Abstract

Energy is one of the most vital resources for the socioeconomic development of any community. Cameroon has the second greatest potential for hydroelectric production in sub-Saharan Africa; however, a mere 2.1% of that potential is developed, and less than 12% of Cameroonians have access to electricity. In the village of Bangang, there are four small hydropower projects in various stages of development. These have the potential to provide 300 kW of renewable energy to the local populace. Development of these hydropower systems has begun with two fully operational turbines, but the projected capacity has yet to be achieved. The current turbine efficiencies are substandard, resulting, in part, from the lack of exhaustive engineering design.

This research aims to evaluate the current systems and use the data to improve the existing Bangang community hydropower turbine designs. To reach this goal, an interdisciplinary undergraduate service-learning team collaborated with a community-based non-governmental organization (NGO) to design, test, and fabricate a cross-flow hydropower turbine with an estimated 150 kW capacity. The device was fabricated at Purdue University according to provincial constraints and tested under real-world conditions on location in Cameroon.


Keywords

Cameroon, development, energy, micro-hydropower, multidisciplinarity, renewable, service-learning, turbine

Mentors

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INTRODUCTION

Micro-hydropower is the small-scale harnessing of energy from falling water, generating from 5 kW up to 200 kW. Micro-hydropower systems usually provide power for a small community or rural industry in remote areas away from the main electricity grid (Nfah, Ngundam, Vandenbergh, & Schmid, 2008).

Micro-hydropower research in Bangang, Cameroon, was initiated in 2007 by the African Centre for Renewable Energy and Sustainable Technology (ACREST), an NGO. ACREST is committed to the research of affordable, sustainable technologies in an effort to eradicate poverty and hunger in Africa. The organization strives to “promote, facilitate and initiate social development projects and programmes that bring tangible positive impact to the basic living conditions of people” (ACREST, n.d.). Dr. Vincent Kitio, the NGO’s founder and director, has invested in locally sourced and manufactured renewable energy technologies: wind, solar, biogas, and hydro. In 2008, a working relationship was established between ACREST and the Purdue University Global Engineering Program (GEP); the following summer, a team of five students and a faculty advisor spent eight days at the ACREST campus in Bangang to explore collaborative potential.

By late 2009, ACREST had prepared an official hydropower plan for designing, constructing, and maintaining a 150 kW system. It is important to note that ACREST was, by this time, already engaged in a number of smaller-scale hydropower endeavors in the range of 0.5 kW to 50 kW, but the technicians at ACREST had yet to achieve the mechanical efficiencies necessary to generate a net 150 kW. ACREST requested technical input from GEP in the form of thorough and explicit engineering design.

To address this complex sociocultural and engineering challenge, an interdisciplinary team of undergraduate and graduate students was formed through GEP’s Global Design Team (GDT) initiative—a program that uniquely positions students to address real-world, full-cycle engineering design through immersion and travel (Mohtar & Dare, 2012). Since 2009, over 30 students have participated in the hydropower GDT at Purdue, with 12 of those students traveling to ACREST. The length of stay has ranged from eight days to eight weeks, with some students returning two, three, or four times, thereby strengthening the relationship between the community around ACREST and Purdue, while gaining valuable technical insights in order to think critically about effective engineering design. The primary objectives of this GDT were determined as: (1) to conduct a comprehensive feasibility study of existing ACREST hydropower resources in development, and (2) to design, fabricate, and install an operational, previously unattainable, micro-hydropower turbine on the scale of approximately 150 kW for the community of Bangang. This was a collaborative effort between Purdue engineering students and local Cameroonian technicians.

