

SMALL WIND TURBINES MOUNTED TO EXISTING STRUCTURES

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The Academic Faculty

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DEDICATION

I dedicate this work to my wife, Brooke Erin Duffy, and my family.

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I would like to thank Dr. Sankar for his assistance and guidance. I am also grateful to my wife, Brooke Erin Duffy, for advising me to do this topic for my thesis.

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LIST OF SYMBOLS / ABBREVIATIONS

AC – Alternating current

AEP - Annual Energy Production

AOA, α - Angle of Attack

AWEA – American Wind Energy Association

β – Blade pitch angle

c - Blade chord

CAD – Computer aided drawing

Cl – Coefficient of Lift

Cd – Coefficient of Drag

Cp – Coefficient of Power

Ct – Coefficient of Thrust

DC – Direct Current

FOD – Foreign object debris

ft – Feet

ft/s – Feet per second

k – Weibull normal distribution factor

kW – Kilowatts

kWh – Kilowatt-hours

L/D - Lift over drag

m - Meters

mph – Miles per hour

m/s – Meters per second

MW – Megawatts

N – Number of blades

NOABL - Numerical Objective Analysis of Boundary Layer

NWTC - National Wind Technology Center

PMG – Permanent magnet generator

R – Blade radius

r – Radial station along blade span

RPM – Revolutions per minute

t/c – Thickness to chord ratio

U_{∞} - Free stream wind velocity

λ – Tip speed ratio (Tip speed / Free stream wind velocity)

Ω – Rotational velocity

Wh – Watt-hours

WWAS – Web-based Wind Assessment System

WWT – Warwick Wind Trials

SUMMARY

Small wind turbines, and especially urban-mounted turbines which require no dedicated pole, have garnered great public enthusiasm in recent years. This enthusiasm has fueled widespread growth among energy conservationists, and estimates predict that the power produced nationally by small wind will increase thirty-fold in the next three years. Unfortunately, most of the wind resources currently available have been designed for larger, rural-mounted turbines; thus, they are not well suited for this nascent market. A consequence of this is that many potential urban small wind turbine owners over-predict their local wind resource, which is both costly and inefficient. According to a recent study published by Encraft Ltd., small wind turbines mounted to buildings far underperformed their rural pole mounted counterparts.

As a proposed solution to this problem, this project introduces the concept of a Web-based Wind Assessment System (WWAS). Through an economically viable wind measurement structure, this system converts wind resources into a web-based, user-friendly interface, for prospective small wind turbine owners to use. The WWAS prevents potential clients from investing in a system that may not be viable for their location.

In addition, a small wind turbine is designed in this project, which has a unique modular mounting system, allowing the same baseline wind turbine to attach to various structures

using interchangeable mounting hardware. This includes such accessible urban structures as street lights, building corners, flag poles, and building walls, among others.

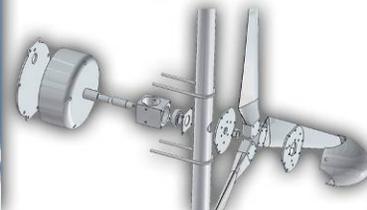
This design also utilizes concepts that address some of the challenges associated with mounting small wind turbines to existing urban structures. These concepts include: swept tip blades and lower RPM to reduce noise; vibration suppression using rubber shims; a netted duct to protect wildlife; and a direct-drive permanent magnet generator to ensure low starting torque.

Finally, the cost of this system is calculated using off-the-shelf components, which minimize testing and certification expense. This small wind turbine system is designed to be grid-connected, has a 6 foot diameter rotor, and is rated at 1 kW. This design features a unique modular interchangeable mounting system. The cost for this complete system is estimated to be \$2,050. If a users' site has an average wind speed of 14 mph (6.5 m/s), this system will generate a return on investment in 8.5 years, leaving over 10 years of profit. The profit for this system, at this sample average wind speed, yields over \$4,000 during its 20-year design life, which is a two-fold return on investment.

This project has implications for various stakeholders in the small wind turbine market, including designers, engineers, manufacturers, and potential customers. Equally important is its potential role in guiding our future national—even global—energy agenda.



**Small Wind Turbines
Mounted to
Existing Structures**



1. INTRODUCTION

A 2009 study conducted by the American Wind Energy Association (AWEA) on the national market for small wind turbines indicated a 78% growth in U.S. installed power for 2008 and a projected 30-fold increase by 2013. Such explosive growth has been in large part fueled by an eight-year 30% federal tax credit passed by Congress in February 2009 [26].

