 

The Savonius Rotor: A Durable Low-tech Approach to Wind Power

An on-farm research project funded by Northeast SARE (Sustainable Agriculture Research and Education)

<u>Project Report and Construction Manual</u>

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Project Report

Introduction

One of the realities of small-scale energy generation is the seemingly inescapable economic disincentive to invest in long-term solutions. This project is an instance of one farmer's effort to see past the present condition of cheap energy (electricity and liquid fossil fuels) to a future where farms will likely be increasingly compelled, as they have in the past, to take responsibility for their own energy needs. But in order to clearly think one's way around this topic, it is important to frame the problem correctly.

We are accustomed to think in dollars-and-cents economics, which rarely have a clear relationship to the amount of energy involved. Although the Savonius is usually considered as an electrical energy generation proposition, let's set electricity aside for a moment and consider one of my major farm operations. My farm captures approximately 70 million kilocalories in our annual square bale hay harvest. In order to accomplish this, we exert probably about 2 million kcal of effort in the following categories:

Horse muscle power	150,000 kcal
Tractor diesel fuel	1,500,000 kcal
Electricity for bale conveyors	24,000 kcal
Wear and tear on all equipment	300,000 kcal
Human muscle power	36,000 kcal
Total energy invested	2,010,000 kcal

All of which seems quite reasonable when you consider that we are stacking up 70 million calories in hay.   But of course we humans can't eat the hay ourselves, can't use it to keep the lights on very easily, so we feed it to our stock, a time-honored practice. This hay contributes to an annual production of beef animals (as well as horsepower for farm work) to the tune of about 7 animals per year at 550 lbs hanging weight each, of which about 350 lbs is eaten. There are about 800 kcal in a pound of beef.

7 beef animals x 350 lbs beef each x 800 kCal = 1,960,000 kCal

If we were to include the use of the draft horses for non-haying farm work then that would add a few more hundred thousand calories in the benefit column. But in the main, our hay harvest is a break-even energy proposition. It is viable economically, but in terms of energy, it does not have significant net production, mostly because the small amount of tractor fuel I use has almost as much energy in it as the beef I sell. I offer this example to illustrate the difficulty of thinking of farm systems in terms of sustainable energy dynamics.

Present-day dollars-and-cents economics are a huge distraction from long term thinking about farm energy and renewable energy in general, since any discussion of finances makes a host of assumptions about what things cost and are worth. If the value of goods and services in our economy bears little relation to the amount of energy their production demands, we are very easily tripped up in efforts to think in the financial long-term and energy long-term simultaneously.

Add to this fact most of us are not easily able to separate energy “needs” from energy “wants.” For instance, my household uses about 800 kWh per month. When it comes right down to it, very little of this usage is truly necessary.

And even on the production side of the farm, wants and needs are easy to confuse. I want to use a square baler because it helps me get the job of haying done. But as I have illustrated, the baling has a large energy cost, much more than a crew of 20 people with pitchforks would. If we lived in a society where energy truly mattered, that society would routinely consume renewable human labor (for instance in the form of a crew of 20 hardy workers with pitchforks) rather than machine labor. But we live in the here and now, and 20 people will not come when I call, at least not for a price less than or equal to that of running a tractor and a square baler. But the need for farmers is great at this time in history. We are here to play a pivotal role. I for one anticipate the day when northeastern fields will not lack for people. We are already on the way there, and the presence of people at work will revise all of our current assumptions regarding renewable energy.

I offer this introduction in order to help frame the problem correctly, and in order that the modest results be put in perspective and not be discouraging. The Savonius Rotor has virtues over an expensive high-tech wind turbine in the way that a crew of workers with pitchforks has virtues over a tractor and square baler. The Savonius (like the crew of workers with pitchforks) is:

1. *Technically easy to create.*
2. *Very low capital costs.*
3. *Simple enough that anyone can understand how it works.*
4. *It is not very dangerous to operate and be around.*
5. *It will function in a wide variety of applications.*
6. *It does not demand specialized parts or maintenance.*
7. *It is modular in nature, and can be made larger or smaller as needs dictate*

If our goal is to develop energy self-reliant farms and communities, these are very significant advantages, and may well outweigh the lower efficiency of this class of device, for which it undeservedly receives the scorn of most wind engineers. As in the case of the square baler, efficiency is not the entire story.

History of the Savonius Rotor

The Savonius rotor was originally designed by Finnish inventor Sigurd Savonius in 1922. It is classed as a drag-type device, and is understood to have relatively low efficiency but high reliability. Interest in the Savonius rotor and other types of Vertical-Axis Wind Turbines (VAWTs) became elevated during the oil embargo and resulting energy crisis. Also, during the 60s and 70s, the Savonius was considered as an example of appropriate technology for rural development in the third world due to its low maintenance requirements.

In that the Savonius is low speed and high torque by nature, it is more similar to the windmills of medieval Europe than most contemporary horizontal-axis wind power devices.

Given that we are currently facing escalating liquid fuel costs, and that the long-term costs of nuclear power are becoming clearer (even more so now that Entergy Nuclear has made clear its intent to operate how it pleases, whether the people of Vermont wish it to or not) I feel it is well worth considering durable generation technologies as a means to meet present-day needs.

Our farm is known to have marginal wind conditions, with an annual average speed of 11 mph. At this velocity, investment in large prop-type wind arrays is seldom advised. But given the low cost and the reputation for functionality at lower speeds, the VAWT seemed a possible alternative. Of the various types of low-tech wind devices, the Savonius stood out for its ability to be constructed out of wood, and its simple design requirements. Retired Charlotte, Vermont engineer Victor Gardy helped us towards a draft design.

Research Questions

Several questions motivated our consideration of the Savonius rotor. Given the high cost and long payback periods for most commercially available wind and solar technologies on the market today, could a home-built Savonius rotor, or collection of rotors, be a financially viable alternative? What is the potential of a modular windmill for non-electric power, such as direct mechanical application or in storage as compressed air? How important is a prime wind site in these considerations? How difficult is the device to build and maintain?

Prototype Mark I Design Process

Our first design is the product of Victor Gardy's 20 year history of working with the Savonius VAWT concept. It is a modular unit based on two rotors and a drive disc. At nearly 6 feet in diameter, the rotor is as large as the nature of the construction material (1/2” thick plywood in 4' x 8' sheets) will easily allow. Other aspects of the design and construction follow from the sizing of the rotor.

We chose to use standard exterior plywood and regular spruce lumber for our prototype with the understanding that a future permanent device could be built out of more durable materials. I would imagine that a rotor built from pressure treated components could last 10 years with a coat of paint or stain from time to time. Some sort of a roof over the rotor would not affect performance and would extend its working life. Savonius rotors are also made out of steel, and I have seen photos and footage of such wind devices installed on flat urban rooftops in Australia and Scandinavia.

We strongly considered testing the unit on a platform on top of one of our steel farm silos. Although we believe that the silos could have handled the load without problems, we couldn't devise a way to do the necessary pre-installation construction at that height (65 feet). This is too bad since there is superior wind available at that elevation.

The Savonius windmill we built consists of a housing tower, two rotors, a drive disc, and a vertical shaft. The housing tower supports the shaft in bearings at the base and at the top, and also serves as a framework for the stator panels. Victor Gardy found the use of stator panels, which shield the back side of the rotor cups from turbulence as they turn into the wind, to increase efficiency. The rotors are mounted onto a 1" (inside diameter) pipe shaft. The pipe shaft is stabilized inside a sealed bearing at the top and is bolted to the plywood drive disc on the base. An automotive wheel bearing beneath the drive disc connects it to the frame.

In early 2010, Victor Gardy built a 1/6th scale working model of the rotor. This helped us visualize the design and refine the construction methods as we began building the prototype on the farm.

Victor Gardy's 1/6th scale working model

The key feature of this windmill, or any other, is the "swept area." This is the figure on which all wind-generation math is based. Our windmill features two rotors, the upper one set at 90 degrees to the lower one. At any given time, one rotor is catching the wind at the point of maximum mechanical advantage, and the other collecting rotor is at a point of reduced mechanical advantage. All together, we estimate the swept area to be 1.33 times that of an individual rotor sail. Each sail is four feet high and 32 inches across. This works out to a total of 14.9 square feet or 2.64 square meters of sail area. This seemed to be a good size for a basic portable experimental unit.

We decided to evaluate our results economically, weighing the cost of materials and hours of labor in construction, versus output over an extended period. We chose, for simplicity, to measure electrical output rather than water pumped or some other alternative measure.

Prototype Mark I Construction Process

With the design outlined by Victor Gardy, we began building in the summer of 2010.

The construction of the tower is all basic framing lumber, primarily 2' x 4's. We chose to use 1/4" bolts for strength at the joints. The draft design featured a great deal of diagonal bracing. We have eliminated most of this bracing from our recommended design in favor of a structural stator panel that will perform a bracing function.

Few difficulties were encountered with the construction of the tower, other than the difficulty of moving it around once assembled. Each side is 6' x 12', and assembled the entire tower is 6' x 6' x 12' and rather heavy. We were still able to move it around with the tractor. Assembly of the tower takes a few days at most. We recommend leaving the center upright and the stator panels off of one side for later insertion of the rotors.

The rotors are assembled of pieces cut from 1/2" plywood. There is very little waste. We used elastomeric membrane (such as Grace brand “Ice and Water Shield”) at the assembled joints and reinforced them with blocking. We used weather-resistant decking screws, and reinforced the joints between the sail panels with light sheet metal, bent to conform with the angle by hand and attached to the plywood with sheet metal screws. At the center of the top and bottom panels, a hole is bored for the pipe shaft and 1 1/2” pipe flanges sandwich either side of each hole, attached to each other with stove bolts and nuts. An assembled rotor can be lifted by two people easily enough.

Lastly we constructed the drive disc, and assembled it into the tower with the pipe shaft and accompanying bearings. The drive disc is 70” in diameter, and is assembled of two sheets of 3/4” BC plywood, glued and screwed together in two layers and cut to a precise circle with a circular saw and radius jig. It required some innovation to get a good circle with basic woodworking tools but we were able to get a good result. Initially we put a 1/4” rubber tire onto the outside of the circle with contact cement but this we later removed as it seemed unnecessary. The smooth, 1 1/2” wide edge of the drive disc is, all by itself, an adequate surface for a friction transmission to a generator.

We installed a Chevy Lumina wheel bearing in the exact center of the drive disc with bolts. We chose that model of bearing because it is cheap and has a simple bolt pattern.

The pieces left over from the building of the drive disc were sufficient to build a sturdy support box, five pieces assembled with screws. We mounted the stationary plate of the wheel bearing onto this support box. The giant wheel balanced perfectly and spun with very little effort on the bearing. We placed the disc on its support box into the tower. We then put the rotors into the tower and inserted the shaft through the two rotors from above, and threaded it into a pipe flange on the drive disc. The unit is designed to spin clockwise so that it will not unthread this joint.

