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Development of guidelines for the construction of wind turbines using scrap material

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Abstract

Worldwide, approximately 2 billion people lack access to reliable electricity. This results in limited access to refrigerated foods and medicines, emergency hospital facilities, and lighting. A lack of lighting alone is known to prevent education of children, especially girls. Providing reliable access to electricity is essential in raising the quality of life for 2 billion people. However, electricity generation is usually expensive, or has high capital costs and requires a high degree of technical knowledge. To help address this issue, a set of guidelines for the development and manufacture of different wind power generation systems has been written. The guidelines are designed such that the users can build wind turbines based on the scrap material that they have available. To ensure the guidelines were suitable, four proof-of-concept devices were made and tested in the field and in a wind tunnel. The results show that power generation is possible with limited equipment and technical capability. However, further work is required to optimise the manufacturing processes.

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Keywords: Wind power; wind turbines; manufacturing

1. Introduction

One fifth of the global population does not have access to electricity. Furthermore, around 84% of this figure represents people living in rural areas [1]. Lack of access to reliable electricity can have significant effects on education, economics, health, and gender equality [2, 3]. There is a need for greater access to electricity worldwide, but financial limitations are a significant impediment. Therefore, it is required to provide reliable access to electricity as inexpensively as possible.

Power generation can be either centralized or decentralized. Centralized systems require high initial investments for power plants and distribution infrastructures, but their larger capacity provides more users with access to electricity. Decentralized systems require smaller initial investments due to their residential or community-sized infrastructures, but provide fewer users with access to electricity. In order to provide reliable electricity to those who do not have access to it, consideration must be given to their limited financial capabilities and to the remoteness of the rural areas where most of them live. Greater focus should therefore be placed on small-scale decentralized power systems. Additionally, in order to promote sustainable power generation, the particular focus of the current work is on small-scale renewable power sources.

There are several types of renewable power systems, but most are not suitable to all users. Hydropower, tidal and wave power systems can provide pseudo-constant and somewhat predictable power generation, but are restricted to regions with sufficient flowing water [4]. Similarly, geothermal power systems provide predictable and controllable power generation, but require large infrastructures to be built and are restricted to regions with sufficient subterranean thermal energy [5]. Solar photovoltaic cells are often expensive [6], while solar thermal systems are not suitable for small-scale energy generation [7]. Wind turbines are

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dependent on sufficient wind speed, but are a proven technology and less expensive than several other power generation systems. Therefore, the implementation of small-scale wind turbines is deemed the most adequate solution to provide electricity to many off-the-grid rural communities.

Commercial small-scale wind turbines are typically unaffordable to those living in impoverished rural communities. However, making use of existing and potential scrap material to manufacture small-scale wind turbines enables users to benefit from renewable power without having to depend on external support. Scrap material is widely available in most parts of the world, and local ingenuity can be used to transform it into wind turbines that are better suited to local conditions. Unless certain skills or materials are required to service the power generation equipment, the construction and maintenance of these systems should be inexpensive, and thus feasible for impoverished rural communities. It is therefore optimal to enable communities in resource-constrained regions to build their own wind turbines that are fit for purpose.

The aim of the detailed project was to create a set of guidelines for the construction of wind turbines using scrap material. This includes assessing the proof-of-concept by manufacturing and testing four different wind turbine designs.

2. Background

Wind turbines are classified as either horizontal axis wind turbines (HAWTs) or vertical axis wind turbines (VAWTs) [8]. These designs have different advantages and disadvantages, thus preventing a universal wind power generation solution. Horizontal axis wind turbines have higher theoretical efficiencies than their vertical counterparts, but their performance is sensitive to wind direction [8]. Yaw control can mitigate this issue, but it also increases design complexity. Furthermore, HAWTs are often subject to a minimum cut-in velocity, and require good structural rigidity to support several components above ground level [8]. Vertical axis wind turbines can be less complex to design and manufacture than their horizontal counterparts. Additionally, they often do not have a minimum cut-in velocity, and are designed such that their gearing systems and generators are located at group level [8]. However, due to being less efficient, VAWTs generate much less power than equivalent sized HAWTs [8]. Based on these differences, the guidelines consider and detail both designs.

The mechanical components with the greatest influence over the performance of a HAWT are the blades. Good blade design should consider the lift and drag generated, structural rigidity, vortex shedding, and tangential velocity, among other factors [8, 9]. Several features can be added to the blades in order to improve their efficiency, torque, and rotational speed characteristics. These include the use of airfoils and cambered cross-sections, taper, and twist [9, 10]. Proper selection of the number of blades used and their radius can also improve the performance characteristics of a HAWT [9, 10].

