

Prediction and Validation of a Micro Wind Turbine for Rural Family Use

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Abstract

This paper summarizes the development of a vertical axis micro wind turbine for families in remote areas. The design philosophy, requirements and constraints are summarized. Development steps are presented, including construction, static testing and measurement of performance. A numerical simulation captures the essential features of the design. Test results indicate moderate success with a 1 meter diameter, 1 meter tall turbine using inexpensive and commonly available materials and construction techniques which allow use of a yawed biplane blade design. A 2m x 2m design scaled up from the 1 meter machine requires stronger blade construction.

Introduction

This paper presents progress towards developing a micro renewable energy device optimized for use by families in areas remote from urban industrial centers. The design takes into account the constraints of access to repair facilities and parts, investment funding, family incomes, device attrition, and the paramount need for safety in environments where children and curious pets abound. Issues such as sustainability, use of commonly available off-the-shelf components, local buy-in, generation of local employment, and clean disposal of broken machines, must be considered in addition to thermodynamics and aerodynamics. This overriding philosophy dictates choices of materials, construction techniques and moving parts. Accordingly, the resulting device is less efficient in pure technical terminology than one that might be optimized for an industrial or military application. We will find that the Figure of Merit, defined as the ratio of what is achieved to the best that could theoretically be achieved, is much less than 1. This provides the technical challenge and motivation for research in this otherwise well-trodden field of endeavor.

The paper takes a somewhat convoluted path, for reasons tied to the above. We first explore the historical development of wind energy devices, and explain the motivation based on the difference between an optimization that might be done for the market in a developed nation, versus what might suit users in a place with very different realities. Next we discuss the design parameters, constraints, their rationale, and a brief history of the lessons leading to the present configuration.

Wind Energy Devices

The idea of extracting useful energy from the wind has been in vogue at least since the ancients put up a sail and set out across bodies of water [1,2]. There is mention of sails used in Egypt as

early as 3200 BCE. Efforts to adapt this technology to stationary devices on land must have come in parallel or later [3-6]. One early implementation was a vertical-axle machine with rectangular sails driving a machine that ground grain, used in Sistan in the 8th century CE. There is evidence of wind turbines made of fabric and wood being used in China and Africa, with some of those technologies still in use in parts of Africa. These typically had wide-chord frames holding sails. Such devices were used for raising water from wells for irrigation, and perhaps also for grinding grain. The horizontal-axle wind turbine became a common landscape feature in Europe starting in the 12th century. Early versions were driven by aerodynamic drag force. More recent versions had airfoil blades that operated on lift, metal gears and machines powered by wooden-frame blades mounted on stone-built structures that doubled as the residence and factory of the mill operator. The Dutch windmill is universally recognized, and represents a highly successful element of the European rural economy of past centuries. In aerodynamic terms, this device is very inefficient. The rotor reaches barely above treetop level (there were not many trees around such windmills) and was at the bottom of the atmospheric boundary layer, thus getting only weak winds compared to today's tall towers. The stubby stone mill posed a large obstruction compared to today's slender towers. However, the devices worked. They delivered power directly to the point of use, and hence did not require conversion to electricity, or transmission through lines. The tower was integrated with the user's (very noisy) home. Most routine operations and maintenance were done by the residents, and related trades no doubt provided a stream of employment for locals.

There are two basic approaches to designing a wind turbine. One is to operate the device such that the blades generate aerodynamic drag, and are all pitched or twisted to a high angle so that a component of this drag force drives the device around the tip path circle. These devices are easy to build from wood or metal, and they operate over a wide range of wind speeds. With some modification, the blades would also generate some lift, but with a poor lift-to-drag ratio. This design was chosen, mounted on wood or metal towers, for the wind turbines that provided mechanical power to miners and farmers in the American West long before the railroad and the electric grid reached them. They are still used whenever one needs a quick and easy design and can build it out of metal sheets with minimal demands on skill. A less common variant of the drag-based design is the Savonius turbine, where the axis of rotation is perpendicular to the wind direction. At its most basic, this design consists of the two halves of a cylindrical barrel, cut along a diameter, and attached facing in opposite directions with some overlap at the middle, to

the shaft. It works on the principle that the drag on the side where the convex surface meets the wind, is about 1/2 to 1/3 of the drag on the side where the wind blows into the concave side. A cup anemometer is a form of Savonius turbine.