The finished unit can be balanced by adjusting the placement of the support box below and the top bearing above. Finished clearances are fairly tight, within a few inches. Once assembled we found the array to be quite sturdy, and it could be lifted from any corner without distortion. The rotors spun in a light breeze. Initially one of the two towers we built had a slight bearing noise, a slight groan that happened once per revolution at low speeds only. But this disappeared after a month of operation and otherwise the unit is very quiet. We proceeded to the evaluation phase in early 2011.

Overall the construction presented no problem. Modest competence with a circular saw and drill are all that is required to build a similar rotor. We had just under 80 man-hours in construction time.

Inventor Job Ebenezer helped design this savonius rotor in conjunction with the University of New Mexico in 1978. At the base is a grain grinder.

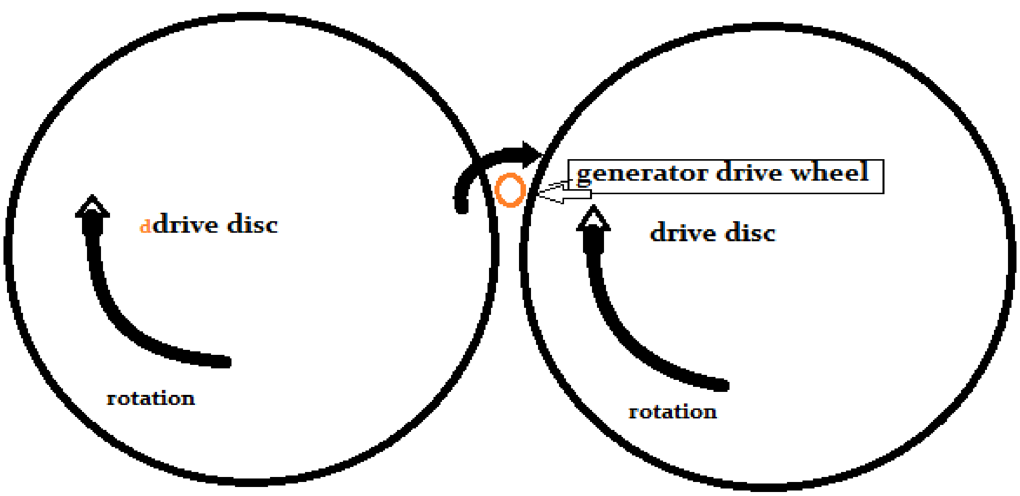
Note the simplified tower and the use of guywires.

Ebenezer went on to found an organiztion called "Technology for the Poor." The Savonius project was aimed at meeting needs for water pumping and mechanical power in remote, undeveloped locations. Mr. Ebenezer was kind enough to offer some suggestions for our project based on his experience.

More can be learned about this project, and you can compare this design to our own, at www.technologyforthepoor.com

Prototype Mark I Evaluation Phase

We began evaluating the rotor's performance in February 2011, and concluded in September 2011.



double drive disc arrangement with single generator

Initially we constructed a side-by-side installation of two rotor towers, each with their own drive disc. We believed that by placing the drive discs so that both would simultaneously bear on the drive wheel of a generator, that combined net generation would exceed generation of two independent generators, as pictured below:
However we abandoned this approach in favor of independent generation. We also decided that the side-by-side installation also compromised our ability to evaluate the basic rotor array since each tower could only receive winds from three sides, so we separated them and continued to trial just one single tower.

The generator can be an automotive alternator (the higher the amperage rating the better) or an exercise treadmill motor. Exercise treadmill motors make good generators since they are designed to function at a range of speeds. An inline skate wheel is mounted on the shaft of the motor, and the motor is fastened into the tower so that the wheel coasts against the moving drive disc, with enough pressure to turn, but not so much as to produce unnecessary friction. Sometimes we found the use of a nylon come-along to be a useful “spring” to help achieve the right amount of contact pressure.

We had persistent problems with moisture getting into our generator and diminishing generation potential. It is important to house motors in a way that sheds water, yet allows modest ventilation. One of our mistakes was to mount the motor below the drive disc with the shaft pointing up. If mounted this way, any water accumulating on the surface of the drive disc will spill off the edge and into the motor. If the motor is mounted above the drive disc instead, can be protected by a simple bucket placed over it, and water on the drive disc will not affect performance.

Only once in the winter did significant amounts of snow fall without enough wind for the rotor to keep itself clear. In other snowfalls there was enough winds that the rotor brushed all its working parts clear as snow fell.

Our first installation site was right next to our house. The rotor remained in this location through late May 2011. We then moved the rotor to a pasture location where we have observed winds to be stronger and steadier than at the farm homestead. The rotor was fairly easy to move; we lifted it onto a haywagon with a tractor bucket and a farm jack, and rolled it to the new location. It remained on the haywagon through the end of our trials in July 2011. We have gotten a good mix of strong winter/spring wind conditions and milder summer winds.

We installed a data logger in order to record wind speed, direction, and generator voltage and current. The output of the generator ranged from about 10 watts at the minimum tip speed of about 5 knots to 1800 watts in sustained high wind conditions in the 30 knot range.

We did not store the resulting electricity, but instead applied it to a load (12 volt lightbulbs, and at one point an electric stove burner). Our main focus was measurement.

The rotor presented no mechanical issues during the testing period. We never stabilized it with guywires, relying instead on the broad 6' base for stability. It never fell over or sustained damage from high winds despite gusts of up to 45 mph during the test period, and despite the additional 3 feet of height when it was in the pasture location on the bed of the wagon. We found that the rotor would not spin much faster than 60 revolutions of the rotor shaft per minute, and beyond about 32 mph, additional wind seemed to *decrease* rpm slightly. Here is an approximation of shaft RPM under light load at various wind speeds:

Although the rotor could not not exceed 60 rpm very often or by very much, under high-wind conditions it turns at that speed with greater force. If we had the means to engage multiple generators for these conditions, we would probably have been able to greatly increase produced wattage. We believe that a second generator, would slow the rotor less in 30 mph winds than in 20 mph winds, even though the observed rpm with a single generator is much the same. We did not have a torque sensor as these are very expensive, but we observed that stopping the rotor under very high wind conditions was much more physically demanding than stopping it under moderately high wind contions, even though the observed rpm was not much higher. The downside of having multiple generators permanently attached is that the additional load on the drive disc would increase the “tip speed,” and render the windmill unproductive in a greater percentage of light-wind conditions.

Because the 70 inch drive disc has a circumference of 220 inches, each rpm of the shaft turns the 3 inch inline skate wheel on the generator 23.35 times. This is the gearing mechanism by which the slow-turning rotor shaft turns the generator at operating speeds with a minimum of friction.

Prototype Mark I Assessment

The value of this first prototype was assessed in various ways. On a strictly economic analysis of its electrical generation capacity, it proved to be of slight benefit. In our conditions, at which there is an average of 11 knots of wind at or near the surface Based on our collected data for the evaluation period, a single two-rotor tower would produce about 650 kWh of power per year. At this rate, depending on whether labor costs were included and if so at what rates, the unit could take up to 16 years to recoup the costs of building it.

In order to last this length of time, the rotor would need to be constructed out of pressure-treated lumber and plywood, and the exposed edges of the plywood should be encased in metal U-channel to prevent delamination. These upgrades might increase the material cost to aboout $870 per two-rotor tower. In order to enhance durability we began to consider building a second prototype from steel. 55 gallon drums are often used for Savonius rotors (as in Job Ebenezer's pictured on page 7), but the resulting sail area is considerably less than on our plywood prototype. Steel 275-gallon fuel oil tanks on the other hand, present an ample sail area and seemed to have the potential to make a great rotor cup, and as a result of our experience with the Mark I we began to consider steel fuel oil tanks as an alternative low-cost material as part of a revised design.

Another observation was that the tower could be much simplified. There may be advantage to the use of stator panels but we were not able to establish this for sure. At any rate most contemporary Savonius designs do not feature them. A simpler tower without stators can consist of just two uprights with a cross-brace at the top of the shaft and another at the bottom. These members can be made out of 4' x 4's or 4' x 6's, and joined at the corners with steel reinforcing plates. Such a tower would be quicker to build and more durable but would need guywires to keep it upright.

Prototype Mark II Design process

The Mark II design aimed to build on the baseline research established by the wooden rotor and enhance durability and tower design without substantial additional cost. The rotor array is all steel for which a different skill set is required than for wood construction, but metal cutting and welding skills are common and the design is easy to execute.

Overall we aimed to retain the advantages of the Mark I including:

1. Simplicity of design and construction methods
2. Use of low cost, common materials
3. High ratio of power output to material costs

While also:

1. Reducing the complexity of the tower
2. Eliminating the drive disc in facor of a PTO-style power train.
3. Enhancing durability

Babbit bearings were an obvious improvement over the Mark I's automotive-style wheel bearings in terms of ease of installation and their ability to support the shaft at an intermediate position. This makes it easier to utilize power from the lower end of the turning shaft, which is accessible in the open area below the rotor. A variety of means of transmission are possible, including v-belts, bicycle or equipment chain, or flat belts. In the end we decided to go for PTO connections and universal joints as this seemed ideal for use with a planned archimedes screw pump.

We decided to build a three-rotor tower using three scrap 275 gallon fuel oil tanks. This size would be small enough to still be easy to install without a crane yet powerful and durable enough to perform long-term service powering an irrigation pump to serve 6.5 acres. While others may find any number of ways to best utilize the power of wind, it became apparent over the course of our work with the Savonius that using our windmill's power to move water would result in a clear savings of both money and labor. As a result we planned to permanently install the second device adjacent to a reservoir used for our wet rice fields. With our revised design, we began construction in fall 2011.

Prototype Mark II Construction Process

The rotors are comprised of halves of 275-gallon used fuel oil tanks, which were obtained from a fuel company dumpster for free. The legs and pipes were removed, and they were cut in half and welded onto a 2” outside diameter steel shaft. Once cut the tanks had a slight element of floppiness, so 3/8” steel rods were added as stabilization straps as shown. In addition, extra steel plating was added to reinforce the weld joining the tank to the steel shaft at the top and bottom. Where the tanks joined each other, it was sufficient to weld them to each other. The three rotors are set at 60 degrees intervals on the shaft, rather than the 90 degree intervals on the two-rotor shaft. We chose to weld the rotors permanently to the shaft, creating a complete structural unit, rather than to have any bolted connections.