In May 2010, three students traveled to ACREST on behalf of the hydropower GDT to survey existing hydropower sites, measure flow rates, analyze the local watershed, and conduct a preliminary sociological survey of the project community impact. These studies yielded a detailed map of the ACREST campus, the hydropower facilities, and the waterfall (Figure 1) from which all hydropower turbines source, as well as the topography...
around the hydropower infrastructure (canal, penstock, powerhouse, etc.), relative flow rates, and a general perception of community interest in micro-hydropower as a local industry. A major constraint in the design of a rural micro-hydropower system in West Africa is the annual fluctuation between the rainy and dry seasons. Research on the rainfall patterns in the Bambouto mountain chain, wherein Bangang is located, indicates that the rainy season starts in mid-May and continues through mid-October (Ngouanet et al., 2006). This run-of-the-river turbine had to accommodate a variable flow system in order to maintain the highest efficiency year-round.

Given this information, a new turbine was designed by Purdue engineering students on campus during the 2010–2011 academic year and was fabricated during the 2011–2012 academic year. The finished prototype can be seen in Figure 2. The team considered three principal criteria in the design of a maximally efficient turbine: variable flow rates, pressure head, and system layout. The new prototype, a cross-flow (also known as Banki-Michell) type, was designed to accommodate local material and fabrication constraints. Research has shown that a cross-flow turbine is preferred over other turbine types for this application (Aziz & Desai, 1991), and the project partner, ACREST, was already very familiar with the maintenance, upkeep, and precision necessary to fabricate, operate, and maintain a cross-flow turbine. Among the cross-flow turbine’s most novel characteristics is its ability to maintain a relatively flat efficiency curve over a much wider flow variety (Joshi, Seshardri, & Singh, 1995). This is accomplished, in part, by using an adjustable regulating plate located at the turbine inlet, which reduces the effective nozzle area, thereby increasing the water pressure striking the blade area and, consequently, producing more torque on the shaft, which yields a higher rotational shaft speed and a higher resultant power output. This mechanical flexibility suggests that the cross-flow type is well suited for rural, run-of-the-river micro-hydropower schemes in communities throughout Cameroon and elsewhere in Africa, which experience extreme flow rate variance from month to month and year to year.

The turbine dimensions are largely derived from the energy equation applied to the hydroturbine infrastructure simplified in Figure 3 (Nasir, 2013):

$$
\frac{p}{\gamma} + a \frac{v^2}{2g} + z = \left( \frac{p}{\gamma} + a \frac{v^2}{2g} + z \right) + h_f + h_i
$$

This states that, while the individual properties of water may change from one point to the next (the velocity of falling water, for example, will be different at different altitudes), the conjunction of those properties remains unchanged between any two points, assuming all losses

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**Figure 1.** Waterfall located near ACREST hydropower infrastructure from which the turbines source.

**Figure 2a.** Elevation view of 2010–2012 hydropower turbine prototype.

**Figure 2b.** Isometric view of 2010–2012 hydropower turbine prototype.
are considered or idealized. For this turbine, losses were considered for the penstock pipeline, pipe connections, and turbine nozzle.

During the design procedure, force analyses were performed on the housing, blades, and other areas of the turbine, which would experience locally extreme water pressures. A shaft analysis ensured that the turbine runner shaft would not fail in fatigue or yielding, and fluid flow analyses were performed to predict approximate streamline patterns using the ANSYS FLUENT modeling application. At the time of design, it was estimated that the turbine efficiency would be approximately 65% and that the power produced would range from approximately 26 kW in the dry season to 169 kW in the rainy season with a 40-meter pressure head, thus fulfilling the design objective of 150 kW (Ileleji, 2011). The final turbine design featured a unique flow regulating plate. In contrast to the classic cross-flow nozzle regulator, which resembles a “tear-drop” geometry (Figure 4) and runs width-wise along the entirety of the nozzle, the 2010–2012 prototype featured a pivoting plate with a length-wise nozzle orientation intended to expose a lesser runner width to the nozzle jet stream (Figure 5), thereby increasing the force exerted on a differential runner segment and ultimately increasing overall efficiency. The effect of this mechanism on the flow properties can be seen in Figure 6.