The growth potential of small wind has sparked significant interest in small wind turbines located in urban areas. Unlike vast rural expanses, urban locations provide many sites upon which to mount small wind turbines. These existing urban structures take the place of dedicated poles, which, on average, comprise 40% of the total cost of small wind systems. The reduced cost of on-site mounting has prompted small wind turbine manufacturers to focus their designs on existing structures and buildings.

Although the concept of the building-mounted small wind turbines is not entirely new, it is only in recent years that it has become a viable option to compete in the global marketplace. Yet challenges still remain, as some independent verification tests of small wind turbines mounted to urban structures have shown. The Warwick Wind Trials (WWT) project launched in 2007, placed various small wind turbine models (rated ~1 kW) to a variety of locations around the U.K. When the study completed in late 2009, it provided evidence that building-mounted small wind turbines greatly under-performed

their isolated rural counterparts as urban areas typically have lower-than-average wind speeds.

In order to address the problem of lower urban wind speeds, several small wind turbine manufacturers have tailored their wind turbines for the low wind speed regime (5 – 8 mph). Yet, the limits of physics are undeniable and dictate that small wind turbines are only viable when wind resources are suitable. This is a difficult fact to contend with, and poses both financial and mechanical difficulties for potential small wind turbine owners and manufacturers.

This is not, however, to say that small wind turbines mounted in an urban environment are doomed to fail. In fact, the same WWT study of wind turbine performance also suggested that small, building-mounted systems could be very effective if carefully placed in a suitable wind resource location.

This leads to the most important consideration guiding the urban-mounted small wind turbine market today: the accurate assessment of localized wind resource. Given that most available wind resource measurements are designed for larger wind turbines set in rural areas, this is not an easy endeavor. Furthermore, urban wind correction factors, although publicly available, are highly dependent on the assumption in which they are based and therefore, not guaranteed to be applied correctly. Finally, urban wind resource predictions based on analytical methods are extremely imprecise due to the complex nature of urban aerodynamics.

These are some of the many challenges that this project aims to overcome. After outlining the problem of assessing the urban wind environment, the concept of a Web-based Wind Assessment System (WWAS) is introduced. The system combines all the necessary resources for potential urban small wind turbine customers into a single web-based tool. The system also presents the concept of a modular wind measurement system, which couples with the WWAS to provide real-time wind data measurements based on user input. The benefits of the system include its ease of use, flexibility of installation, data accessibility from any web browser, and expert advice. Essentially, the WWAS and the modular wind measurement system bring the same high quality wind assessment tools available to large-scale wind farmers into the hands of small wind turbine investors

After exploring the facets of these systems, this project examines the design of a small wind turbine system that can be located onto various existing urban structures including building rooftops, flag poles, light poles, building corners, and walls, among others. Indeed, one of the central features of this system is its flexibility in mounting, ensuring that the user can optimize the placement of their small wind turbine in order to maximize its performance. As discussed later, this is accomplished with a modular mounting design, which uses interchangeable attachment hardware customized for a variety of mounting locations.

This project also explores concepts that address some of the challenges typically associated with mounting small wind turbines to existing urban structures. This includes swept tip blades and lower RPM to reduce noise, vibration suppression, a netted duct to protect wildlife, and a direct drive permanent magnet generator to ensure low starting torque. These design features are included as optional modular components to the baseline design, which enhance its functionality to maximize performance for urban operation.

Performance and cost estimates for this project were based on existing data from a variety of sources. The small wind turbine performance in this project is calculated using the National Renewable Energy Laboratory (NREL) wind turbine performance code called WTPERF. Three dimensional drawings are done using a Computer Aided Drawing (CAD) package from Dassault Systems called CATIA V5. Finally, as cost is a major driver for a viable small wind turbine system; real, off-the-shelf components were used in this design to minimize testing and certification costs. A complete cost breakdown is provided and stacked up against the predicted performance to yield customer return on investment.

This project has implications for various stakeholders in the small wind turbine market, including designers, engineers, manufacturers, and potential customers. Equally important is its potential role in guiding our future national—even global—energy agenda.

2. SMALL AND MICRO WIND

“Small wind” is defined as wind-powered electric generators with rated capacities of 100 kilowatts (kW) or less. “Micro wind” is a subset of the “small wind” classification and is generally defined as turbines with rated capacities less than 1kW [25].

2.1 Microgeneration

Microgeneration is the concept of distributed power generation using renewable resources that exist in and around the home to generate and store heat and/or electricity. In general, microgeneration is associated with reduced carbon emissions because it does not require the use of fossil fuels to generate power. Microgeneration technologies include small scale wind turbines, hydroelectrics, photovoltaic solar systems, ground source heat pumps, Micro Combined Heat and Power (MicroCHP) installations. Small wind microgeneration is the focus of this design study.

