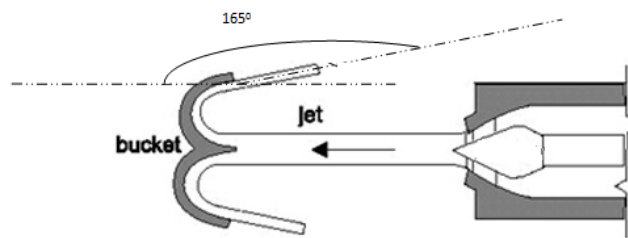Figure 2: Water jet being deflected back at an angle of 165^0. (Betp, 2011)

For optimum efficiency the speed of the jet, v_j, should be about twice the speed of the bucket, v_b. Because the runner is moving away from it, the speed at which the jet enters the bucket is given by $v_j - v_b$. The jet is split by the ridge and flows round the two cups to emerge at the sides of the bucket. The inside of the bucket should be as smooth as possible and evenly curved so that the water does not loose much speed as it goes round. Lack of smoothness reduces efficiency. If there were no losses, the water jet would leave at a velocity equal to $v_j - v_b$. If the jet speed, v_j, is twice the bucket speed, v_b, then the water, relative to the bucket, leaves at a speed of: $v_j - v_b = 2v_b - v_b = v_b$

So if the bucket is moving at a velocity of v_b and the water is coming out of the bucket at a speed of v_b, in almost the opposite direction, this would mean that the speed of the water coming out relative to the housing is nearly zero; its energy having been completely removed by the bucket.

2.5 Characteristics Of The Pelton Wheel Runner That Affect Turbine Efficiency

The characteristics of the runner that affect efficiency are: diameter of runner, number of jets, number of buckets of a runner and method used to attach buckets to a runner. As a general rule, a small runner is cheaper to make than a larger one. It takes less material and the housing and associated components can be made smaller. To use smaller runners requires dividing the flow of water among a large number of jets. Multiple-jet Pelton turbines can have up to six jets before interference effects between jets lead to too much inefficiency.

In order to optimise efficiency, the number of buckets on the turbine runner is generally between 18 and 22. (Thake, 2000). Too few buckets means that some of the water in the jet will not be caught by any of the buckets but will go through the gaps between the buckets. Too many buckets result in runner turning too slowly. For the Pelton wheel turbine to function as expected, the buckets must be attached securely onto the runner. There are a number of ways of mounting buckets onto the runner hub. The whole runner and buckets may be cast as one piece or buckets may be cast separately and are then bolted, clamped or welded onto the runner.

2.6 Materials Used To Make Pelton Wheel Turbine Buckets

The efficiency of a turbine is affected by the type of material used to produce the turbine buckets. The chief material requirements are high strength, abrasion resistance, casting suitability and ability to withstand extended

use in water. Materials in common use and their advantages and disadvantages are Aluminium, Copper Alloys, Grey Cast Iron, Stainless Steel and Plastic.

2.7 The Control Of Flow Rate For Maximum Pelton Wheel Turbine Efficiency

The efficiency of Pelton turbine is heavily dependent on the flow rate of the water jet. Therefore in order to maximise the efficiency of the turbine, it is of paramount importance to be able to control the flow rate. The need to control this flow arises due to site conditions that include change in water flow rate with changing seasons. There are various options that are used to control the flow of the water jet, and these include the varying of number of jets, the spear valve and the replacement of nozzles.

2.8 Friction

The issue of friction appears to have a great impact on the efficiency of a Pelton turbine. Turbine efficiency maybe separated and is better improved when dealt with separately. The efficiencies of the turbine are hydraulic efficiency, mechanical efficiency, volumetric efficiency and overall efficiency.

    i.   **Hydraulic Efficiency -** Hydraulic efficiency is defined at the ratio of power given by water to the runner of a turbine to the power supplied by the water at the inlet of the turbine. The power at the inlet of the turbine is the highest and this power goes on decreasing as the water flows over the buckets (or vanes) of the turbine due to hydraulic losses as the buckets are not as smooth. Hence the power delivered to the runner of the turbine will be less than the power available at the inlet of the turbine.