The prototype material, one-quarter-inch 1020 cold-rolled steel, was pre-cut at Purdue using a waterjet cutting machine at the Purdue Artisan and Fabrication Lab (AFL). Parts were then welded using E6013 weld wire, and all joints were calibrated to a high precision. These ideal conditions are not replicable in Bangang, given the material and tooling constraints at ACREST, but in the interest of time, it was deemed necessary to use these fabrication techniques to acquire proof of concept. This prototype was delivered to Cameroon in May 2012 during the team’s fourth trip and, after calibrating the machine to fit the ACREST hydropower infrastructure, was tested under real-world, rainy season conditions in June 2012. The test was conducted by ACREST technicians without oversight by Purdue researchers. No discrete record of daily operation/maintenance or turbine performance was kept during this time. All resulting data (power output, functionality, rain conditions, debris frequency, etc.) were recorded subjectively via informal interviews with key ACREST personnel in January 2013 and are considered valid only for the purposes of qualitative design reiteration.

The prototype was tested for approximately three weeks until a catastrophic, indeterminable failure resulted in the loss of at least eight runner blades and the partial shearing of both runner end discs. The prototype was left in disrepair, and all testing ceased by July 2012. ACREST technicians reported that the turbine produced
...approximately 80 kW with a 25-meter head, so determined by the cumulative electrical loading of appliances (the sum of these differential appliance loads was assumed to be equal to the net power output, neglecting switch-on surges), though the validity of this determinant is contested. At the time of failure, the runner was reportedly rotating at a rate of approximately 2,600 rpm—well above the design rating of 900 rpm. This suggests there was a conjunctive failure of the ACREST load controller that allowed the runner to spin unregulated.

It is theorized that the extensive internal runner damage was caused by large debris contacting a runner blade and, perhaps, consequently, exploiting an anomaly in the turbine materials, such as a small crack in a runner blade or faulty fabrication practices (welds exhibiting insufficient penetration, for instance).

METHODOLOGY

Failure Analysis

After the failure of the 2010–2012 turbine prototype, it was necessary to perform a failure analysis to justify design recommendations for a new turbine iteration. As none of the missing runner blades were ever recovered, the primary source of information used in the failure analysis was a series of pictures taken of the failed turbine in January 2013, two of which are seen in Figure 7. These images clearly show the missing runner blades and the fractures left at the welding locations. Valuable information was collected from visual inspection of the fracture grains and the remaining weld beads. A stress analysis was also performed on the blades to assess the fatigue experienced during normal turbine operation.

Turbine Redimensioning

The decision was again made to consider solely the cross-flow type turbine due to a request by ACREST Director Dr. Vincent Kitio. The cross-flow is a design with which the ACREST technicians are familiar and which suits the environmental platform. As mentioned in the introduction, the turbine dimensioning calculations are largely derived from the energy equation, though some variables are a judgment call (Nasir, 2013).

RESULTS AND DISCUSSION

Failure Analysis

Initial analysis of the failed turbine photographs led the following observations:

- High-stress concentrators exist at the bottom of runner blade slots
- Irregular welds and spot welds were used
- Possible high-cycle fatigue arose in single spot welds
- Failure mode exhibited multiple initiation sites
- Blades may have broken on one side and then torqued the other side to fatigue failure

Previous trips to Cameroon revealed large, dense debris, most notably the mature raffia palm seeds (Figure 8) that, when fully ripened, become extraordinarily compact. The team recorded seeds as large as 5 cm by 3 cm by 3 cm, ellipsoidal in geometry. Because the clearance between the runner and the housing in the turbine prototype was approximately 1.2 cm (Figure 9), it is speculated that a raffia seed, or similarly dense object, spontaneously and abruptly halted the runner rotation. As mentioned in the introduction, at the time of failure the runner was reportedly operating at 2,600 rpm but was designed for a 900 rpm maximum. Additionally, the team of students fabricating the turbine at Purdue only welded one side.
Figure 7. Evidence of catastrophic runner disc and blade failure.