2.2 Small wind market size

The small wind global market size was \$156 million in 2008, which was a 53% growth over 2007 [25].

2.3 Small wind market share

U.S. manufacturers contributed to 49.4% of market share for small wind systems at the start of 2009. As of 2009, 219 small wind manufacturers were identified, 35% of which were US based [25].

2.4 Growth of small wind installed capacity

The installed small wind capacity in the U.S. was 17.3 MW during 2008 and is projected to grow 30-fold by the end of 2013. This explosive growth is primary fueled by a new eight year 30% federal Investment Tax Credit, which was passed and augmented by Congress in February 2009. This extreme growth in small wind capacity is expected to translate into a large increase in market size [25]

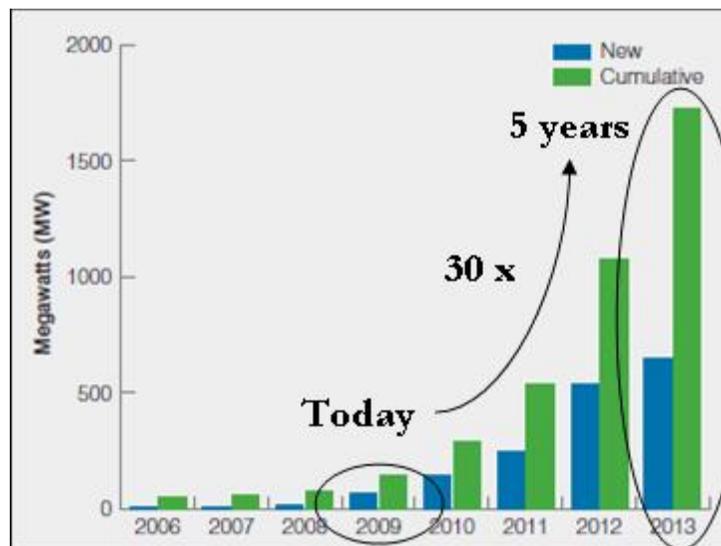


Figure 2-1: In the next 5 years a 30-fold growth of the U.S. installed small wind capacity is projected [25]

2.5 Market barriers

A survey done by the American Wind Energy Association (AWEA) surveyed 72 participants to rate the top market barriers for small wind. The three highest rated barriers were: upfront cost, zoning permits, and lack of government incentives as shown in Table 2-1 [25].

Table 2-1: “What are the key market barriers for small wind turbines?” Ratings of the following issues from 1 - Not an Issue to 8 - Largest Barrier [25]

Issue	Rating
Cost	6.53
Zoning and Permits	6.03
Lack of Govt. Incentives	5.73
Visual Impact	5.14
Low Public Awareness	5.00
No Certification of Turbines	4.87
No Certification of Installers	4.42
Lack of Detailed Wind Maps	4.19
Lack of Net Metering	4.18

2.6 Small wind turbine cost drivers

Upfront cost is a primary market barrier for small wind systems. Figure 2-2 shows the cost comparison of tower vs. the turbine (including all components) for several small wind systems on the market today. The primary cost driver is the tower.

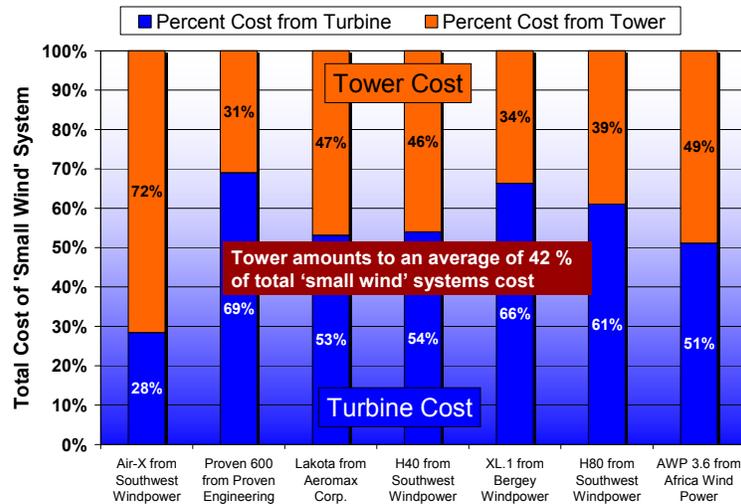


Figure 2-2: The above chart is a cost comparison of the tower vs. the turbine for several small wind systems on the market today. On average the tower makes up 42% of small wind systems total cost [1].