    ii.   **Mechanical Efficiency -** The power delivered by water to the runner of a turbine is transmitted to the shaft of the turbine. Due to mechanical losses, the power available at the shaft of the turbine is less than the power delivered to the runner of a turbine. The ratio of the power available at the shaft of the turbine to the power delivered to the runner is defined as mechanical efficiency.

    iii.   **Volumetric Efficiency -** The volume of the water striking the runner of a turbine is slightly less than the volume of water supplied to the turbine. Some of the volume of the water is discharged to the tail race without striking the runner of the turbine. Thus the ratio of the volume of the water actually striking the runner to the volume of water supplied to the turbine is defined as volumetric efficiency.

    iv.   **Overall Efficiency -** Overall efficiency is the ratio of power available at the shaft of the turbine to the power supplied by the water at the inlet of the turbine.

Friction has the greatest impact on hydraulic efficiency and in turn hydraulic efficiency is one of the factors affecting the overall efficiency. This makes friction an important factor in overall turbine efficiency.

3. Materials and Methods

Data for this project was collected through:

    i.   Document reviews - this was carried out through document reviews and online research. Text book research offered well accepted methods of designing and manufacturing Pelton and Cross-flow turbines. Online research gave information on Pelton turbines manufacturing processes that produce turbines of higher efficiency.

    ii.   Interviews - information on micro-hydro designing and current methods used in the designing Pelton turbines was provided by the NGO through interviews of key personnel.

    iii.   site visits – physical visits to where the turbines are manufactured and the actual sites where the MHPS are built

    iv.   Physical testing of efficiency of turbines was done at MHPS sites using a Tachometer.

    v.   Data collection and analysis – after all the data was collected tables and graphs were used to compare the data on current methods used by the NGO to manufacture turbines and show how efficiencies can be better improved.

4. Results Analysis and Discussion

4.1 Factors Affecting Pelton and Cross-Flow Turbine Efficiency

The improvement of efficiency of a turbine heavily depends on its design and manufacturing process. The friction within the Pelton buckets, the interaction of the water jet with the buckets, and the method of welding of the buckets to the runner all have major roles in the efficiency of a turbine. Working with the NGO engineers and the site visits to and interviews of key personnel at the workshop where Non-governmental organisation turbines are manufactured revealed the following as the process followed in the production of Pelton turbines.

    A.   Design and Manufacture of Pelton Turbine

The head and flowrates were collected from each of the four study sites. This data was used to calculate the gross power output hence the size of the runner, number of buckets, number and size of water jets. The efficiency of the turbine is designed at 60%. Two of the four sites that were analysed have Pelton wheel turbine working on them. Data from the sites is given in Table 2.

Table 2: The two MHS sites that have the Pelton wheel turbine installed on them

SITE	GROSS HEAD (m)	FLOW RATE (m³/s)	CAPACITY (kW)	TURBINE TYPE	EFFICIENCY (%)
A	51	0.325	88	Pelton	60%
B	138	0.035	20	Pelton	60%

The capacity for each site is the actual power output that was determined using Equation 2. Technical drawings are then made. Patterns of Pelton buckets are then made. This is a very crucial stage and is done by specialised skill. A pattern has to be perfect, having the exact dimensions of the required products. Sand casting then follows. Buckets are sand cast individually and bolted to a runner. Figures 3 to 5 show this process.

Figure 3: Pelton bucket that has been sand cast and after it has been machined

Figure 3 is showing a single bucket that has been sand cast. The feeder and the riser are still attached to the bucket and the bucket after being machined to remove the feeder and riser. It has 2 holes drilled through it for bolting to the runner. It is important to have the holes expertly drilled otherwise the buckets will not sit on the runner perfectly and the turbine is misaligned. This reduces the efficiency of the turbine as some energy is lost to heavy vibrations and noise since the water jet will not be hitting on the correct spot anymore.

Figure 4: Alignment of buckets on the runner and a complete turbine

Figure 4 shows how individual buckets are aligned on the runner and a finished turbine. They sit at an angle to each other. This allows for the full force of the jet to be applied on each bucket one after another without hindrance from the previous bucket. This ensures maximum efficiency of the turbine. Seventeen buckets are bolted onto the runner. The number of buckets per runner is important in making sure there is enough space between the buckets to allow the water jet to hit individual buckets with the same force. For Non-governmental organisation turbine sizes 17 or 18 buckets are used per turbine.