Vertical axis wind turbines can be classified as being based on lift or drag. The Darrieus and H type wind turbines are the most common lift based designs, while the Savonius wind turbine is the most common drag-based design [11]. Despite having smaller efficiencies [12], Savonius wind turbines are simple to manufacture and suitable for different environmental conditions [13]. It could be argued that the larger efficiencies of the Darrieus and H-type wind turbines validate their difficult manufacture, but HAWTs are still able to achieve greater efficiencies and are easier to build [14, 15]. For these reasons, Savonius wind turbines were the only VAWTs detailed in the guidelines.

Rotor design has significant influence on power production from Savonius wind turbines. Similarly to HAWTs, consideration should be given to lift and drag generation, structural rigidity, vortex shedding, and tangential velocity, but differently. The performance characteristics of Savonius wind turbines can be improved with proper selection of blade radius and shape [16], number of blades used and their positioning [17], and aspect ratio [18, 19, 20]. They can also be improved with the addition of endplates [12] and multiple vertical stacks [17].

Generators are components common to HAWTs and VAWTs that convert mechanical power into electricity. Ideally, the generator should have low start-up torque and high efficiency in order to maximise the performance of a wind turbine. It should also be able to produce a suitable voltage output at a low rotational speed. The most adequate generators for DIY small-scale wind turbines are the direct current, permanent magnet synchronous, and wound-field synchronous configurations [21]. Alternatively, their motor counterparts can also be used.

The guidelines present different alternatives for the construction of HAWTs and Savonius wind turbines, in addition to information on how to source and use generators. Recommendations are given on how to improve the performance of a particular wind turbine design, while keeping in mind the material and manufacturing constraints present in developing nations. Effectively, the guidelines are an interactive manual that encourages the user to choose their own wind turbine designs based on what capabilities and materials are available to them.

3. Methodology

Assessment of the wind turbine prototypes was conducted by first testing the generators in isolation from the blades, and then testing them in conjunction with them. The generators were tested by connecting their shafts to a metal lathe capable of controlled torque and rotational speed. The metal lathe allowed for rotational speeds between 60 RPM and 2000 RPM, but the testing speed range varied for each generator based on their recorded outputs and vibrational movement during testing. In order to determine the start-up torque, an Extech 475044 force gauge, which has a 20 kg range and 0.5% accuracy, was used. In order to test the power and voltage output, a Digitech QM1523 multimeter, which has a 1.2% AC voltage accuracy and a 0.8% DC voltage accuracy, was used. Rotational speed was measured using a Digitech QM1448 tachometer, which has a test range of 2.5 RPM to 99999 RPM and a 0.05% accuracy.

After the wind turbine prototypes were built, field and wind tunnel tests were conducted to access their performance. Field testing was conducted in order to first determine if the prototypes would operate when subjected to wind, and to identify any issues with them. The wind turbines were set up in various open outdoors locations. The wind speeds were measured using a QM1644 anemometer, which has a wind speed range of 0.3 m/s to 30 m/s.

Wind tunnel testing was conducted at the Thebarton Wind Tunnel in order to determine the overall efficiencies of the wind turbines built. The Thebarton Wind Tunnel is a closed-loop wind tunnel with a working section of 3mx3m, and a minimum development length of 10 m as determined using reference pitot-static tubes and wind tunnel calibration.

During wind tunnel testing, the wind speed was increased by increments of 0.5 m/s to a maximum of 16 m/s, unless excessive vibration was observed. To produce the power curves for the wind turbines, it was required to determine the coefficient of power and tip speed ratio at each wind speed. In order to determine the coefficient of power, the voltage and current were measured using a Digitech QM1523 multimeter, the temperature was measured using a Digitech QM1601 thermocouple, which has a 0.5% accuracy, and the airflow density was determined from the temperature measurements. In order to determine the tip speed ratio, it was required to measure the rotational speed of the blades using a Digitech QM1448 tachometer. Three measurements were taken for the rotational speed of the rotor at each wind speed in order to decrease systematic errors.

4. Design and Results

Four different wind turbines were designed and built based on the recommendations given in the guidelines: Two HAWTs and two Savonius wind turbines. All of these wind turbines were designed to charge a 12V car battery, and therefore needed to produce a minimum of 14 volts [22].