The shaft stems out above and below the rotors. We used babbit bearings that were easily bolted to the tower and allowed the shaft to stem out below the bottom brace for easy connection to a 90-degree gearbox in that space as shown. A short spacer pipe transfers the weight of the array from the weld on the lowest sail to a locking collar, which rides upon the lower babbit bearing. We welded a category 1 male PTO stem to the bottom of the shaft and were able to use this to couple a 90 degree belt drive gearbox using this connection. To the gearbox we welded an additional PTO stem to which a shaft can be coupled. The belt drive pulley can also be used for power transmission with a flat belt, and can also be used to friction-brake the rotor for servicing.

The revised tower is comprised of pressure-treated 4 x 4s and stands about 19' tall. We installed the tower without a crane or gin pole. First the ground post 4 x 4 s were set in concrete footings and cut off at 5 feet of height and cut for a lap joint. Next the 16' tower sides were cut for the opposite face of the joint below and assembled with a 4 x 4 and a 2 x 8 at the top. 2 x 6 x 8' members carriage bolted to the outer face of the lower section of the tower add strength to the lap joint area. Once the top of the tower was complete, we bolted the lap joint connection with a single bolt. The top beam was now laying on the ground with the lower legs of the tower bolted onto the ground posts so as to serve as a “hinge” during raising.

We laid out ground anchors for guywires as follows. The guywires were made out of 1/4” steel cable and were cut to approximate length. We attached the two cables on the same side of the ground posts as the upper part of the tower was lying before we lifted. This way the cables would come taut when the tower became vertical and would not allow it to fall over to the opposite side. The remaining two cables were attached to the upper corners but hung free for the time being. Using a tractor bucket and poles for initial lifting and a light winch from the opposite side once lifing was underway, the tower went up easily. Once bolted together with 3/8” galvanized carriage bolts the tower was easily made plumb by adjusting the guywires. With the guywires tight the tower was now strong enough to lean an extension ladder against the top beam and climb.

In December 2011, the assembled rotors on the shaft were brought into position on an 8' x 16' haywagon. The base of the shaft was moved close to the lower beam, with the upper end lying on the ground. Some denting of the rotor cups occurred during this moving but we were able to pound them back out with sledgehammers. Then the bearing and bearing bracket were assembled ont o the shaft and strapped to the beam with nylon ratchet straps, allowing enough slack for the bracket to rotate during raising. We chained a pulley onto the top beam and threaded 1/4" steel cable through it, with one end looped around the upper stem of the rotor shaft and the other attached to a tractor drawbar. A farm jack was used to assist with the initial lifting of the upper end of the tower—the tractor pulling has little mechanical advantage until the shaft is 20 degrees or so above vertical. It would have been good to have several volunteers to help start the lift but we accomplished the job with just two of us.

The tower is already anchored in place. The rotor assembly is in position and ready to be raised. The tractor, visible on the right, lifts the half-ton unit into place.

With the bottom or the shaft anchored to the lower cross beam, the rotor was raised into position with a cable pulled by a tractor, threaded through a pulley on the top beam.

Once the shaft approached vertical, we climbed the tower and passed the top babbit bearing over the top of the shaft and bolted it to the top beam using 1/" x 8" carriagef bolts. Then we the farm jack and the tractor bucket to lift and position the rotor array to affix the lower bearing bracket to the lower beam with carriage bolts. The weight of the device being considerable, we found it necessary to install a 4 x 4 diagonal brace to support the steel bracket and to prevent it from rotating from the downward pressure of the shaft onto the babbit bearing. We checked the final plumbness of the bearing bracket with a spirit level. Once plumbed the rotor turned under light winds with no bearing noise.

Prototype Mark II Evaluation Phase

This second prototype was, as mentioned earlier, installed in a permanent location adjacent to an irrigation reservoir pond. This site is in a broad flat plain with no wind obstructions within 1000 feet in any direction.

We becan evaluating this unit on January 7th, 2012. It was found to be very quiet except when turing at very slow speeds, when bearing noises could sometimes be heard at close range. In the following two weeks we were able to observe it during snowstorms, light winds, and in heavy winds up to 35 mph. It was observed to turn in very light winds (5 mph or less) and did not suffer damage in high windspeeds. In fact, regardless of windspeed the RPM of the unit was never observed to exceed 60, which mirrored our experience with the mark I.

This Mark II unit does not incorporate a generator so we opted instead to evaluate its production by measuring the velocity and force ot the turning driveshaft in order to establish horsepower under typical wind conditions. The windmill drave shaft terminates in a PTO stem at its lower end. To this is coupled a 90-degree belt thresher gearbox designed to bolt onto a tractor. This bolts onto the lower bearing bracket which has holes drilled to receive it and to allow the output shaft to be pointed in multiple directions. Our gearbox increases the RPM of the primary driveshaft at a ration of 2.5 to 1. The thresher belt pulley has a circumference of 28.26 inches (2.36 feet). Under winds of 6 mph (just under the site average) the rotor turned at 30 RPM, which results in the thresher belt pulley turning 75 RPM.

- **30 RPM tower shaft * 2.5 pulley gear ratio = 75 pulley RPM**

Establishing torque is slightly more invloved, and involves the use of a "prony brake," which we constructed using a short leather belt, a lever and a pair of spring scales. One spring scale is hooked to each end of the belt. One of the scales is hooked to a fixed point on the frame of the rotor, the other to a lever. When the belt is looped over the rotor's belt pulley as shown when the pulley is not moving, and force is applied to the lever, both scales register equal poundage of force applied.

We then removed the belt and allowed the rotor to resume turning with the wind. When it had reached full 30 RPM in 6 mph winds, we reapplied the belt and applied tension with the lever. When the lever scale registered 35 lbs and the fixed scale read 5 lbs, the rotor began to slow somewhat from the braking force, so we took a reading at this point. The fixed scale reading is subtracted from the lever scale for a net load of 30 lbs.

To determine horsepower, we used the following equation:

$$\textbf{Hp.} = \frac{\textbf{net load x circumference x RPM.}}{\textbf{33,000}}$$

Inserting our numbers into the equation gave us a horsepower reading of 0.16 This exceeded our expectations given the light winds. Even under such light wind conditions the windmill has enough torque to turn our archimedes screw pump to pump 4500 gallons of water per hour, or to turn a grain mill.

Using this rough measurement, engineer Sam Gorton and I approximated the efficiency of Mark II device (or, in other words, the percentage of the energy in the wind that it captures) at around 30 %, which is quite respectable for a VAWT. This is an estimate of course, as the exact efficiency could only be completely and accurately measured over time with a torque transducer that was beyond our budget for the project. Nevertheless these results suggest that this device is likely to be a cost effective energy-capturing tool. Of course any use of this captured energy must be adaptable to the lower output shaft speed and any efficiency losses through gearing or transmission.

Using our approximate efficiency rating, we estimate that the Mark II device would produce 182 watts of actual power under typical site conditions of 11 mph winds, for an estimated total annual production of around 1600 kilowatt hours per year, which for our farm is equal to about 3 monthly bills of about $110, or about $330 per year. The unit only required $935 in materials and thus has a quite low payback period of only 3 years. If the fabricators are paid $25 per hour to build and install it (a total 104 hours in our case) for a total labor bill of $2600, then adding labor costs still results in a low payback period of 10.7 years. Most likely this Mark II device could function well beyond that payback horizon.

Project Conclusions

Revisiting Our Research Questions

Ultimately we determined that the Savonius rotor, particularly when constructed of cheap yet durable materials as in the Mark II prototype, is a financially viable investment. Its potential for non-electric power is particularly compelling. On farm uses for the direct-drive power of our rotor might include:

- irrigation and drainage pumps
- stone-burr grain mills
- vacuum pumps for maple syrup operations
- ice cream makers or cream separators
- stationary woodworking equipment or small lumber mills
- square bale conveyors
- cement mixers
- feed mixing units
- wood splitters
- cordwood saws
- two-stage air compressors

We also asked at the outset whether a prime site would be important for an economically viable installation. Both units were found to reach peak velocity at around 12 mph windspeed when no load was present, and to begin turning at a windspeed of 5 mph or less. Additional torque is generated at higher windspeeds.

We also wondered about the ease of building and maintaining a unit. While the Mark I and Mark II are both fairly easy to build, the Mark II is better from a maintenance perspective due to the higher durability of its components. The Mark I as described demands carpentry skills only while the Mark II demands both carpentry and welding skills. The Mark II is also more challenging to erect, but was still accomplished by a crew with no prior experience putting up windmills and towers with no incident. In general we feel this device is quite easy to make and master, much more so than a fussy tractor or bailer.

An additional significant finding is that the VAWT may also be quite regionally-appropriate. Wind patterns at our farm in the Champlain Valley, and in the northeast in general, are not directionally constant. Often we have a windy day with predominant winds from a given direction, often the south or north-northwest, but steady winds from this main direction are often interrupted by strong, sustained gusts from an alternate direction. For horizontal wind devices this is a problem, since the spinning propeller acts like a giant gyroscope, and changes in direction while under load result in extra wear and tear on all moving parts, reducing the lifespan of horizontal wind devices in the region compared to those of the great plains. But VAWTs have an advantage in this area because they receive wind from all quarters equally and thus do not need to be aimed or to aim themselves; a sudden change in direction does not result in significant wear. For this reason, all other factors being equal, the VAWT deserves additional consideration in the gusty northeast for its ability to function in changeable wind conditions without degradation.

An additional thought in closing: there are many possible installations depending on the site and the end use of the rotational power. Multiple units, each with their own generator, could charge a common battery bank. Both the Mark I and the mark II type towers can be expanded vertically to accommodate more rotors on a common shaft, though bear in mind that any shaft should be stabilized with babbit bearings every 10 or 15 feet. The steel Mark II rotor could be installed in the Mark I style tower and vice versa.

We feel that our Savonius project was modestly successful and that our prototypes can be recreated by any reasonably handy person, and the power output recreated on any site with winds equal or greater to ours. As the monetary and externalized costs of our current energy system continue to stack up, there is a growing need for farm and community power that can be created and managed by generalists. Perhaps the strongest future possibilities for future wind use are those that have dominated wind power's past: water pumping and mechanical power. The Savonius is a proven, adaptable concept that can be put to work for such needs around the region.