Figure 5 shows the turbine housing being welded together and the inside of the turbine housing.

Figure 5: Turbine housing being welded together and the inside of the turbine showing the nozzle

The individual parts of the turbine housing were cut using a cutting torch. The nozzle through which the water jet goes through to the turbine is seen in the picture. The sizing of the nozzle is important in having the correct size water jet, hence the right amount of force on the turbine that ensures maximum efficiency.

B.   Effect of Roughness Due to the Manufacturing Process

The turbines at the NGO operate are designed to operate at 60% efficiency and the processes used to manufacture them are sand casting, oxyacetylene welding and flame cutting. Each manufacturing process has a different roughness. This combined with material roughness determines the friction of a turbine and it will then translate to turbine efficiency, in particular hydraulic efficiency. As indicated in Equation 11 hydraulic efficiency affects overall turbine efficiency directly: Table 3 compares different manufacturing processes against the overall turbine efficiency associated with each process.

Table 3: The turbine efficiencies associated with roughness of different manufacturing processes (Ramsdale R., 2012)

	Manufacturing Process	Turbine Efficiency	Roughness
Pressure die casting	A	85.0	1.6
Investment casting	B	85.0	3.2
Milling	C	85.0	6.3
Laser	D	80.0	6.3
Electron beam	E	80.0	6.3
Oxyacetylene welding	F	60.0	25.0
Sand casting	G	60.0	25.0
Flame cutting	H	60.0	50.0

Figure 6 shows a graph that relates this roughness to the turbine efficiencies.
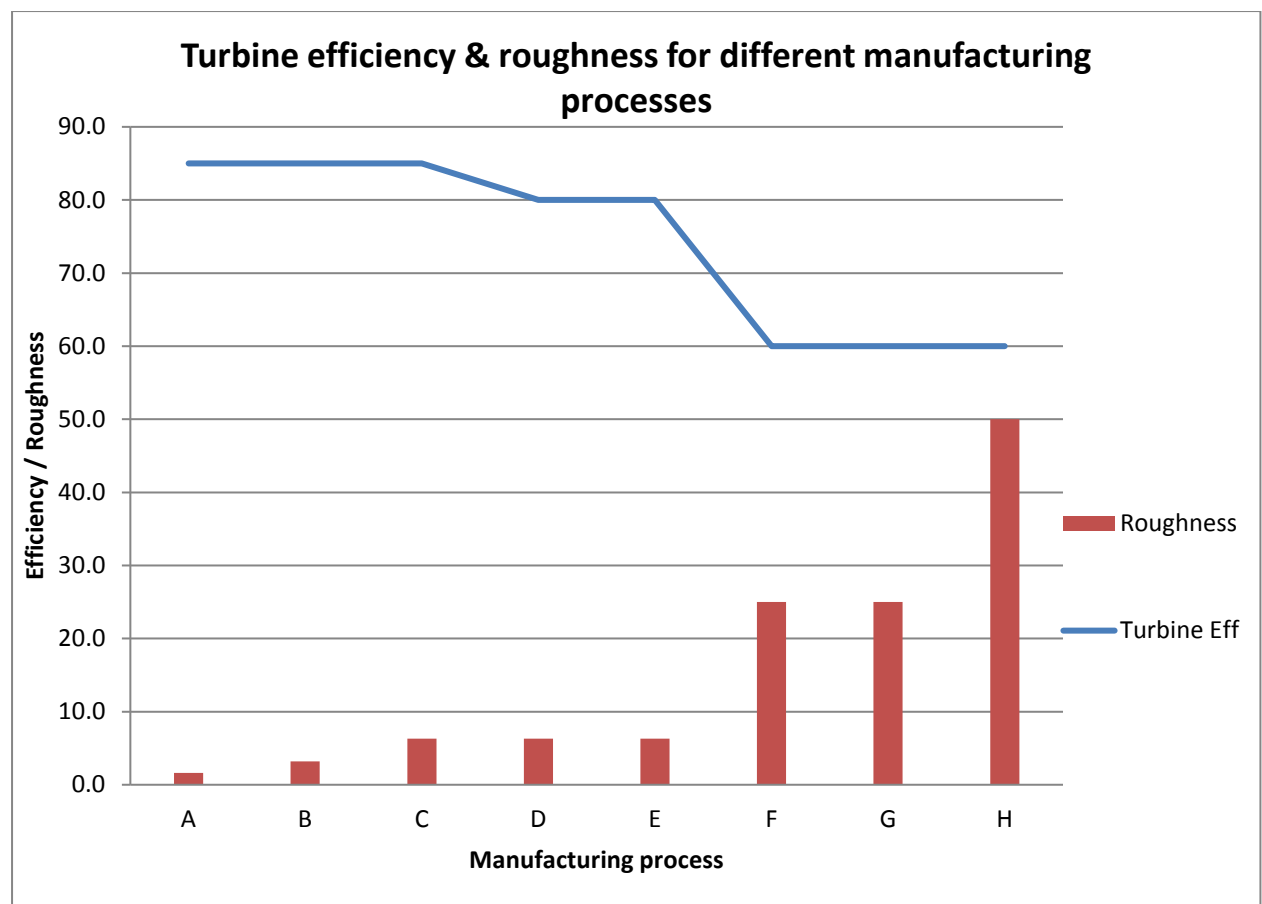