(Exterior) of the blades to the runner discs. The other side (interior) was welded in Cameroon, under insufficient power to achieve proper penetration, as evidenced by the weld flux pooling on the surface of the steel discs.

During failure, at least eight blades were lost, as well as sections of the runner discs. At an approximate operating speed of 2,600 rpm, it would require a torque of about 20 kN-m to stop rotation. A conservative, one-second deceleration time assumption was made. Although the turbine likely experienced deceleration at a fraction of one second, the blades and runner discs fractured under this assumption, and a faster deceleration time would only increase the calculated stresses. The following stress states were calculated using equations (Ashby, 2005; Bowman, 2004) that assumed debris was stuck at the midpoint of the blades between the blades and the housing. This would cause an effective stress on the runner plate, at the bottom of the slot (Figure 7), of about 800 MPa, well above the yield strength of 200 MPa and tensile strength of 400 MPa for plain carbon steel. The welds would experience a high-shear stress, about 500 MPa. Likewise, the ultimate tensile strength (UTS) of E6013 weld wire is 490 MPa. The blade would have a maximum stress of 350 MPa at the slot location, below UTS for the blade. Additionally, the weak weld joints would lead to failure at a lower than predicted stress. Figure 7 corroborates the calculations—the welds and runner discs should have failed while the blades would yield but remain intact—no blade fragments were left in any fractured runner disc slot. It was calculated that under the 2,600 rpm operating conditions, with no debris hindering rotation, the blade and welds experience stress (approximately 55 MPa) well under the yield stress of each material. Thus, it can be concluded that a foreign object likely interrupted blade rotation suddenly and caused a catastrophic failure. Figure 7 shows a brittle and fatigue-like fracture. It is possible that a foreign object caused the initial event and the resultant fatigue and/or subsequent high-speed impacts from the dislodged blades caused further failures.

For future turbine designs, this team recommends that anything contacting water be painted with an anti-corrosive paint, especially the weld-to-base metal interface area. After looking into multiple methods of corrosion protection, a layer of protective paint is the cheapest and most feasible option for application in Cameroon. If possible, all materials contacting water should be stainless steel (304SS or 316SS); however, paint will most likely substitute due to the high cost of stainless steel. Additionally, since no heat treatment facilities are available to stress relieve welds in the Bangang village, proper welding techniques will prevent stress corrosion cracking arising from large grains of a heat-affected zone.

The 2010–2012 turbine prototype was welded with E6013 weld wire. Using a low hydrogen electrode (such as E7018) will help prevent hydrogen-induced cracking (HIC). HIC often occurs when hydrogen is trapped in solid solution in the metal and can cause cracking or blistering of the metal; it is typically seen as underbead cracks (Bailey, 1993). A low hydrogen weld process and paint will help eliminate the possibility of stress corrosion cracking. Also, placing one or more runner discs at intervals along the runner assembly (as opposed to the two end discs on the 2010–2012 prototype), as seen in Figure 10, will provide extra support and will aid in preventing catastrophic failure if another object is impulsively lodged in the turbine. The bottom of the runner slots (Figure 7) should also be

Figure 8. Example of a raffia palm seed specimen.
allowed the team to update calculations and dimension recommendations. The results of these analyses (Nasir, 2013) can be found in Table 1.

**CONCLUSIONS**

Future turbine design iterations must reflect these results and recommendations. It is well understood that local constraints (material availability, precision tooling, ideal debris filtration, etc.) in Bangang, Cameroon, pose an obstacle to achieving maximum efficiency. Likewise, the final turbine design must be appropriate for the ACREST technicians’ skillsets (Figure 11). This means that, while final redesign recommendations can be made with regards to the dimensions and fabrication conditions, future successes and failures will be determined by the constructive collaboration between Purdue engineering students and ACREST technicians (Figure 12). In hindsight, what appeared at first inspection to be inherent turbine inefficiencies in previous ACREST micro-hydropower designs are actually careful calibrations made to allow debris to flow through the machines unfettered—an oversight that resulted in the ultimate mechanical failure of the 2010–2012 prototype.