Comparing the Mark I and Mark II

Our chief aim in this project is to design, build, and evaluate a prototype that can be built by farmers and serve farm energy needs. In most respects, our Mark II design excels the Mark I. However for some individuals, the Mark I design or aspects thereof may be more desirable. For purposes of easy comparison, let's look at the following table:

	Mark I wooden unit	**Mark II steel unit with pressure-treated wooden tower tower**
Cost of materials	$871.00	$935.00
Our hours of labor to build	60	104
Value of labor at $25/hr	$1,500.00	$2,600.00
Total unit cost, labor and materials	$2,371.00	$3,535.00
Wind swept area (m2)	4.46	9.29
Portability	feasible	Not portable
RPM in 11 mph winds	60	50
Output	Drive disc	Low-speed pto shaft
Estimated watts in 11 mph winds	75	200
Annual est. energy production at our site (kWh)	650 kWh	1752 kWh
Paypack period, materials alone, at $0.25 per kWh	5.4 years	2.1 years
Payback period, labor and materials, at $0.25 per kWh	14.6 years	8 years
Approximate projected working lifespan	10 years	20 years

It's significant that if labor costs are considered, the payback period of the Mark I (at current energy costs) exceeds its working lifespan. However if this is the case it is far from alone in this regard as this is also true for many conteporary wind and solar applications. The Mark II steel unit on the other hand, has a very competitive payback period even when labor costs are included. With a much greater durability and sail area, it represents a better investment in most regards. The Mark II unit lacks the high-speed drive disc of the Mark I and would need either to be fitted with one or with a gearbox of some kind to be effectively employed for electricity generation or other high-speed low torque use.

A single 12' tower can be moved around on a flatbed trailer or hay wagon. This allowed us to trial our Mark I prototype in multiple locations.

Pressure-treated “Mark I” Wooden Savonius Rotor Construction Manual

Tools Required:

Circular Saw
Drill with various bits and square-drive screwdriver tip
Wrenches
Tape measure
Square
come-alongs
sledgehammer
drill press (optional)

Part One – Building the Tower

Materials list

14	2” x 4” x 12', pressure-treated
6	2” x 4” x 8', pressure treated
4	2” x 4” x 10', pressure treated
3	sheets 5/8” thick pressure-treated plywood
3	2”x 6” x 12, pressure-treated
5	2: x 8” x 10, pressure treated
4	joist hangers for 2” x 6” and joist hanger nails
1	sealed bearing, 1 3/8” inside diameter, with a bolt flange.

Box of 1/4” x 4” carriage bolts, galvanized, with nuts and washers
Box of 1/4” x 3” lag bolts
Box of 2 1/2” square-drive exterior deck screws
Box of 1 5/8” square-drive exterior deck screws

Directions:

First, cut eight of your 12 foot long 2” x 4”s to exactly 12 feet long, squaring both ends. (they often come with an extra inch or so). Then cut the remaining six into pieces exactly 72” long. Cut two 2” x 6” x 12's to 72” into four 72” pieces as well. Lastly cut the four 10-foot long pieces to 110 1/2”

On a broad, flat surface, lay two 12-footers parallel about 6 feet apart and temporarily pin a 72” piece connecting the top ends but 1 1/2” back from the outer edges of the 12-foot-long uprights. Then do the same on the bottom though you might wish to set it up an inch from the end of the 12-footer to make a short “foot.” It can be easier to level when the bottom rails are a little above ground level. Now you have a four-sided frame. You are looking at it from the back.

Square the frame by measuring diagonals and adjusting until both measurements are equal. Then install the remaining two 72” pieces (also set 1 1/2” in from the outer edges of the uprights) the first with its top edge 54 1/2” from the top and the second at 107” from the top. Secure them with one screw each. Flip the frame over. Measure 36” from the left edge on the top and second-lowest rails and install the center upright to the right side of this mark.

Take the sheets of plywood and rip each one into three pieces 48” wide (factory width) and 32” long. This will give you 9 pieces of which one is extra. Then flip the frame over so you are working on the back side again. Re-square it one more time. Then place two panels on the *left* side openings B and C (remembering that you are looking at it from the back).. Fit each one so that it bumps into the rail above it and laps equally over the side and center uprights. This should leave an opening about 3” at the bottom of each panel. Fasten this panel securely with 1 5/8” deck screws around the perimeter.

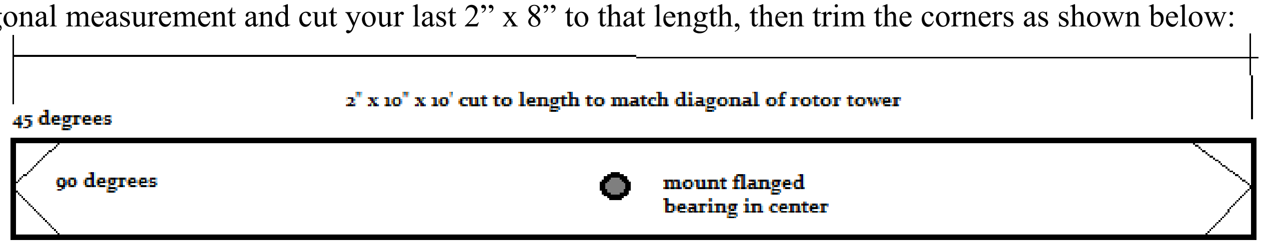
Then flip the panel back over. Cut four of the the 10-foot long 2” x 8” into pieces to precisely fit between the center and side uprights, bridging the joint between the plywood stator panel and the frame. If you like you can bevel the upper edge of the center and lower pieces to shed water away from the panel. The center one can be set just a half inch below the center rail, allowing it to contact both the upper and lower stator panels. Secure these pieces to the rest of the frame with a few 2 1/2" screws. Then flip the frame over again and attach the panels to them from the backside with 1 5/8" screws. You now have a complete panel. Reinforce the screwed joints with 1/4" bolts, nuts and washers. Best to have the nuts face inward.

Repeat for the remaining three panels, but do not install the center rail or stator panels on the last panel, so that you have an opening to insert the rotor when time comes to assemble the windmill. The offset attachment of the uprights allows the panels to mate together for a clean corner. To assemble the tower, lean two sections side by side, topsides up, against a high wall. Secure their uprights together with a come-along or rope, then walk one section, folding the two panels with the come-along serving as a hinge. The panels should mate nicely at 90 degrees. Then you can clamp or come-along them securely together and fasten with lag screws.

When the four sides are secured together, square them by checking the diagonals and adjusting with a sledgehammer.

Cut 6 diagonal braces from the 2" x 4" x 8' stock and apply them as shown, D, E, and F. The top pair of braces are different in that they do not rest on the edge of the top rails, but instead butt into the inside face, and they must be cut accordingly. They should also be left uninstalled for the time being.

Check the top for square along the diagonals. If it is out, adjust with a come-along. Then take the diagonal measurement and cut your last 2" x 8" to that length, then trim the corners as shown below:



Layout of top brace/ bearing block

Mark the exact center of the board along length and width. Bolt your bearing's attachment plate to this board so that the bearing aligns with the exact center. Then set it aside.

Take a measurement between the inner surfaces of the base rails from one side of the square to the other, and cut two base joists to fit from 2" x 6" material. Attach the first at 24" from the left edge and the second at 48" with joist hangers. These two members support the weight of the rotor and must be secure and strong.

Your tower is finished, for now.

Building the prototype tower under our pole barn.

Part Two—Building the Rotors

Materials:

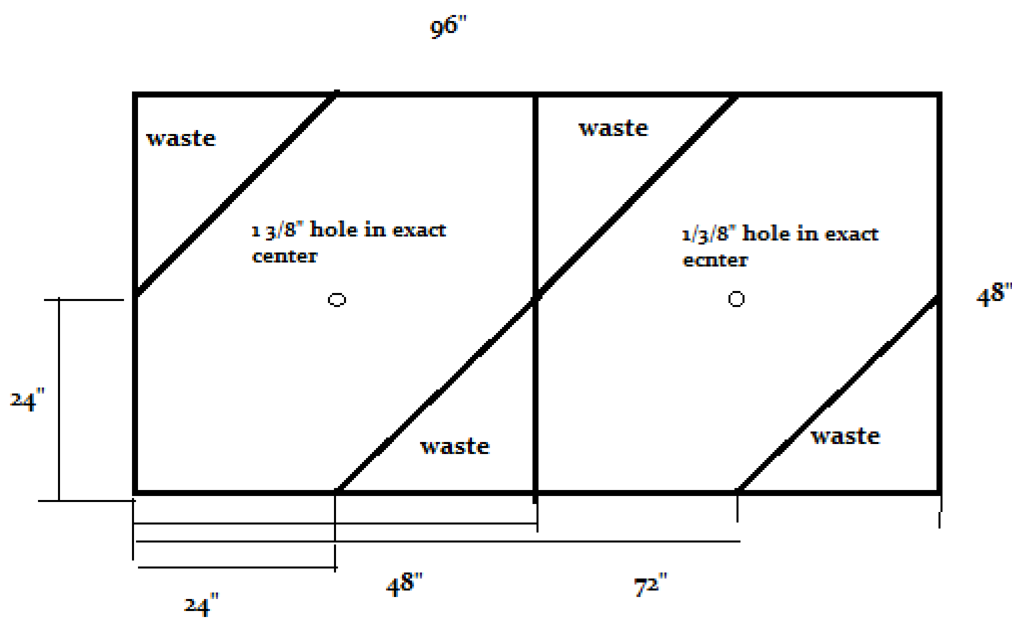
5 Sheets of 1/2” pressure-treated plywood
8 1 1/2” pipe flanges, galvanized
4 large cotter pins
scrap galvanized roofing or a roll of 4 to 6-inch wide flashing, for a total of 32 linear feet in 4- foot lengths
1 box 3/4” self-tapping sheet metal screws
1 roll 6” wide elastomeric membrane (Grace Ice and Water Shield ™ or similar)
plus- 1 5/8” decking screws left over from the tower project
1 dry 2” x 8” pressure-treated or several shorter dry pressure -treated scraps
1/2” inside measurement aluminum u-channel (optional)

Directions:

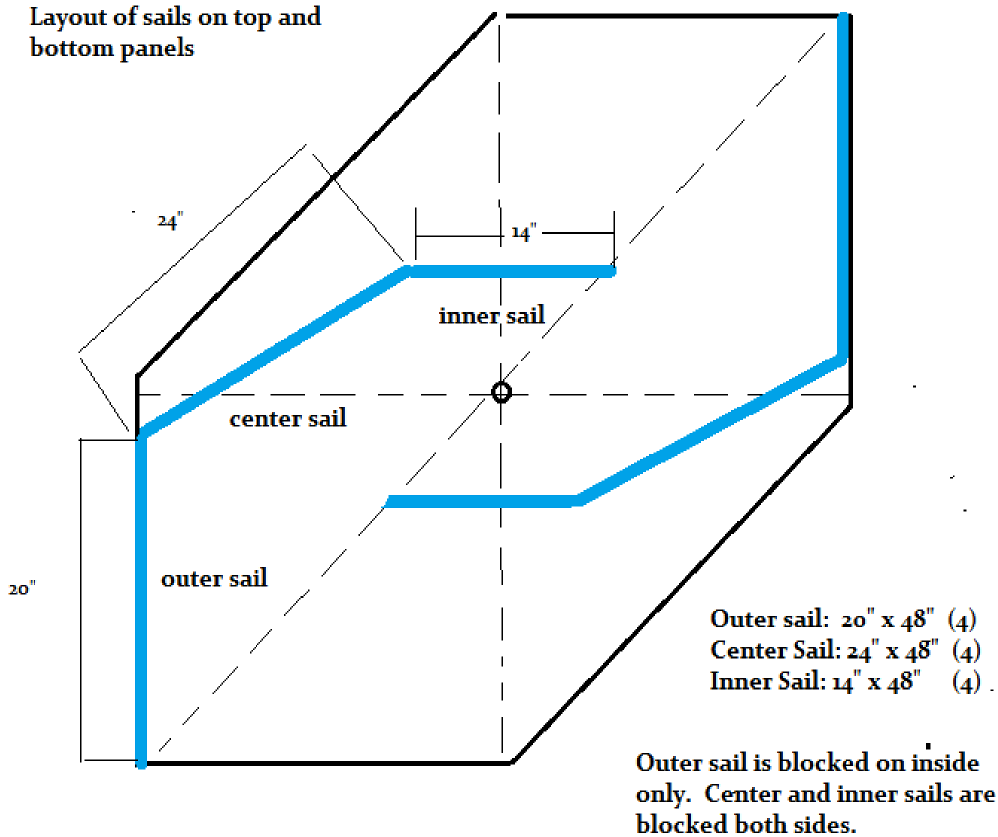
Hint--try to select sheets of pressure treated plywood that lay flat, if possible. as this makes construction easier..