Most wind turbines today operate as lifting rotary wings, reaching lift-to-drag ratios above 60. This is much more efficient, and has led to the proliferation of ever-larger horizontal-axis wind turbines (HAWT, axis aligned with the wind direction) as primary wind-power extractors. The Darreus design of vertical axis wind turbines (VAWT) also uses a lift-based design. Thus it can achieve higher efficiency than the Savonius type, but at a considerable cost in complexity.

One complication is that a Darreus type machine cannot start itself as the wind starts from zero speed, and in fact operates most efficiently when the rotor tip speed is 3 to 5 times the wind speed. Thus large vertical axis wind turbines are typically started using an electric motor and taken to a relatively high speed. The power required for acceleration drops as the turbine picks up power from the wind, and the motor becomes a generator.

Design Parameters and Constraints

Our focus is on small machines suitable for operation by families in remote off-grid communities. When the machine becomes small, its aerodynamic efficiency is poor for various reasons. Low Reynolds number, low inertia, higher friction losses, and the low, fluctuating wind speeds available near the ground are obvious reasons. The cost of the non-power-extracting components becomes a larger part of the total, so that the cost per unit installed power becomes high. One unfortunate fact in dealing with commercial advertisements for micro renewable power devices is that actual performance rarely comes anywhere near the claims. Micro wind turbines, though relatively simple, pose installation issues and operational safety hazards [7] and may not survive weather conditions that are quite probable at least once every year. Many small commercial wind turbine models come with “rated power” values that exceed the physical limits of kinetic energy flux through their swept areas at the “rated wind speed”. As may be expected, the reality of their operational performance is nowhere near these claims. The real mechanical figure of merit on most such systems, compared to the theoretical Betz efficiency of 59% of the kinetic energy flux for horizontal axis machines, is on the order of 10%. The electrical conversion efficiency is also low because of the wide range of torque and power encountered. It turns out upon careful investigation that the marketers of such devices, unlike those of large wind turbines, are not obliged to cite the rated power at the rated wind speed. The rated wind speed (typically around 12 m/s) is just a number suggested by the government. The rated power is what the manufacturers claim at the maximum wind speed (perhaps 40 m/s) that they claim the device will survive! Given that power is proportional to the cube of wind speed, one can easily calculate the consequences to optimistic customers who buy these systems. This is an increasingly strong cause of market resistance [8] to micro renewable power devices.

In reality, micro power devices need not compete with utility-scale devices on marginal cost per unit energy. Where the efficient power grid is not accessible, the real value [9] and the cost [10] of competing alternatives (mostly batteries) for the first several watts of installed power, or of the first several watt-hours of energy, are 3 to 4 orders of magnitude above the utility energy cost paid by grid-connected urban customers in developed nations [11]. Diesel generators are not much cheaper.

In this low-power regime of 10 watts to 1 kilowatt, we project that the vertical axis machine can be made competitive through research, and will offer real value to people in off-grid communities [12]. The blades of this machine encounter a large periodic fluctuation in aerodynamic load through each revolution, and in fact only a small portion of each blade’s travel actually generates positive power. So the analysis and design of such machines are quite complex [13], even without the kinematic mechanisms used on commercial models to optimize blade loads through a cycle. However, these machines can be located close to the ground, and are hence more portable and accessible. They survive bad weather (they can be moved to shelter or dismantled) and high winds better. The centrifugal stresses are small compared to those on the blades of the horizontal axis machine, and the consequences of blade failure are far more benign. For these reasons, we focus on VAWTs.