Figure 6: Turbine efficiency & roughness for different manufacturing processes

The graph indicates that as the manufacturing process roughness increases the overall efficiency of the turbine produced decreases. This emphasises the need to use manufacturing processes with minimal roughness.

This indicated that the flow friction in the Pelton buckets has a substantial impact on the system efficiency of the turbine. The efficiency drop resulting from the flow frictions represents the greatest part in the total loss in the system efficiency of a Pelton turbine. Mechanical efficiency is the other determining factor of the overall efficiency. One way to improve this efficiency in casting procedures is to cast segments comprising of a number of buckets or whole runners, comprising the runner and all the buckets.

C. Effect of the Water Jet Movement

Of great importance in the mounting of the Pelton turbine is its interaction with the water jet. For the NGO the mounting of turbines is done expertly, by the manufacturer of the turbines and inspected by the engineers. To maximise efficiency the jet must hit precisely the centre of each Pelton bucket. That way the jet gives the maximum drive to each bucket as noted earlier in the design of the buckets that the rotation of the turbine depends on the water jet velocity.

D. Turbine Material

The type of material used to fabricate a turbine affects its efficiency. Good materials are hard and must be able to resist erosion and corrosion. This ensures that the turbines will function at their best efficiency for the expected life span on the micro hydro power plant. At the NGO Stainless Steel is mainly used for Pelton turbines. Mild Steel is mainly used for casings.

However this study revealed that other materials that maybe used for turbines are Aluminium, Cast Iron, Copper based alloys such as Brass and Bronze, and Sheet steel. The properties of these materials and their prices per kg are tabled (Table 4).

Table 4: Properties of different materials and their prices per kg (Ramsdale R., 2012, MetalCorp, 2012)

MATERIAL	MATERIAL	ROUGHNESS $(\times 100^{-2})$	BRINELL HARDNESS $(\times 100)$	PRICE/KG (US\$/kg)
A	Aluminium	0.2	1.2	1.32
B	Grey cast iron	25	3.02	0.83
C	Brass	1	3.6	5.54
D	Bronze	1	3.6	5.54
E	Stainless steel	3	4.15	1.47
F	Sheet Steel	15	4.5	0.29