Cut the rotor top/bottom panels to the pattern illustrated. Cut the rotor sail pieces from the remaining sheets as shown:

Rotor Top/Bottom panel cut layout. Four pieces required.



Rip the 2” x 8” or pressure-treated scraps into pieces of diagonal blocking on a table saw. You need about 16 linear feet for each rotor.
Stack all the top/bottom panels together and clamp all around. Mark out the location of the sails as shown below.



Drill a series of pilot holes through all four sheets at once, in pairs with one hold each side of the sail attachment lines. Drill one pair of holes every two or three inches. Also drill a few holes through the sail attachment pattern line itself.

Mark the center of the panel by drawing lines from all opposite corners. Drill a 1 3/8" hole through all four panels, taking care to keep the hole as straight as possible. Drill a 1/4" hole clear through one side of the collar of each 1 1/2" pipe flange and out the other side. A drill press is helpful for this. Then place one pipe flange precisely over the 1 3/8" hole in each top/bottom panel and drill pilot holes at each of the hole locations in the pipe flange. Then, using 1/4" x 1" stove bolts, lockwashers, and nuts, fasten a pair of pipe flanges to each other through the pre-drilled holes. Make sure the holes drilled in the flanges aim along the longest dimension of the top/bottom panel.

The outer sail blocking pieces are easiest to install. Cut four pieces of blocking 19" long (the blocking can end a little short of the joint with the center sail panel) and screw them to the rotor top/bottom panel with the diagonal-cut facing the center of the panel, and the block's edge set 1/2" back from the outer edge of the panel. It's easier and stronger to screw these diagonal blocks from the backside, but it is helpful to have a second pair of hands to assist.

For the center and inner sails' blocking we found it helpful to use a scrap of 1/2" plywood as a gauge. For the center and inner sail pieces, place the gauge piece so that it covers the pilot holes you drilled to mark the location of the sail. Then attach lengths of blocking to either side of it. Remove the gauge. Repeat until all blocking is installed and you have two pairs of mirror-image panels. The blocks on the bottom panel face upwards, and those on the top panels face downwards.

When you are ready and have a helper, set a bottom panel on a pair of sawhorses, and set the outer sail pieces against the blocking and attach with screws. Next, affix the center sail pieces with screws as well, adjusting left to right as needed for a tidy joint at the junction with the outer sail piece. Lastly attach the inner sail piece. The sail pieces will be floppy and loose until the top panel is secure. If you are having trouble getting a sail piece to remain seated in its blocking, you can secure it in place by using one of your sail-line pilot holes for a screw to hold it down.

With a helper, lower the top panel onto the upper edges. It is tricky to get the six floppy pieces to insert into the blocking all at once and requires some patience. Once inserted, try to optimize left to-right alignment and affix with screws. The finished rotor should be quite symetrical.

Cut some strips of the elastomeric memberane and attach it so that it waterproofs the joints, bridging from the surface of the sail, over the blocking, to the surface of the top or bottom panel. It is less important to weatherproof joints on the top panel than the bottom.

If you wish you can protect the raw edges of the plywood on the outer sail edge and around the lip edge of the top and bottom panels with metal u-channel.

Robin, 3 years old, finds the Savonius rotor a great place for hide-and-seek.

Part Three: Drive disc, drive shaft, and assembly

Materials:

1	automotive wheel bearing
8-9	hex 2 1/2” hex bolts to fit the holes in your wheel bearing. Probably 1/2” thick. With two washers, one nut, and one lockwasher each.
3	sheets 3/4” thick BC or AC plywood
1	box 1 1/4” deck screws
1	wide-kerf 7 1/4” blade for your circular saw
1	length 1” galvanized pipe, 11' long

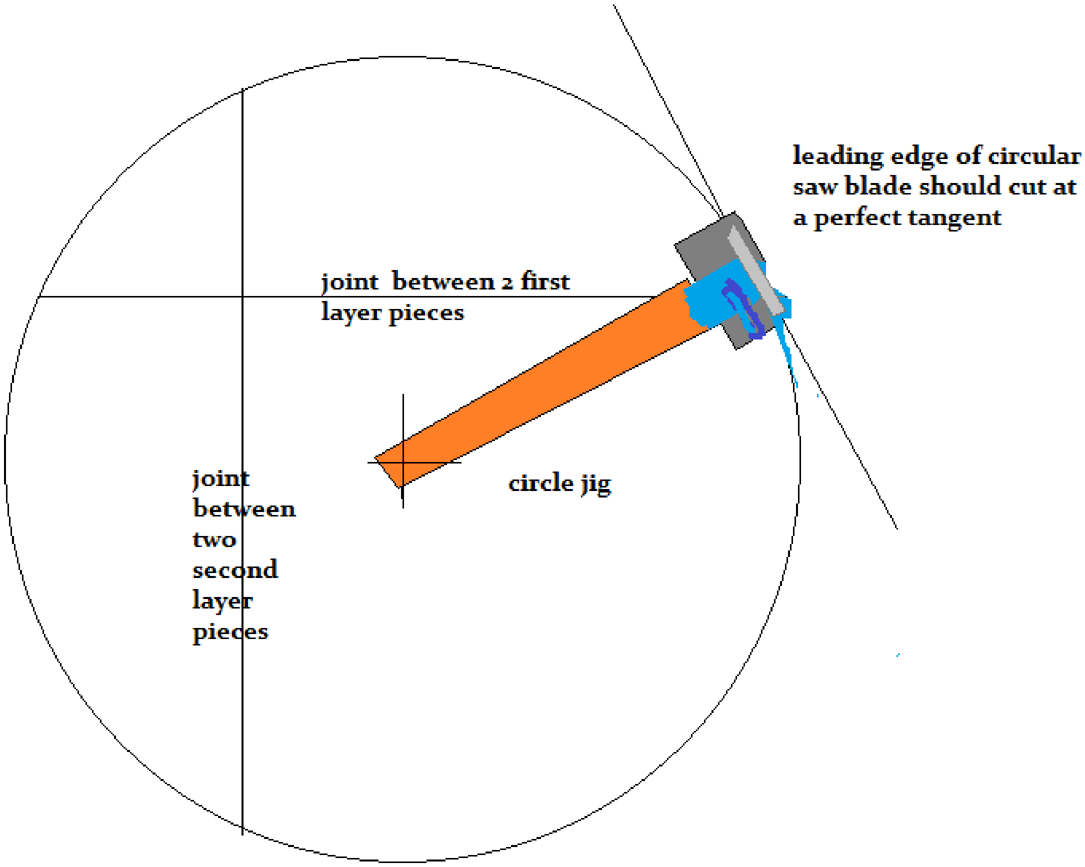
Directions:

The drive disc is built up out of two layers of ¾” plywood. Take one of the three sheets of plywood and rip it in half on the tablesaw, lengthwise. Then cut the four remaining sheets at 72” long, and do the same to the ripped halves. You now have two pieces 48” x 72” and two pieces 24” x 72”.

Lay one of the two-foot wide pieces next to a four-foot wide piece to make a square 6 feet on a side. Next, at right angles to the first layer, lay the remaining two pieces in a second square. Make sure all the joints are tight, then clamp and screw in a handful of places. You have now made a big square wafer 1 1/2” inches thick.

Measure to the center of the piece in both directions and drive a screw partway in. Take a piece of non-stretchy string and make a loop at each end so that in tension it is exactly 35” long. Loop one end around the central screw and insert a pencil point into the other. Keeping the string in tension, draw an arc until you have a complete circle. Now drive a great many 1 1/4” screws all over the inside of the circle, particularly around the perimeter, but not too close to the line. Remove any screws you may have driven earlier that fell outside the drawn circle.

Now, make a jig for your circular saw. This can be made out of a strong, thin piece of wood or a piece of sheet metal. Most models of circular saw have an attachment screw hole on the front of their table for the attachment of a rip guide. Devise a creative way of attaching your saw at this point so that the leading edge of the blade will land just at the line when inserted in a plunge cut. Before you take the leap you will need to triangulate the back of the circular saw table so as to keep the front edge of the blade blade traveling in tangent to the circle. You can do this by means of a second radial guide and clamping it to your saw with a c-clamp, or by using a single radial guide that is wide enough to attach to your saw in front and in back. It is best to use a very sharp blade with a wide kerf for this next step.



Once you are ready, you can drop the blade so that it cuts slightly, say about an eighth of an inch, into the wood. Your saw should be set to cut to the pencil line when at full depth, so this first cut will fall well outside the pencil line. With a good grip, cut around the circumference. How did it work? If you have a perfect circle you are all set to go ahead. You can drop the blade slightly with each pass, continuing around and around until you have cut through the first layer of plywood. Then the corner scraps will come loose and can be discarded. Continue until you have cut through both layers. Remove sawdust as necessary. Continue dropping the blade until it is fully dropped.. At this point you should have a disc that is 70" in diameter and perfectly round.

A router and a straight bit are also a perfectly good way to go, but not everyone has a router up for this job. I do not recommend a sabre saw as the blade will deflect in the cut and give an inferior result.

Next you must find a good automotive wheel bearing. We used Chevy Lumina bearings because of cost. Most any automotive wheel bearing with a bolt flange on both the wheel side and the frame side will work. Bolt the wheel bearing to the disc, taking care to stay true to the exact center. We had to cut a hole in the drive disc to allow the bearing to seat into it. So long as it is bolted firmly and flat into the exact center it is fine.