In our laboratory, a 1m diameter x 1m high VAWT was originally conceived as a half-scale model, but was then seen to be useful in its own right. It is intended to be portable, and to allow a user to set it up easily outside his residence or on the roof. The power level is not anticipated to be above 100 watts mechanical. Accordingly the constraints are:

1. All rotary bearings are to be from bicycle components. The bearings are likely to be the highest cost items if custom-specified. However, bicycle components are familiar to residents, especially children, all over the world, and hence this provides a route for community “buy-in” of the maintenance of the device. An initial small-scale concept that constructed from a bicycle wheel is shown in Figure 1.
2. The blades must not be high-cost items. In fact we aim to make the blades easily disposable. In a practical environment, the blades are likely to be hit by objects such as farm tools, children’s toys or balls, or falling branches. These things should not become catastrophically expensive terminators of the useful life of the device.
3. The blades should be bio-degradable in the long term and the products of their decomposition should be environmentally friendly. This rules out metal blades and sophisticated carbon fibers, which may not degrade. Many plastics are ruled out since they produce toxins if burned. To answer a reviewer’s concern, “biodegradable” does not imply something that will dissolve in the first rain or become brittle in a year’s worth of sunshine. Wooden parts are considered biodegradable, but have been used on ships and buildings for ages. On the other hand, many plastics are disastrous when dumped in backyards and landfills. Thus it is harmful to provide such “advanced” materials to areas and populations that lack the regular garbage removal, sorting/separation/recycling systems and tough waste disposal law enforcement of American suburbia.
4. Blade-making techniques must be compatible with generating semi-skilled jobs using local materials and labor. This helps “buy-in” and reduce cost of ownership.
5. The machine must “fail gracefully” and exhibit only benign modes of failure. Thus if a blade comes loose or breaks, it should not become a dangerous sharp-edged missile or flying sword. While studies on helicopter blade failures indicate that blade pieces quickly become unstable in flight and flutter down, there is no assurance that this will always occur in a failure situation. This makes it difficult to accept wooden blades without protective netting.

Having noted the above, we now go on to describe the research efforts. At this stage, blade materials and blade-making techniques are chosen with different objectives than those that will drive the final production versions. The first tentative experiments use the materials and designs that minimize cost and delay for small numbers of blades, and yet allow us to learn lessons that can be used in the design.

Early on, we recognized that the cheap-blade approach allowed us to attempt a biplane blade design. We conducted static wind tunnel tests to determine the lift and drag curve slopes of the blades, and how these were degraded when two blades were in proximity. The above constraints drove us to test flexible blades held stiff by tension. We believed that these would be amenable to production using textile and mat-weaving skills [14].

Early tests showed that incorporating a guide vane upstream of the machine would allow it to self-start, albeit slowly. A split 50mm diameter tube incorporated near the axis to serve as a Savonius starter has worked best to-date. Initial tests were conducted using a 1meter, 4-armed device with flexible double window-blind slat blades on each arm (Figure 2). These allowed generation of up to 260 rpm in the wind tunnel at 64 kilometers per hour wind speed. However, they degraded and tore in time, and this occurred rapidly when the machine was under load. Keeping both blades on each arm in tension proved to be difficult with the flexible blades, despite our developing special floating bracket attachments for the purpose. Going to a 3-armed version reduced the vibrations that were induced by resonant antisymmetric loading of symmetrically placed blades. For instance, consider what happens when identical blades pass through the 0 – 180 degree positions of the VAWT with respect to the wind direction. The blades at the front and back experience aerodynamic loads in the same direction. One adds to the centrifugal load whereas the other relieves the load, so that the net force on the machine is antisymmetric, setting the machine into a flapping mode of vibration. The flexible blade approach offered advantages for the 1m machine, but failed with a double-scale (2m x 2m) turbine (Figure 3) as discussed below.