4.1. Generator Testing

Initial tests determined that four of the six generators sourced are suitable for wind power generation. These were a treadmill motor, a washing machine motor, a centrifuge motor, and a car alternator. However, before being used as a generator, the washing machine motor required alterations due to the excessively high voltages it produced at low rotational speeds.

The four generators were assessed for their start-up torque, the results of which are shown in Table 1. It was revealed that the washing machine motor has the largest start-up torque of the generators tested, for both its original and rewired configurations. This need for a larger torque was considered when designing its blades. It was also noted that the difference in start-up torque for the remaining three generators is minimal.

Table 1. Generator start-up torques

Generator	Start-Up Torque (Nm $\times 10^{-3}$)
Washing Machine Motor	84.0
Treadmill Motor	59.5
Centrifuge Motor	51.1
Car Alternator	41.2

The three motors also underwent power and voltage testing. Fig 1a) shows the output power (W) generated for the three motors when subject to changing rotational speed (RPM) and connected to a 20 ohm resistive load.

Fig 1b) shows the output voltage (V) generated for the three motors when subject to changing rotational speed (RPM) and connected to a 20 ohm resistive load. For all motors, the relationship between the rotational speed and output voltage appears to be linear.

Fig 1b) shows that the alterations to the washing machine motor produced a voltage reduction ranging from 5 to 25 volts, with a more pronounced difference occurring with increasing speed. However, Fig 1a) shows a significant power loss associated with the motor alteration, possibly due to an increase in electrical resistance within the wires and their connection points. Therefore, it was preferable to use the original configuration for the washing machine motor, and use an external charge controller to decrease the output voltage. It was also decided that the washing machine motor was appropriate for a direct drive HAWT, due to the low rotational speeds it requires.

The treadmill motor requires approximately 400 RPM to produce 14 volts. Implementing this generator into a VAWT would require gearing in order to achieve the required rotational speed. Instead, it was decided to use the motor in a direct drive HAWT, as the rotational speed required was still considered within the achievable range.

The centrifuge motor requires approximately 1000 RPM in order to produce 14 volts. It was allocated for use in a VAWT since these wind turbines require gearing to produce significant power in the first place.

The car alternator was not assessed because its donor had tested it before using a dynamometer. It produces a constant 14 volts at 5 amps at rotational speeds greater than 1000 RPM, which corresponds to a constant power output of 70 watts. It was delegated for use in a VAWT for the same reasons as the centrifuge motor.

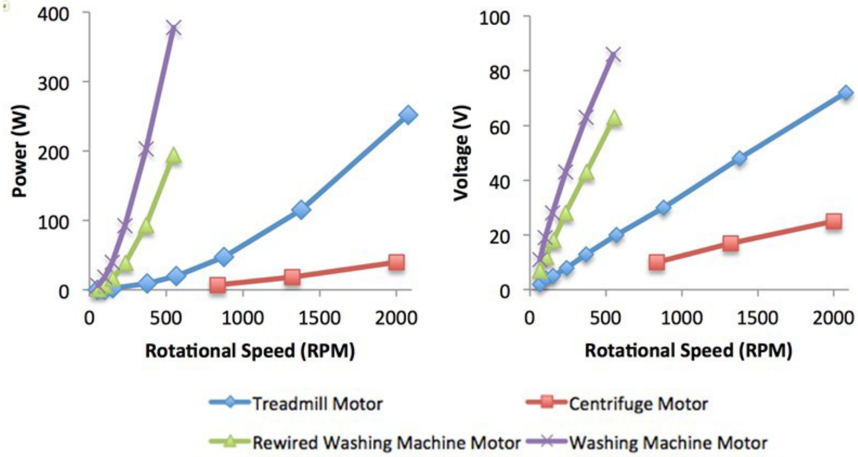

Fig. 1. (a) Left: Power output vs. RPM for the tested generators (b) Right: Voltage output vs. RPM for the tested generators.

Fig. 2. From left to right: (a) HAWT using the treadmill motor; (b) HAWT using the washing machine motor; (c) VAWT using the centrifuge motor; (d) VAWT using the car alternator.

4.2. Horizontal Axis Wind Turbines

Fig 2a) shows the HAWT using the treadmill motor. Its manufacture was accomplished using an oscillating multi-tool, a saw, a drill, a filer, and a sander. In order to reduce mechanical complexity, this design contains the fewest number of components required for it to operate.

This design uses blades that were manufactured from old wooden floor boards. The blade radius was selected considering the largest possible radius within the material constraints, as well as the rotational speed required for the generator to produce 14 volts. A blade radius of 680 mm was selected under these criteria, for which the generator produces 14 volts at a wind speed of 5.7 m/s.