You will have several pieces of 3/4" plywood, 2 feet square, left over from the disc construction. You

can use these to construct a sturdy box that will sit on the base joists of the tower and support the disc at the appropriate level. The exact height of the support box will be determined by the height of your wheel bearing. It is better if he top piece of the support box overlaps the sides, so that the weight is transferred directly to them, rather than relying on the shear strength of the screws. Drill holes into the center of the top of the support box to match the bolt pattern of the remaining flange of your wheel bearing. Place your support box onto the base joists so that it straddles them. Then, with a helper, set the drive disc onto the box and thread hex bolts down through the holes. Attach nuts, washers, and lockwashers from the underside (you have to lie on your back under the disc) and screw the last side of the support box into
place.

Give your disc a spin! It should travel with very little wobble and very true. If it wobbles, check the mounting of your bearing. If it is not true, you can correct it by clamping a belt sander in place and spinning the wheel so as to wear down high spots only. Continue wearing down high spots, moving the sander slightly closer to the center with each pass, until your wheel is true.

Install a 1” pipe flange onto the top face of the drive disc. This flange is primarily a locator so don't worry if the four small screws don't seem like a very strong attachment.

The time has come to assemble the rotor!

With plenty of help, or a bucket loader, feed the rotors into the open bays of your tower. Make sure the back side of the cups faces clockwise, looking downwards. It is a good idea to use some 2 x 4 s as skids so that the rotor has something to slide in on besides the diagonal braces, and so that there is no chance of it falling through the hole. Once into the opening, the rotor should be moved and shimmed until it sits level in the center of the structure, with an equal amount of space between its top and the 2 x 4 rail above it and its bottom and the 2 x 4 rail below. There should be an inch or so of clearance on each side. Viewed from above, you should be able to sight through the rotor's pipe flanges clear through to the pipe flange on the drive disc.

Insert the lower disc first and get it positioned. You might want to secure it in place with a screw or two. Then proceed to the upper disc. When you can sight through both rotor discs to the drive disc flange, you are ready to put the pipe shaft in.

The pipe shaft is just a length of 1 inch galvanized pipe. The bottom end should be threaded, and the top not threaded, unless you plan on adding more rotors above. Standing (carefully) on top of the tower, pass the pipe shaft through the flanges until it seats in the drive disc flange. Thread it into the flange for a few turns.

Next, the rotors need support blocks. These are short lengths of pressure treated wood, perhaps left over from the tower, that form a ring around the pipe shaft and aid in the support of the rotor and the transmission of power. They can be made of 2 x 6, 2 x 8, or 2 x 10 material. Cut four blocks to XXX long for the drive disc-lower rotor connection. Insert them in a ring, each a foot away from the shaft and parallel to it. If you keep the diameter small, this will make it easier to construct a weather shield to protect your drive disc and electronics if you wish to do so later. Attach with screws into the rotor and the drive disc. Repeat this process to support the upper rotor on the lower rotor, but these blocks are a short 5 1/2”. These ones you can insert close to the sail attachment points where the rotor has the greatest structural strength. It is easiest to drive screws through the inside face of the rotor top/bottom panel into the blocking. These blocks transfer the majority of the load to the drive disc.

The rotors are assembled onto the shaft but the whole arrangement is still held together with blocking. Carefully, crawl into the rotor and drill through the 1/4” hole in the pipe flange collar into the pipe itself, using a sharp 1/4” bit. You probably won't be able to drill through both sides in one go, but will have to approach each side separately. Then insert a big 1/4” cotter pin to secure the rotor and peen back its tails. This is a tough job, but you only have to do it four times, on the inside top and bottom of each rotor.
Finally you can place the top bearing block/diagonal brace over the top of the shaft. You can either trim the shaft as necessary to seat it exactly in the bearing or drill a hole in the brace and allow the shaft to protrude through the block. Covered is better for your bearing, but sticking through is necessary of additional rotors are to be added later.

Now remove any temporary skids or support shims on the rotors. It should spin freely. The connection between the rotor and the disc should be strong. You can adjust the position of the support box below and the top bearing block/diagonal brace above to ensure that the sails have maximum clearance from all tower framing members when spinning. When in high wind, the rotors will flex somewhat and will become as much as an inch larger in diameter.

Finish the last side of the tower by installing the center upright and stator panels as described earlier.

If made out of new pressure treated wood, the finished rotor will be very wet and heavy. Use caution moving it if you are not able to build it piece by piece on its final site. We were always able to transport our rotors upright, and have used skids, jacks, and hay wagons to good effect. Placed on a firm, level surface the 12' high model does not seem to require guywires. We have registered 45 mph winds and ours has not tipped yet.

Electrical and mechanical connections

So far we have only experimented with friction-drive components which roll against the surface of the spinning drive disc. The drive disc is primarily useful for increasing available rpms to a device like a generator that has high rpm requirements.

Most D.C. Generators have a 5/8” shaft. You may need to use bushings, but good-quality inline skates can be mounted sturdily on the shaft. The wood tower structure makes it easy to affix the generator in place. If you have additional components, you might consider enclosing the portion of the tower by building a “roof” out of plywood at the level of the lower cross-braces. There would need to be a 2' diameter hole in the center for the rotating support blocks, which should have a shallow lip around it to prevent pooling water from flowing into the hole. This entire roof, and sides below it too if desired, can be covered with elastomeric membrane and your components will stay dry.

Selecting electrical components is left to the builder. You need to consider your budget, site wind properties, and the degree to which you wish to manage the device. If you are willing to manually engage additional generators as winds pick up, you may pick up quite a few additional kilowatt hours. In general we have had good luck with exercise treadmill motors (which are designed for AC consumption but produce DC), and automotive alternators of the high-amperage variety.

Here you can see an alternator riding on the surface of the plywood drive disc. Installed in this way, a generator is easy to protect from weather with a bucket-like shield, which we removed for this photo. An inline skate wheel is affixed to the alternator shaft. The wheel rolls against the moving edge of the drive disc.

Steel “Mark II” Savonius Rotor (with Pressure-treated Tower) Construction Manual

Tools Required
Circular saw
Drill
Welding kit
Winch
Wrenches and/or sockets
Level
Shovel and wheelbarrow
Sharp, long drill bits (3/8” and 1/2”)
Drill press also recommended

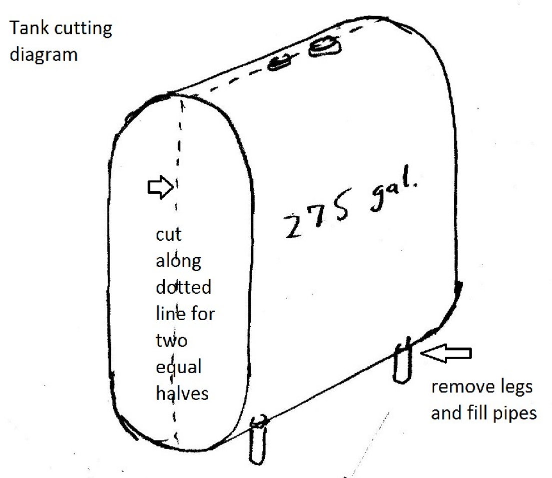
Part I: Building the Rotor Array

materials list

quantity	description
1	1 1/2” inside diameter steel pipe, 17'7” long
2	Babbet bearings with bolt flange, 2” inside diameter
4	1' square steel plating, 1/4” thick for rotor / shaft joint reinforcements
1	1' length of 2” inside diamter steel pipe (spacer pipe)
1	90 degree pto/belt drive gearbox, or other 90 degree gearbox
1	Pto stub or other coupler for receiving end of above gearbox
1	44” length C-beam, 3/8” x 6”
1	1/2” x 12” x 12” steel for gearbox mounting plate

1	Additional PTO stub to weld onto output shaft of 90 degree gearbox
3	Used (or new) 275 gallon fuel oil tanks

The first step is to locate three 275-gallon fuel oil tanks. We were able to get these for free from the scrap dumpster of a local fuel oil company. A few mall pinholes or dents are not a problem, though it is better to use tanks that are not badly damaged or rusted. Remove the filler pipes and legs. The tanks should be then marked out to be cut in half, like so:

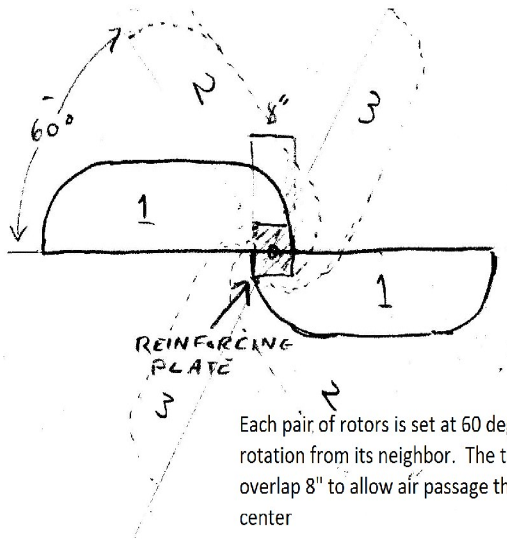


The cut can be made with a circular saw with a metal blade, or with torches. It is a good idea to file the rough edges smooth to avoid injury and to achieve a nice finished result. The threaded holes for the filler pipes can be cut right through the middle.

Used tanks will have some oil residue. This should be cleaned out and disposed of in accordance with local regulations.

Unfortunately I can't offer too much detail on the welding and metalworking aspects of fabrication, as this was done by others. But I will offer such guidance as I can.

A 1 1/2” inside diameter steel pipe can be purchased from a plumbing supply outfit. We laid out the tanks to receive the pipe shaft with an 8” overlap like this:



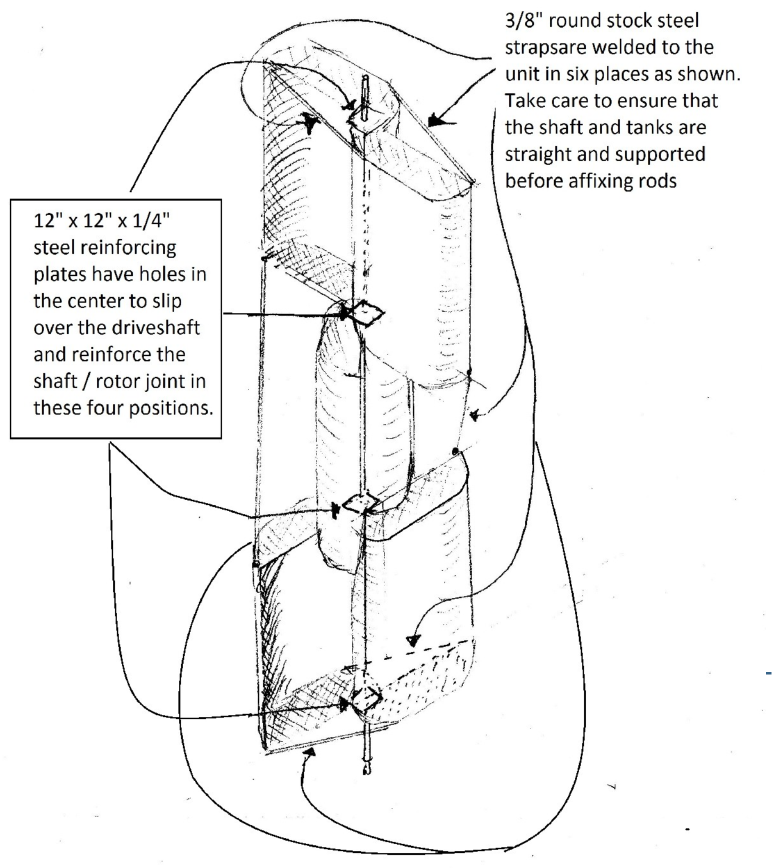
Each pair of rotors is set at 60 degrees of rotation from its neighbor. The tanks overlap 8" to allow air passage through the center

To secure the tank halves to the pipe and to each other, an extra plate of steel was used at each of the three principal welding points. Our unit was assembled lying horizontally. Note that in this array of three stacked rotor units, the axis of each differs from the one above or below it by 60 degrees. This aids in balance and starting.