A third-generation blade design used S2027 (low-speed, laminar-flow) airfoil section templates cut from plywood, with a PVC pipe acting as the spar and providing some torsional rigidity (Figure 4). PVC roof flashing sheets were bent and glued to the ribs, and stapled or glued together along the trailing edge. The blade roots terminated in PVC pipe fittings that are easily set at the designed blade pitch angle. While PVC sheets and pipe are not environmentally friendly, this technology can be used to demonstrate prototype machines, and get buy-in due to the easy availability and maintainability of the components. The blades of a VAWT generate driving torque and hence power, primarily when the blades are in two sectors of their orbits. To minimize the periodic fluctuation in power as the blades turned, the blades were yawed as seen in Figures 4 and 5.

Our other wind turbine prototype is a 2x version of the smaller turbine, reaching 2m diameter and 2m height. This still has a small enough footprint to be placed outside a rural or urban home, and the components are small enough to be transported, for instance in a Sport-Utility Vehicle or pickup truck, though probably not in a small car. In many parts of the world, pieces that large are routinely transported a few at a time, strapped alongside bicycles. This device is believed to be capable of 1 KW power. The initial design still used bicycle bearings, but this may be changed either to motorcycle bearings, or to use multiple bearings from bicycles. The efforts to operate it at low wind speeds in the low-speed diffuser of our wind tunnel (See Figure

3), failed. The Savonius tubes started the device and reached a slow speed, but the flexible blades went into uncontrolled flutter and generated net drag. The device actually worked better when the “lifting” blades were removed and the machine was operated as a Savonius turbine. The purpose of this device has been redefined. It is now viewed as something that should be designed to survive very high wind speeds, permitting it to be left, for instance along a sea wall or beach ridge along the Pacific Northwest coast [15] where strong winter winds are expected. Accordingly, the blades of this machine have been redesigned with steel tubes, foam core covered with fiberglass sheets, and metal ribs. Blade construction is shown in Figure 5. Wind tunnel testing is scheduled for mid-2011.

Results

A DC generator was initially coupled to the VAWT. However, this generator was optimized for 5000 rpm, and at the 100-250rpm speeds that were reached by the turbine, its conversion efficiency was poor. The generator allowed us to directly power a compact fluorescent bulb equivalent to a 40-watt incandescent, but this only drew 6 watts and hence does not constitute any great demonstration of success. Given the difficulties in the power conversion, we decided to focus on mechanical power extraction. Hub-based power generators for bicycles are still too expensive [16] for many applications of the 1m turbine.

A rope dynamometer was used to maintain a constant torque on the device, using a pulley and weights. Thus only the shaft rpm has to be monitored to obtain mechanical power readings. A laser non-contact rpm counter was tried for initial tests. Subsequently an optical shaft encoder connected to a USB power supply was installed at the top of the shaft. Because this was difficult to install and was failure-prone, it was replaced with a magnetic shaft encoder. This permits the detailed time-variation of rpm to be recorded on a laptop computer, suitable for remote transmission via the internet. A constant load of 2 lb (08.9N) is applied to the rope dynamometer. Of course a production version of the machine will not have such instrumentation.

In the spring semester of 2010 the VAWT went through a series of tests. Material static bending strength tests were used to develop the low-cost blades. Results are shown in Figure 6. Pipes made of CPVC, available easily for home use, provide a good alternative to ordinary PVC and to wood, as shown in Figure 6. In order to reduce the deflection of the blades in the VAWT, a gardening spike was placed in the center of the CPVC tube. After reassembly of the reinforced blades, the VAWT was tested over a range of wind-speeds ranging from 10 to 44 MPH. The increased bending stiffness of the blades improved performance. Video monitoring of the turbine operation helped analyze blade deformation through the power-generation area, located approximately 120° of azimuth counter-clockwise (i.e., along the direction of rotation) from the front of the VAWT. The blades bend inwards in this region, with the inner blades having higher deflection so that the spacing between the two blades increases with wind speed. The blades of the 1m VAWT survive wind speeds over 80 kmph, but over time, the surfaces deform and the blade aerodynamic performance degrades. Figure 7 shows the turbine in operation, with the deflection of the blades visible.