Engineers’ constant pursuit of higher efficiencies in lieu of a true understanding of appropriate technologies, often a function of culture, and the resultant failures of those biases are well documented (Ika, Diallo, & Thuillier, 2011; Dey, 1981). The subsequent necessity for cross-disciplinarity is also well understood (Fisher & Schoenberger, 2008; Chase, 1990). The most compelling prospect for future research in the micro-hydropower field relies critically on the intersection of culture and engineering. All facets of true cross-disciplinarity and multiculturalism should be explored for successful project design and implementation.

One does not have to look far to find abundant examples of well-intended development projects that have failed due to some oversight or cultural gaffe (Nolan, 2002). Although this project is grounded in a strong commitment from ACREST and GEP, further efforts should be made to strengthen the involvement of the rest of the community of Bangang so that each resident feels a sense of ownership and responsibility for the project. Experienced consultants from anthropology and the engineering disciplines have been instrumental in efforts to reinforce the cultural appropriateness, acceptance, and sustainability in the hydropower scheme.

**ACKNOWLEDGMENTS**

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Table 1. Ideal micro-hydropower turbine calculations for ACREST facility.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N\text{turb} \text{= 750 rpm}</td>
<td>Speed of turbine (2:1 gear ratio assumed)</td>
</tr>
<tr>
<td>D\text{runner} \text{= 33 cm}</td>
<td>Diameter of runner</td>
</tr>
<tr>
<td>D\text{runner, int} \text{= 23 cm}</td>
<td>Diameter of runner interior</td>
</tr>
<tr>
<td>D\text{shaft} \text{= 4 cm}</td>
<td>Minimum shaft diameter</td>
</tr>
<tr>
<td>t\text{jet} \text{= 3.4 cm}</td>
<td>Thickness of jet</td>
</tr>
<tr>
<td>b\text{e, max} \text{= 27 cm}</td>
<td>Width of runner and jet</td>
</tr>
<tr>
<td>r\text{e} \text{= 5.5 cm}</td>
<td>Runner blade radius</td>
</tr>
<tr>
<td>n\text{blade} \text{= 20}</td>
<td>Number of blades</td>
</tr>
<tr>
<td>β \text{= 33 degrees}</td>
<td>Angle of blade inlet</td>
</tr>
<tr>
<td>α \text{= 16 degrees}</td>
<td>Water jet angle of attack</td>
</tr>
</tbody>
</table>

Turbine Redimensioning

The acquisition of cumulative environmental information from four years of return trips to Cameroon, as well as new publications in the micro-hydropower field, has

rounded if possible, as any sharp corners will cause a stress concentration. Cracks are not only more common for these regions, but will propagate faster. Speed of the turbine must be limited to its maximum rated operating speed (in revolutions per minute). Back-calculating from the stresses caused by debris, it was determined a speed of about 1,550 rpm or lower may have prevented catastrophic failure.
authored by the 2013 design team, the work of previous hydropower teams remains an invaluable foundation for our research. Members of those teams from 2009 to present, while too numerous to acknowledge by name herein, are very much appreciated, and their contributions are represented in this article. Thanks also to Mary Schweitzer, Anne Dare, and Tiago Forin from the Purdue GEP for project assistance and planning support; to Dr. Riall Nolan and Jonas Ecke from the Purdue University Department of Anthropology and Dr. Jun Chen from the Purdue University School of Mechanical Engineering for consultation on various project components; and to our project partner, ACREST, its director, Dr. Vincent Kitio, its North America representative, Dr. Isaac Zama, and all of the ACREST technicians for their input, support, and partnership with this initiative. This project is funded by the EPA’s P3 Program, under EPA agreement number SU834723, with additional support from the Purdue University Office of Engagement, the Purdue Engineering Student Council, and the Global Engineering Program.

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