It was determined during testing that the treadmill motor has a small start-up torque. For this reason, this wind turbine has three tapered blades. Linear taper was added for ease of manufacture, with the chord at the root measuring 120 mm and the chord at the tip measuring 30 mm.

Blade cross-section was modelled after the NACA 0015 airfoil in order to obtain detailed information about the lift and drag coefficients. This particular airfoil was selected because its symmetrical outline is simple to manufacture, and because it has the largest coefficient of lift of all symmetrical NACA airfoils [23]. For this airfoil, the ratio between the coefficient of lift and the coefficient of drag is maximised for an angle of attack of approximately 8 degrees [23]. In order to optimise blade efficiency, twist was added to the blades to maintain this optimal angle of attack constant throughout their length.

Yaw control was added to this wind turbine. The structural pine nacelle was used as the boom, and it provides a large moment arm of 760 mm to allow the yaw control to operate at lower wind speeds. The tail vane was manufactured using medium-density fibreboard (MDF) offcuts insulated with duct tape. A PVC barrel union was used as the bearing for the yaw control.

Fig 2b) shows the HAWT using the washing machine motor. Its manufacture was accomplished using a grinder, a welder, a file, and a sander.

This design uses blades manufactured from standard 100 mm PVC pipe cut axially. Since the washing machine motor requires a small rotational speed in order to produce 14 volts, the blade radius was chosen such that it would be the largest within the existing dimensional constraints. Under this criterion, a blade radius of 750 mm was used.

Table 1 indicated that the start-up torque for the washing machine motor is the largest out of all the generators used. In order to match the large requirement for torque, this wind turbine has four blades with no taper. The cambered cross section resulting from the use of PVC in the manufacturing of the blades also improves the torque characteristics.

Twist was not added to the blades due to material and manufacturing capability constraints. Instead, the blades were pitched at approximately 23 degrees to improve lift distribution near the rotor hub. Based on Bruining (1979) [24], this pitch angle was determined considering an angle of attack of 6.5 degrees for maximum efficiency.

Yaw control was implemented with the use of a circular pizza pan with a diameter of 400 mm as the tail vane, and a circular hollow steel section with a length of 500 mm as the boom for the tail. This large moment arm compensates for the small area of the tail used, allowing the yaw control to operate at lower wind speeds. Instead of using a bearing for the yaw control, a circular hollow steel section with a diameter of 45 mm slides on top of the circular hollow section used for the tower. In order to minimise rotational friction, both circular hollow sections were greased, and a circular piece of plastic from an old cutting board was placed in the interface between them.

4.3. Vertical Axis Wind Turbines

Fig 2c) shows the VAWT using the centrifuge motor. Its manufacture was accomplished using a grinder, a jigsaw, and a drill.

This design uses blades manufactured from two plastic barrels used to import cucumbers from India. The drums were cut into halves to produce semi-circular blades. The blades were aligned with a 15% overlap ratio to increase efficiency [17, 20], such that the system has a rotor height of 1.6 m and diameter of 1 m. The blades were bolted to three endplates. The top endplate was built from two semicircles that were cut from a door, and the middle and bottom endplates were built from structural plywood. In order to improve the efficiency, their 1.1 m diameter was chosen such that it would be 10% larger than the diameter of the blades [12, 19].

Due to the typically small rotational speed of VAWTs, a gearing system was implemented. The gears used consisted of a disc of wood with a 60 mm diameter and a bicycle wheel with a 540 mm diameter, which resulted in a gearing ratio of 9. The belt used consisted of stockings that were sewn together.

Fig 2d) shows the VAWT using the car alternator. Its manufacture was accomplished using a grinder and an arc-welder.

This design uses blades that were manufactured from two metal cooking oil drums. Each drum was sawed in half in order to form two semi-circular blades for one stack. This resulted in a rotor with a 1.1 m height and 0.6 m diameter, with a 15% overlap ratio for increased efficiency [17, 20]. Its endplates were cut out of the side of a washing machine. Similarly to the previous wind turbine, their 0.66 m diameter was chosen such that it would be 10% larger than the diameter of the rotor, for improved efficiency [12, 19].

This wind turbine includes a gearing system in order to overcome the 1000 RPM required for the generator to produce electricity. The gears used consisted of a pulley with a 45 mm diameter and a bicycle wheel with a 540 mm diameter, which resulted in a gearing ratio of 12. The belt used consisted of a bike tube that was stitched with fishing wire. The pulley and the car alternator were mounted on an adjuster that was bolted to the frame, allowing for the belt to be tensioned.