Figures 7 and 8 show the relationships between roughness and price per kg of material and hardness and price per kg of material respectively.
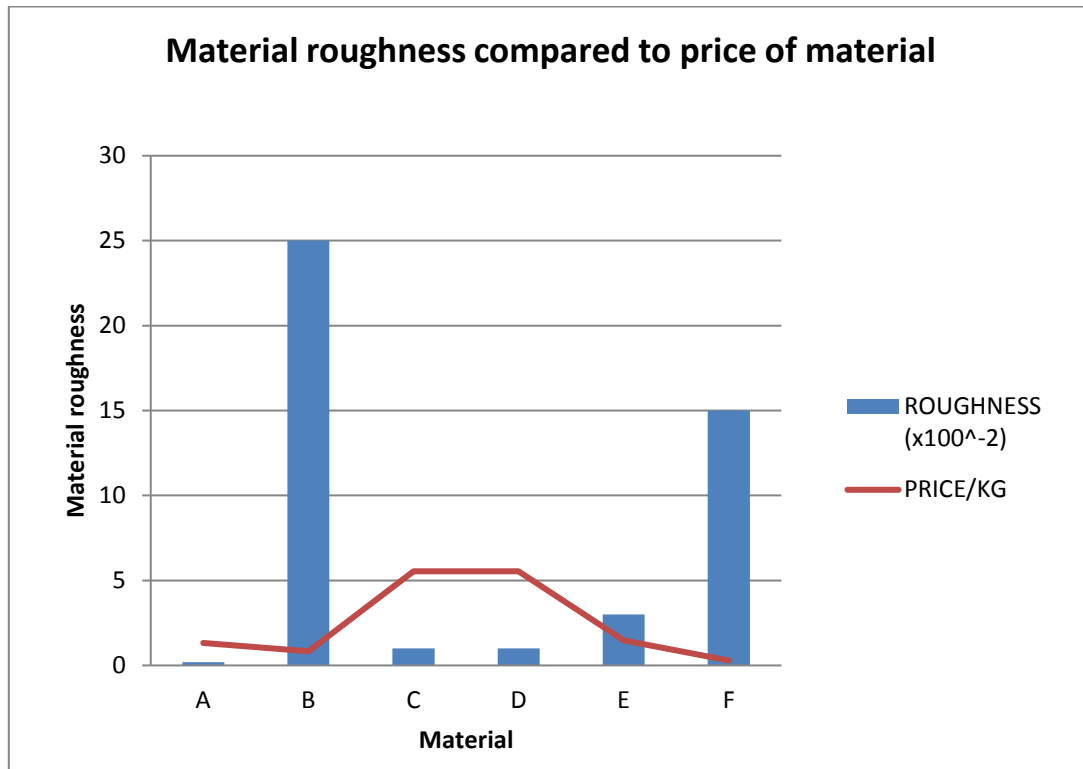
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Material roughness compared to price of material

Figure 7: Material roughness compared to material price
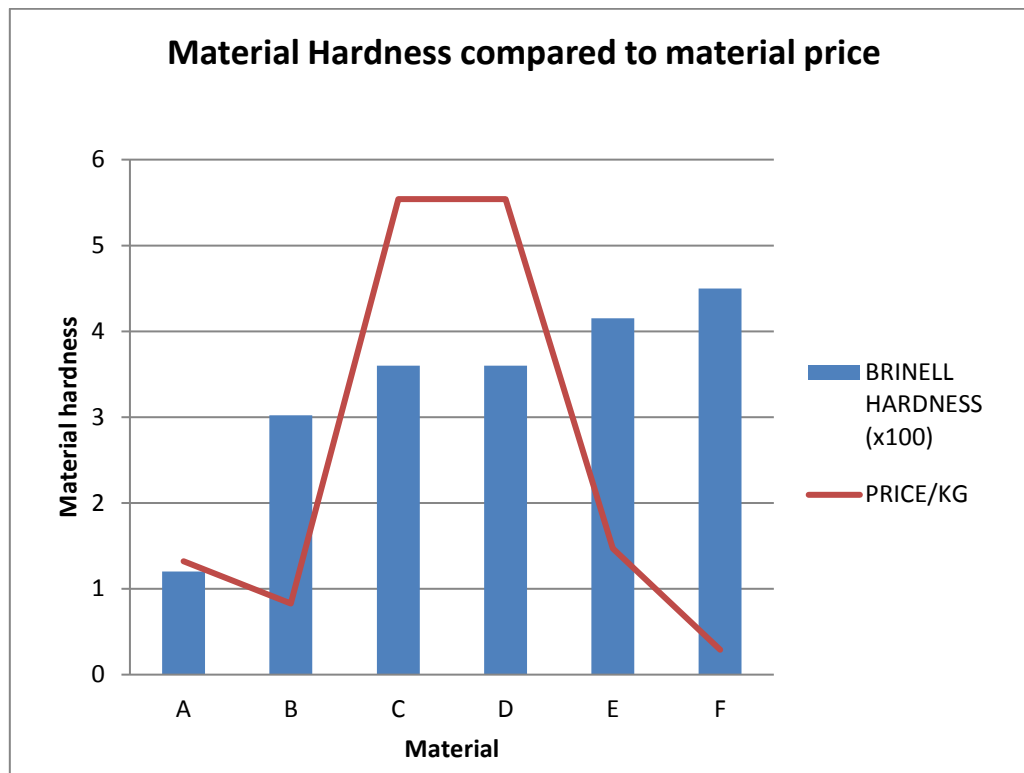
Material Hardness compared to material price