Once cut the tanks halves become somewhat flexible. We mitigated this by adding 3/8" round stock to brace the unit as shown below. Here you can also see how the splined PTO coupling is welded to the base of the shaft. If you are using a gearbox that has some other input shaft requirement, then you may need to weld some other coupling or material to your steel shaft base. The top of the shaft requires no special treatment though we did cap it to prevent it from filling with rainwater.

Completed, the rotor array is a structural unit and can be transported on a flatbed truck or wagon. It's helpful to support the shaft ends with a wooden x-brace to avoid shifting of the load or damage during transport. We used a 16' haywagon to transport the complete rotor unit from the welding shop right up to the installation site. We waited to build the tower until the finished unit was on hand to measure, and built the tower exactly to fit.

Prior to installing the unit, we painted the tanks with oil-base rust-inhibiting paint, inside and out. Two coats were needed. We scraped off rough scale and peeling



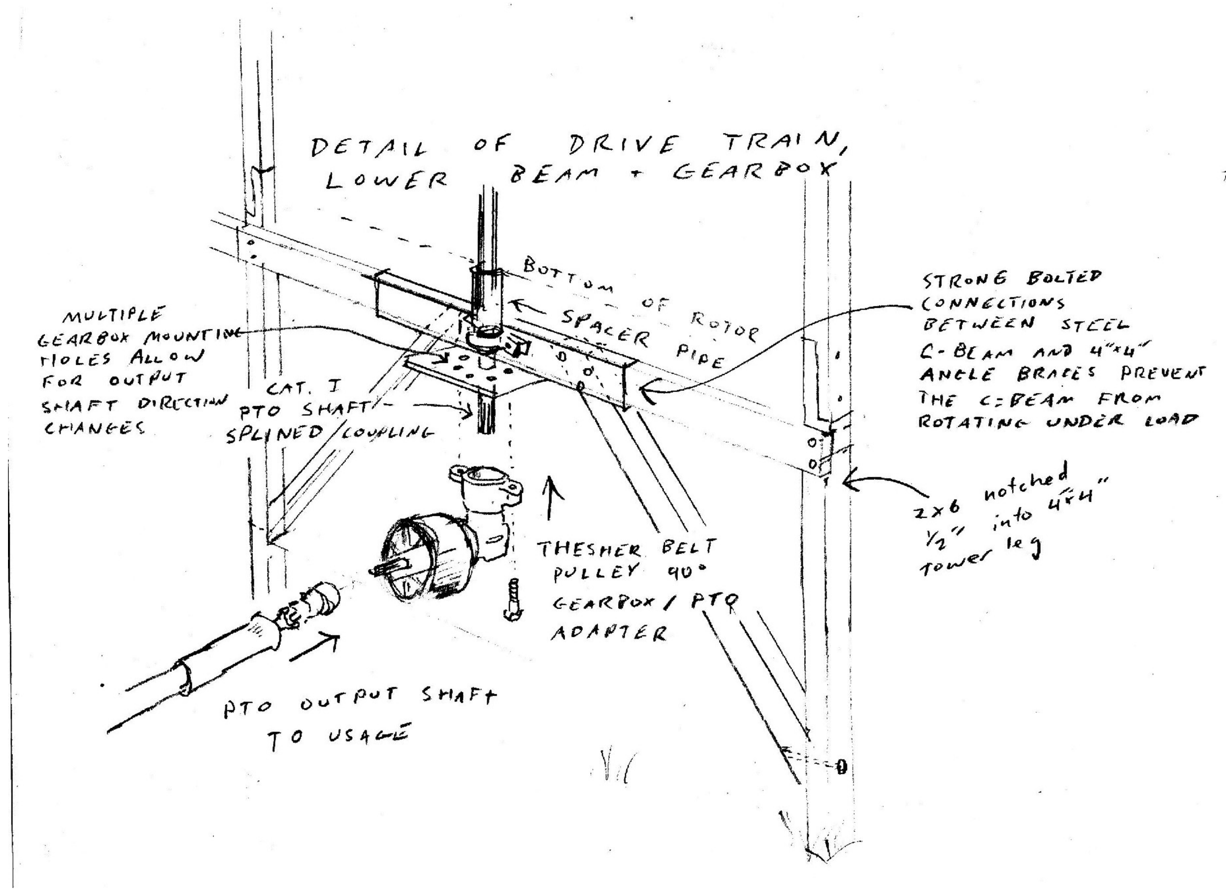
paintbut didn't bother removing light surface rust.

We also ordered babbit bearings with a bolt flange to receive the outside diameter of our pipe shaft with close tolerance. It is important to select bearings that can be greased and that are designed to bear 1000 lbs of lateral load. The lower bearing in particular does all the work of holding the unit up. The top bearing can be identical, but it mostly holds the shaft in place. For extra strength, the lower bearing was bolted to a 42” length of 6” steel c-beam, which also had a plate welded to it to receive the bolt-on 90 degree gearbox.

Note that the distance between the bottom of the lowest rotor and the pto stem must correspond to the mounting position of the 90 degree gearbox. The installed gearbox should receive the pto stem to an appropriate depth and also be firmly bolted to the gearbox mounting plate. If necessary, the rotor assembly can be moved up and down within a limited range and held there by changing the length of the spacer pipe, a short piece of 2” inside diamter pipe that fits over the driveshaft and allows the weight of the rotors to bear directly onto the lower bearing. The rotor assembly of course must maintain adequate clearance from the tower sides, and the upper and lower tower beams.

As indicated in the following illustration, it can be useful to have multiple holes available in order that the 90 degree gearbox can be pointed in more than one direction. In our case this will allow us to use the windmill for water pumping some of the time but also to use the rotary power for other jobs, like powering an ice cream maker or a flour mill. We are thinking about making a small mobile work building. The building could be positioned right next to the windmill with the pto shaft coming right through the side of it.

Naturally the pto system is but one of many possible ways of transmitting rotary power from the windmill. Others include v-belts, flat belts, bicycle, motorcycle or equipment chain, a friction drive disc, and various kinds of gearing.



Part II: Building the Tower

2	4” x 4” x 16' pressure treated
4	4” x 4” x 8' pressure treated
3	2” x 6” x 8' pressure treated
4	Triangular gusset plates, (two cut from a 12” square along the diagonal), 1/4” thick
box	3/8” x 8” carriage bolts, w/ nuts and washers
12	3/8” x 5” hex bolts, w/nuts and washers
2	Bags concrete
4	Earth anchors, at least 2' long
1	250' spool of 1/4” stainless steel cable
8	1/4” cable clamps
4	3/8” turnbuckles
--	Extra lumber for props and bracking

Once your rotor assembly is complete, verify the radius at several points. Your tower legs should allow clearance (ideally 2”) from the moving sails of the rotor, so add 7 1/2” to the largest diameter measurement of the completed rotor assembly. This is the distance between the centers of the two legs of the tower. Mark out the locations and dig your post holes below the frost line. Pour one bag concrete per hole and set the short leg bases in the concrete, and brace them plumb, parallel, and the correct distance from one another (diameter plus 4” between inside surfaces) with temporary lumber.

Once you have refilled the post holed and the concrete has cured, you can remove the bracing and cut lapped scarf joints at 4'9” of height as shown on the dimension drawing in the appendix. The tower's upper legs will have the opposite halves of this scarf joint cut into them later. Notch a 1/2” deep recess 5 1/2” tall into the face of each lower leg, ensuring that the two notches face the same direction and are level with each other. This will receive the 2” x 6” lower beam, which is cut to final length and through-bolted to the legs. 4” x 4” diagonal braces reinforce the lower beam, and are also through bolted to the tower legs near ground level.

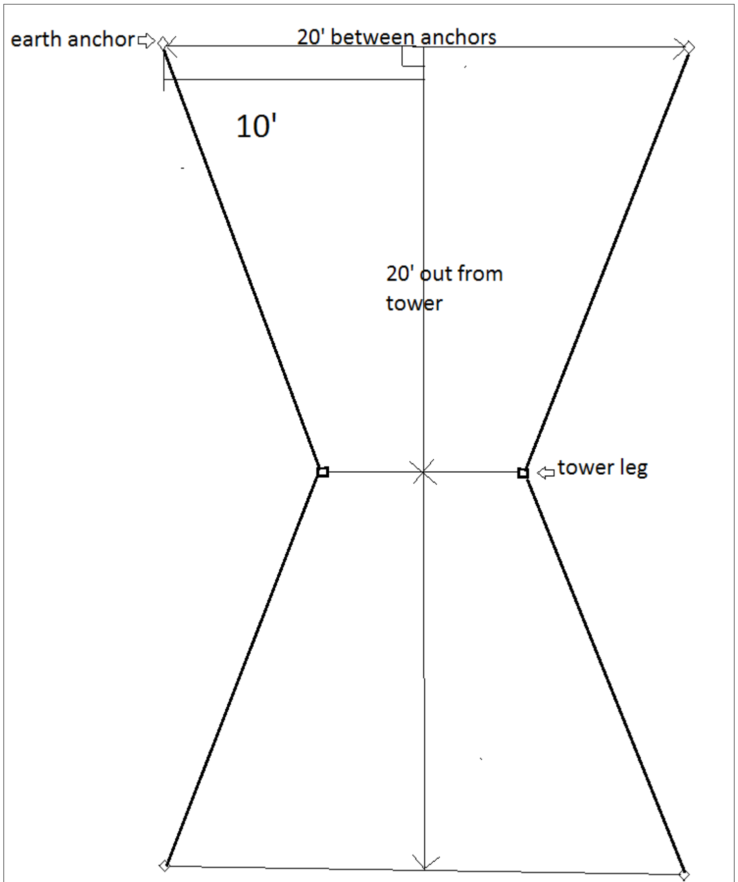
2” x 6” members a full 8' in length flank the outside faces of the tower legs and bridge the weak scarf joint. These braces are through bolted every 2' or so with extra bolts around the scarf join itself. Precision is not necessary here, about half the piece lies above the joint and about half below.