Horizontal Axis Wind Turbine Tests

A “400-watt” horizontal axis wind turbine (HAWT) of 54 inch diameter was acquired for reference, and tested at the same location as the 1-m VAWT was tested. With a 50-Ohm resistor

as load, the power curve of the HAWT is shown in Figure 8. The rotational speed of the HAWT was limited electronically. Clearly the power output under these conditions is very small. One reality of the HAWT is that at rated power, it must operate at an rpm of between 500 and 1000 rpm, posing the dangers cited before. Such an installation would only be suitable well above reach of children and pets, implying a tower or rooftop installation.

Numerical Simulation

Initial efforts at numerical simulation of turbine performance used a blade-element formulation to construct the change in the velocity diagram with azimuth. The simulation was conducted using MATLAB coding. This was used to confirm that we were calculating the expected variation of power extraction with tip speed ratio. The peak extraction was found to be at tip speed ratios close to 5, although values above 3 were good. Values above 2 were essential to really start seeing good aerodynamic lift.

This blade element simulation was carried forward to test finite aspect ratio blades, and to see the relative effects of profile drag and induced drag. The results showed that aspect ratio has a high effect, since induced drag can become a large component of total drag for this ideal calculation. Lift curve slopes and profile drag values for this calculation were derived from the static wind tunnel tests performed with the blades.

The effect of the drag generators (for starting) was also incorporated into this simulation. Net power generation was calculated by averaging the power around the tip circle. However, the simulation results remained well above the measured power results. Typical results are shown in Figure 9. The abscissa is the tip speed ratio, between the machine tip speed and the wind speed. The power is in watts, and is far above any power measured to-date. The results show that the power curve is sharply peaked as expected for vertical axis wind turbines, and the peak occurs between tip speed ratios of 3 and 5. The parameter of interest in the particular study from which Figure 9 is taken, is the blade thickness, keeping the thickness to chord ratio constant. This means that aspect ratio decreases as the thickness (or the chord as indicated in the figure) changes. The purpose of this study was to check whether there is an optimal thickness or aspect ratio, because a larger thickness means blades of greater bending stiffness. The results show that the chosen baseline is close to optimum, both for peak power and for the peak occurring at the lowest tip speed ratio which is still near 5.

The above simulation also shows that the expected mechanical power of the 1m vertical axis machine is well below 100 watts at tip speed ratios lower than 2. This corresponds to observed results. The simulation lacks the detailed drag and interaction modeling required to accurately capture the experimentally found power. Figure 10 shows mechanical power measurements made using the 1m VAWT, using the rope dynamometer. The power levels are only on the order of 20 watts or less at 12 m/s, as expected.

Conclusions

The philosophy behind the design of small, low-cost vertical axis wind turbines for family use is explained, and leads to a design where blades are inexpensive and the rotating parts come from bicycles. The measured power levels are low, but these are justified by the cost of alternatives at these low power levels. Specific conclusions:

1. The figure of merit of small vertical axis wind turbines is low.
2. A double-bladed turbine design is effective where blade cost is low.
3. Flexible-blade designs are fairly effective for the 1m turbine in the 100 watt regime, but are inadequate for a 2m version of the design at any power level, due to flutter issues.
4. Blade element theoretical predictions of the power show that high rotational speeds are required to obtain good figure of merit where the turbine radius is small.
5. A simple self-starting vertical axis turbine design has been demonstrated.