4.4. Universal Battery Charger

Results from the voltage and power output testing show that the recorded generator outputs varied substantially for each generator. Since batteries require a certain voltage input to be capable of charging, wind turbines without voltage regulation are limited in their use. In these instances, a universal battery charger is required.

The designed universal battery charger (not shown) consists of a three-phase rectifier, a charge controller, and a dump load. This is all stored within a 10L container with a hinged lid. The three-phase rectifier converts alternating current into direct current, and prevents current back flow. It was made using six hot carrier diodes that were sourced from old computer monitors, old electrical wire and brass nails.

When the voltage levels are higher than 20 volts, the charge controller diverts the output power of the wind turbine from the battery to a dump load, in order to prevent damage to the battery. It also has pushbuttons that allow the output power to be directed manually to either the dump load or to the battery. The design of the charge controller was based on Davis (2014) [25], and it was made using basic electrical components that can be easily sourced from electrical hardware and other forms of e-waste.

The dump load consists of four down lights connected in series, and is embedded in a perforated metal sheet on the side of the sauce container in order to dissipate the heat generated. The wind turbines built did not incorporate mechanical brakes or furling systems due to their complexity. However, the dump load also serves as an electrical brake when the voltage levels are higher than 20 volts, and thus moderates the rotational speed of the wind turbine.

4.5. Field Testing Results

The HAWT using the treadmill motor was field tested for wind speeds that varied between 1 m/s and 6 m/s. It was found that blade rotation occurs for a wind speed of approximately 3.5 m/s, and that the yaw control operates at even lower wind speeds. The wind turbine also experienced excessive vibration and rotor imbalance issues during field testing. These issues could be solved through securing the wind turbine with tensioned ropes, and adding known masses to the lightest blades.

The HAWT using the washing machine motor was field-tested for wind speeds that varied between 2 m/s and 8 m/s. It was found that the blades and the yaw control start operating at winds speeds of 2 m/s to 3 m/s. This test also revealed that the thrust applied on the rotor increases substantially with increasing wind speeds. As a result, the wind turbine overturned and the blades flexed backwards. In subsequent tests, the wind turbine was secured with tensioned ropes and heavy weights, and the blades were reinforced using aluminium rods.

The VAWT using the centrifuge motor was subjected to wind speeds of about 7 m/s during field testing. The test revealed that the wind turbine experienced structural issues at high speeds. The central shaft detached from the top of the frame, which led to the implementation of a stronger bearing and bracket assembly. Furthermore, the MDF endplates bent when exposed to rain, which led to the replacement of the MDF with structural plywood.

The VAWT using the car alternator was field tested for wind speeds of 5 m/s to 8 m/s. Despite rotating at these wind speeds, the blades did not achieve the rotational speed required for the alternator to produce electricity. This could be a result of high bearing friction, belt slippage, or insufficient wind speeds. One of the aims of wind tunnel testing for this prototype was to detect the cause of this issue.

The problems identified during field testing were used within the guidelines as points of consideration for the user, as well as the potential hazardous effects associated with them.

4.6. Wind Tunnel Testing Results

The HAWT using the treadmill motor was tested for wind speeds of up to 7.5 m/s, at which point it experienced excessive vibration. It was observed that one of the main causes of vibration is the clearance fit between the top section of the tower and the PVC barrel union used as the yaw control bearing. The PVC barrel union should therefore be substituted for a bearing that provides a tighter fit.

Table 2 shows the power and voltage outputs measured for the tested range of wind speeds. It indicates that the wind turbine did not achieve the 400 RPM required for the treadmill motor to generate 14 volts. Hence, a gearing system should have been added to the wind turbine in order to improve its rotational speed characteristics.

Table 2. Wind tunnel testing results for the HAWT using the treadmill motor.

Wind speeds (m/s)	Power (W)	Voltage (V)
3.5	0.00	0.00
4.0	0.04	0.50
4.5	0.08	0.83
5.0	0.18	1.45
5.5	0.63	2.45
6.0	1.08	3.10
6.5	2.15	4.30
7.0	3.01	4.50
7.5	5.01	6.15

The power curve shown in Fig 3a) was obtained using the data of Table 2. It shows that the data collected was not sufficient to obtain a comprehensive power curve for this wind turbine, as wind speeds could not be increased above 7.5 m/s.