The lower beam may need to be shaped with chiesels or planes in order that the c-beam fit snugly around it, and in close contact. Pre-fit the c-beam now so that it can be easily fitted into place later once the rotor assembly is raised.

Now the lower portion of the tower resembles a capital H. We turn our attention to the upper part. The three rotors joined end to end should measure about 180”. If the scarf joint in your lower posts begins at 4” above the top edge of the lower beam, then the if the upper tower legs are scarfed and used at full length, then the total distance between the top of the top beam to the top of the upper posts should be 196”. This gives you enough to allow for 3 1/2” for the top beam and still have 6” of clearance with the rotor centered between the upper and lower beams.

Cut the corresponding faces of the scarf joints as shown in the drawing and law the upper legs on the ground. Cut the top beam to length (rotor diameter plus 4”for clearance, same as with the lower beam. This assumes the top beam will but into the sides of the tower legs rather than overlapping them, but it can also be done the other way. The triangular steel gusset plates in the materials list are a strong way of joining this corner that will also ensure a sound cable connection. Through bolt them to the 4' x 4' members with hex bolts. Square the top beam of the tower to the legs and hold in this position with temporary diagonal bracing. Lastly drill through the gusset plates and thread lengths of 1/4” cable through.

We positioned our cable anchors about 20' out from the tower and about 20' apart, as shown below. We used auger-type earth anchors and attached turnbuckles to them. Using the pythagorean theorem, we estimated the length of the guywire cable to be Abour 28.3 feet. We clamped the cable at this length on the lifting side and left the pulling side cables dangle free. This way when the tower reaches a vertical position the cables will come up taut and not allow the tower to fall over to the opposite side.



layout for guywires. The guywires run from the upper corners of the tower to earth anchors. These wires can be adjusted to secure the tower in a plumb position

We manually lifted the tower legs into position so that the scarf joints partially fitted together. The tower top beam remained on the ground. We used a piece of lumber blocking to keep the tower upper legs positioned in the joint, and some clamps as well, though not set so tight as to prevent rotation as the tower was raised. We anchored a hand winch at some distance on the pulling side with the cable reeled out to a central point on the top beam.

The initial 8' of lift was accomplished by lifting the top beam with a bucket loader. After that the next few feet of were made with the assistance of props and pieces of lumber to push. Once the top beam was about 10 feet off the ground the winch was able to lift with good advantage. Being fairly light the tower winched into a vertical position and the cables came taut as we had expected. The loose pulling side cables were quickly anchored to the remaining two positions, and the scaft joints were bolted home. Once the tower was "trimmed" into a perfect vertical position by tensioning the four cables in succession as necessary, we brought all four cables as taut as could be managed and got ready to lift the rotor unit into the four-sided frame.

Part III: Installing the Rotor Array

The finished rotor assembly is quite heavy and installing it is very tricky and also moderately dangerous. We really recommend the use of a small crane, which could do the job with a great degree of safety. Due to the time of year and the ground conditions, crane hire wasn't a good option for us, so we used simple machines instead. I will offer our methods with the understanding that a crane is the preferred method, both from a safety standpoint and to avoid severe damage to the rotor or tower.

We dragged the assembled, painted rotor into place with the lower end of the driveshaft next to the lower beam and the top end of the shaft pointing away from the tower. We fitted the spacer pipe, babbet bearing and the lower beam brace (c-beam) onto the shaft. We then chained and strapped the c-beam to the lower beam, but not too tightly as the c-beam needs to rotate as the assembly is lifted.

The tower is now sturdy enough to leam an extension ladder against the top beam and climb up. We chained a large pulley around the top beam and threaded a 1/4" cable through it. This cable stretched from the driveshaft stem at the top end of the rotor unit, through the pulley to our tractor drawbar.

With the upper end of the rotor lying on the ground, the tractor had little lifting advantage, and we seemed likely to distort the tower rather than lift the heavy unit. So instead we used a farm jack and blocking to obtain the first 10' or so of lift and after that the tractor was able to walk away with the load, easily lifting the assembly into place.

From the top of the ladder we were then able to through bolt the upper babbet bearing to the center point of the top beam. Once the shaft was thus secured to the beam we removed the pulley and lifting cable.

The lower end was more problematic. With the tractor no longer needed for raising the unit, we used a combination of the bucket and various jacks to take the weight of the rotor assembly so that the c-beam could be fitted and bolted onto the lower wooden beam. Then the chains and straps can be removed. We also had to remove and resize our spacer pipe for optimal clearance at this time. Once the c-beam is securely bolted to the lower beam and the diagonal braces, it will stay in a plumb and level position and the rotor will turned with very little noise in light winds. Any loud noise or bearing noise is a sign of trouble, and all bearings should be greased and checked carefully for proper alignment.

The finished product: A big green windmill. It's job beginning in the 2012 growing season will be to pump water from the reservoir (frozen water on the left) to the rice paddies (off to the right of the frame).

General Installation Considerations

There are three main things to consider when contemplating any wind power installation:

1. *Your tower is too short*
2. *Your tower is too short*
3. *Your tower is too short*

Joking aside, exposure to stronger winds has an exponential effect on the productivity of the device. It stands to reason that the windmill should be sited to maximum advantage. The 12' high unit is about as big of a device as can be moved around easily, but additional height could be achieved with a basic empty tower matching the rotor tower's footprint. With creativity and a crane, rooftop installations may be possible. Vibrations typical to horizontal turbines were not observed on our prototype, so it seems likely that no significant noise or vibration would result from a rooftop installation. Be sure to get an opinion from an experienced builder or structural engineer before committing to a rooftop installation.

If multiple towers are deployed, it is best to not place one upwind (in the predominant wind direstion) of another. It is also best to space towers at least 20 feet apart. Our side-by-side installation was observed to have one of the two rotors turning at half the speed of the other a good percentage of the time, so we don't recommend this installation. If additional power is desired, better to build vertically if at all possible.

Although the constuction manual for the Mark I wooden unit features stator panels, at this point we're quite unsure if they are of any benefit. They may even reduce the efficiency of the unit by blocking winds falling on its quarter. So if you consider a Mark I, consider omitting these panels, or even using a Mark II-style tower with cable stays.

Above: Yellow Savonius rotors grace the skyline of Melbourne, Australia. They are part of a comprehensively-designed energy-conserving office building.

Right: A European three-rotor Savonius tower of striking design in a triangular frame.

Acknowledgments

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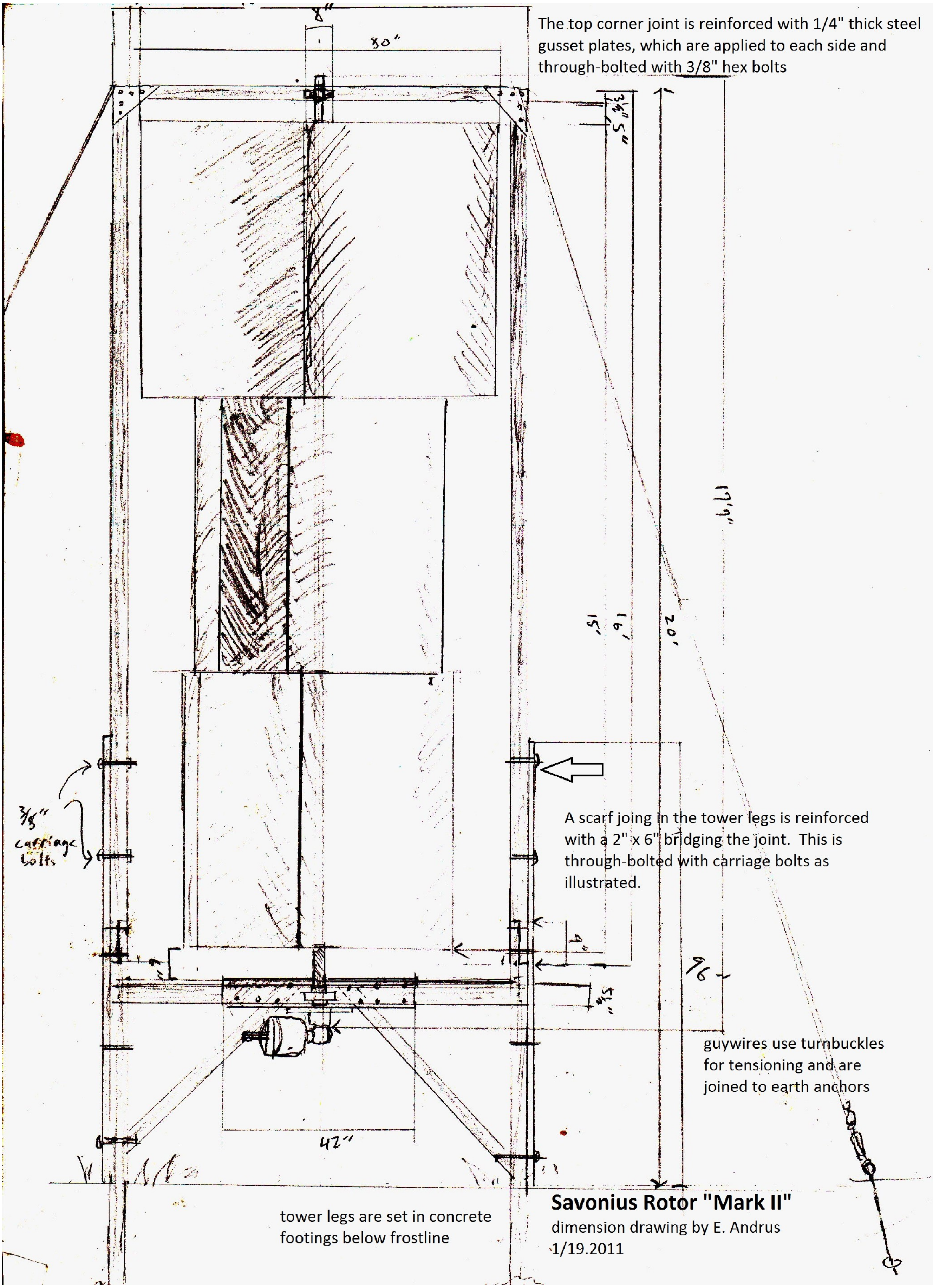

Savonius Rotor "Mark II"
dimension drawing by E. Andrus
1/19.2011