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Figure 4: Slanted-bi-blade 1m self-starting vertical axis wind turbine

Figure 5: Blade Construction for the 2m VAWT

Figure 2: 1m x 1m tensile, flexible bladed VAWT at the exit of a wind tunnel

Figure 6: Material stiffness tests leading to choice of CPVC

Figure 1: 2m x 2m tensile, flexible bladed VAWT at the exit of a wind tunnel



Figure 7: Blade deflection is visible in this strobe-lit snapshot of the 3-armed VAWT in operation. The blue guidevane is visible to the left.

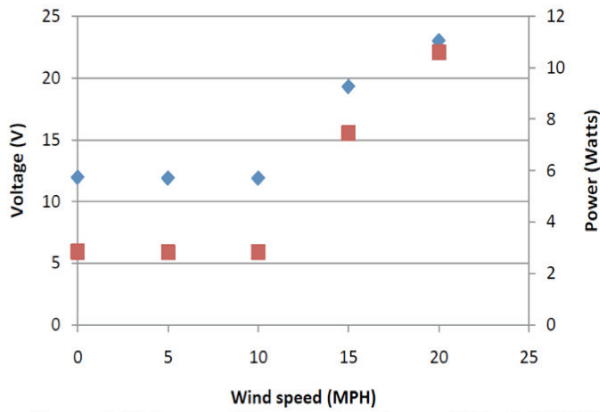


Figure 8: Voltage and Power output from a 54-inch HAWT vs. wind speed, with 50 Ohm resistive load

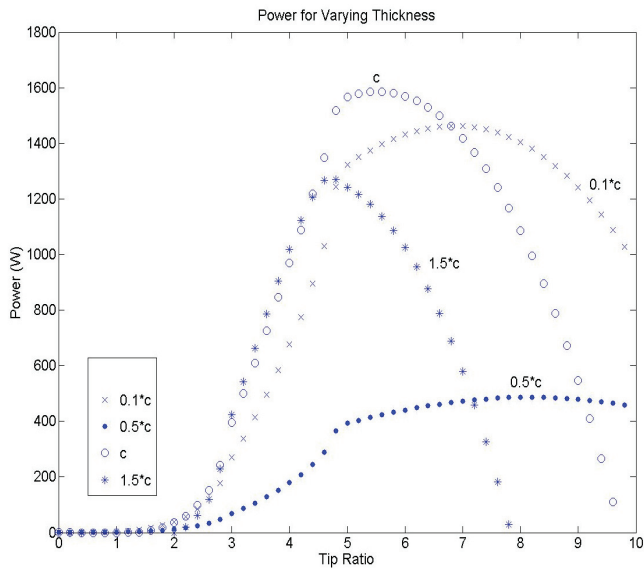


Figure 9: Blade element predictions of the mechanical power output of the 3-armed, bi-bladed VAWT, for different choices of blade chord compared to the baseline chord, with fixed span.

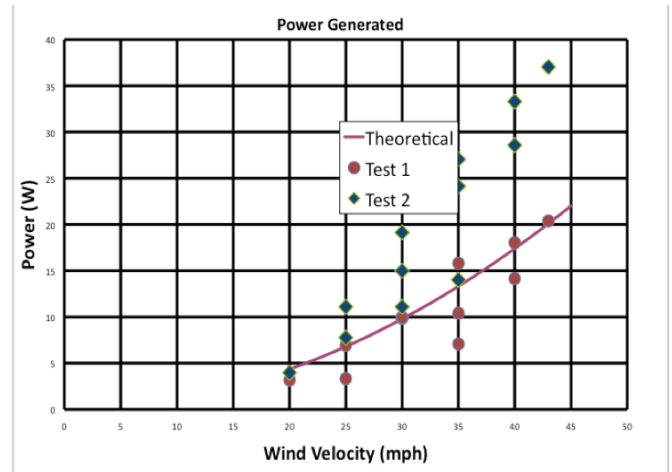


Figure 10: Measured power in two tests of the VAWT, vs. preliminary predictions from momentum streamtube theory.