The HAWT using the washing machine motor was tested for wind speeds of up to 15.5 m/s. It should be noted that the universal battery charger built was not used during this test. Table 3 shows the power and voltage outputs measured for the tested range of wind speeds. The data obtained was used to draw the power curve shown in Fig 3.

Fig 3b shows that this wind turbine has a greater power coefficient for all tip speed ratios tested than the previous one. This large difference in power coefficients indicates the importance of meeting the generator requirements for a wind turbine. The washing machine motor is better suited for wind power generation since it is able to produce power at low rotational wind speeds. Its large start torque was met with the addition of four blades with no taper. In contrast, the treadmill motor was not able to achieve the rotational speeds required for effective wind power generation. Ultimately, the use of blades with several features for improved efficiency did not match its requirement for the use of a gearing system.

Table 3. Wind tunnel testing results for the HAWT using the washing machine motor.

Wind speeds (m/s)	Power (W)	Voltage (V)
6.0	42	18
6.5	61	22
7.0	85	26
7.5	106	29
8.0	121	31
8.5	136	33
9.0	146	34
9.5	155	35
10.0	186	39

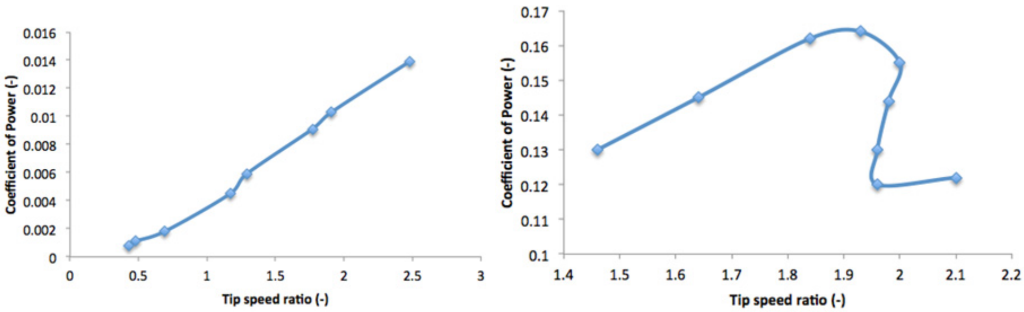

Fig. 3. a) Power curve for the HAWT with the treadmill motor b) Power curve for the HAWT with the washing machine motor.

It is also important to note that three of the data points used for the power curve are outliers. These data points occur for tip speed ratios between 1.95 and 2, for which it was difficult to measure the rotational speed due to the vibration of the rotor. This would be the main cause for the inaccuracy of this set of data points.

The VAWT using the centrifuge motor could not be wind tunnel tested due to its size. Field testing could produce quantitative results with the use of an anemometer. Although it will not be possible to construct an accurate power curve using this method, a rough estimate of the power that can be expected for various wind speeds can be obtained.

The VAWT using the car alternator was tested for wind speeds of up to 15.5 m/s. This wind turbine did not generate power even when the blades were rotating at speeds surpassing 120 RPM, which should correspond to rotational speeds larger than 1440 RPM for the car alternator. This suggests that the belt connecting the two gears suffered from slippage at high speeds, and did not transmit power to the car alternator. Another issue occurred when the belt became unattached from the smaller gear at a wind speed of 14 m/s. Although the wind turbine was not damaged and its vibration was not excessive, the blades were able to rotate at very high speeds, which could have been hazardous. Therefore, the test conducted on this wind turbine led to the conclusion that the introduction of a gearing system increases the chances of failure significantly.

5. Conclusion and recommendations

This paper presents the main results of a project with the aim of creating a set of guidelines for the construction of wind turbines from scrap material. The overarching motivation of this project was to empower people living in resource-constrained regions to build their own wind power generation systems. As resources and technical capabilities differ substantially around the world, a range of solutions is needed. Hence, the guidelines were designed such that wind turbines can be produced based on various resources.

In order to test the guidelines created, four different wind turbines were built and tested in the field and a wind tunnel. Testing revealed that only one of the four wind turbines built produced power in realistic wind speeds. The main causes of failure on the other wind turbines were gearing slippage, excessive vibration, and resistance associated with bearings. It is expected that some of these problems might be overcome with the optimisation of the wind turbines designed.

The conclusions drawn from testing were used to refine the content provided in the guidelines. However, the guidelines require additional work in order to better communicate the technical aspects involved in wind turbine design. This is particularly important considering that the guidelines are targeted to communities with non-technical backgrounds, where English might not be spoken as the first language.

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