Figure 8: Material hardness compared to material price

The two graphs shows why Stainless steel is the most commonly used material in the manufacturing of turbines for MHS. It has a high hardness, a very low roughness and price is close to the lowest. Sheet Steel maybe the cheapest and its hardness is slightly higher than that of stainless steel but its roughness is much higher than Stainless Steel. Such a roughness means that it has a much higher friction than Stainless Steel and this is not good for the hydraulic efficiency of the turbine and hence the overall efficiency. Brass and Bronze are too expensive

for MHS. This is because they are alloys of Copper which is a very expensive metal. Its price is about $8 per kg. (Metalcorp, 2012)

Aluminium has a price close to Stainless Steel and the lowest roughness, but is susceptible to damage if debris such as stones and sand find their way to the turbine. This is because it has the lowest hardness. The roughness of Grey Cast Iron is too high. This compromises the turbine efficiency despite having a low price and a fairly high hardness.

4.2 Performance Measurements

After the turbine has been set up and the micro hydro is just starting to run, it is of utmost importance to measure the efficiency of the turbine in order to verify if it is meeting the expected efficiency. This is done using a tachometer. This is done at the initiation of a project and after it has run for six months to check if all is performing as expected. During the period of study the tachometer was used to check the performance of the turbine at Site B where the project had been running for six months.

4.3 Effect of Increasing Turbine Efficiency on the Micro Hydro Scheme Power Output

Turbine manufacturers who use manufacturing processes that give the least roughness possible using Stainless Steel supplied quotations and their superior Turbine efficiencies. Two MHPS being constructed by the NGO were analysed further looking at the change that these turbines will bring in terms of the power output. The change in actual power output due to increase in turbine efficiency of the two MHPS that were studied is shown in the Table 5.

Table 5: Differences in power output due to increase in turbine efficiency

Site	Turbine Type	Current Tubine Eficiency	Current Power Output (Kw)	New Turbine Efficiency	Possible Power Output (Kw)
(A)	PELTON	0.60	88.00	0.85	124.67
(B)	PELTON	0.60	20.00	0.85	28.33

In both cases there is a remarkable increase in power output coming from the same resources. MHS are small projects that are usually donor funded. Therefore using the materials and manufacturing processes that give the highest possible yield from each site and resources is most ideal. The prices of turbines in the quotations supplied were such that the project costs remained within the budgets.

5. Conclusion & Recommendations

This study has revealed that turbines of better efficiencies can be manufactured, made available for MHS and the projects remain financially viable. This was achieved through the comparison of current fabrication methods used at the NGO to methods used by different suppliers of turbines. Even though the better efficiency turbines are more expensive than the ones being used currently the overall benefit is clear. More electricity is generated hence the cost per unit kW actually decreases making the projects even more viable. The financial viability of a project was determined by the project cost per kilowatt produced. Use of better efficiency turbines will make it possible to harness more electrical power from the same resources.

The NGO is highly recommended to consider investing in processes that produce turbines with higher efficiencies such as:

- Pressure die casting of turbines. They may be cast as whole turbines or as segments made up of a number of buckets.
- Investment casting of whole turbines.
- CNC milling of Pelton buckets.
- Cutting of Pelton runner and Cross-flow runner and blades using CNC laser, CNC plasma.
- Electron beam and laser welding of blades to runners.

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These processes offer far less roughness compared to current methods that include sand casting, flame cutting and oxyacetylene welding. That reduction in roughness lessens friction and the overall efficiency of a turbine is increased.

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Biography

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