2.7 Removing the tower from the small wind turbine system

Building roof tops have been utilized in an effort to reduce cost, and simplify the installation of small wind turbine systems. Using building roof tops provides the needed height above the ground to clear obstacles such as trees and other buildings. In general, the higher the building above the surrounding obstructions, the higher the average wind speeds. Issues arise when small wind turbines are mounted to insufficiently tall buildings, which have low, turbulent winds from surrounding buildings, trees, and other urban structures. Additionally, there are other considerations with building mounted wind turbines, such as: vibration, noise, and appearance, which are generally exacerbated by proximity to people.

3. REALITIES OF BUILDING ROOF TOP MOUNTED WIND TURBINES

In order to better understand the performance of small wind turbines in an urban environment, a literature search was completed. It revealed an independent study performed by a research company called Encraft. The study, completed in 2009, called the Warwick Wind Trials, collected data for small wind turbines mounted to various building roof tops in Warwick, U.K. The primary purpose of the study was to collect data of wind speed, power, and cost. The study highlighted the importance of location for setting small wind turbines in urban areas [9].

3.1 Warwick Wind Trials Project [9]

The Warwick Wind Trials (WWT) project, which began in July 2007 and successfully installed small wind turbines at 26 urban locations around the U.K., was completed by 2009 [9]. Various small wind turbine models, manufacturers, and location types were tested. Findings included: measured wind speeds during the trial were lower than the U.K. national database. Small wind turbine manufacturers published performance varied in accuracy, mostly optimistic compared to measured data. Setting location for building mounted small/micro wind turbines was critical to yield viable performance.



Figure 3-1: Images of two micro wind turbine sites that were monitored during the Warwick Wind Trials Project, image source: reference [9]

3.1.1 Measured wind speeds

Measured wind speeds did not correlate with predicted wind speeds from historical databases, even with corrections made for height and urban environment. The averaged measured wind speed over the different sites was 67% lower than that of the current U.K. Numerical Objective Analysis of Boundary Layer database (NOABL) [9]. It was determined that the variance in mean wind speed was heavily dependent on mounting location, and thus great care was suggested when choosing an installation site.

3.1.2 Measured turbine performance

On average the small wind turbines during the study produced 214 Wh of electricity per day (this included times when turbines were off for maintenance). This equates to an average of 78 kWh of power for each site or an average capacity factor of 0.85% (measured power divided by theoretical maximum output); however, if the results were adjusted to exclude data from turbines that were off, the power per turbine per day rises to 628 Wh or an average capacity factor of 4.15%. The capacity factor for large turbines

with free standing towers typically ranges from 10% to 30%. The best small wind turbine location measured an average power output of 2.382 kWh per day, which is equivalent to a capacity factor closer to 15%. This highlights importance of location and also indicates that small wind turbines mounted to buildings can yield viable performance, if optimally placed. [9]

3.1.3 WWT Recommendations [5]

Important lessons were learned from the WWT project, which can be applied to next generation small wind turbine designs, specifically for ones to be mounted to buildings and structures:

- Selecting a suitable site for building mounted wind turbines is critical for viable operation, and eventual return on investment.
- More robust methods for predicting average wind speed in urban areas is needed.
- There is a need for an industry standard method to produce and publish power curves for manufacturers of small wind turbines.
- Noise complaints can become an issue, noise and vibration reduction should be designed into next generation building mounted wind turbines.

4. URBAN AERODYNAMICS

Given the criticality of setting small wind turbines to viable energy generation, the first step taken in designing the next generation small wind turbine located in urban area was to examine urban aerodynamics. After studying urban aerodynamics it became clear that there was no one formula or piece of empirical knowledge about urban aerodynamics that will guarantee accurate predictions for a given location. This led to two conclusions for the design of the next generation small wind turbines for urban areas: First, doing local measurements would be ideal so that local environmental effects not considered in models, and in current databases, would be accounted for. Second, in order to allow for maximum viable placement, the mounting capabilities of the next generation small wind turbine had to be flexible enough to allow for the setting location to be optimized. In addition to this concept of flexible mounting capability, the next generation small wind turbine design will need to be tailored for a low wind speed environment.

4.1 Urban Boundary Layer

Urban aerodynamics is dominated by the boundary layer from turbulent unsteady flow passing over buildings and structures. This means that micro wind turbines are generally operating in relatively low average wind speeds. Figure 4-1 shows development of the surface boundary layer, which causes a reduced wind velocity and turbulent flow environment, in and around urban areas [19].

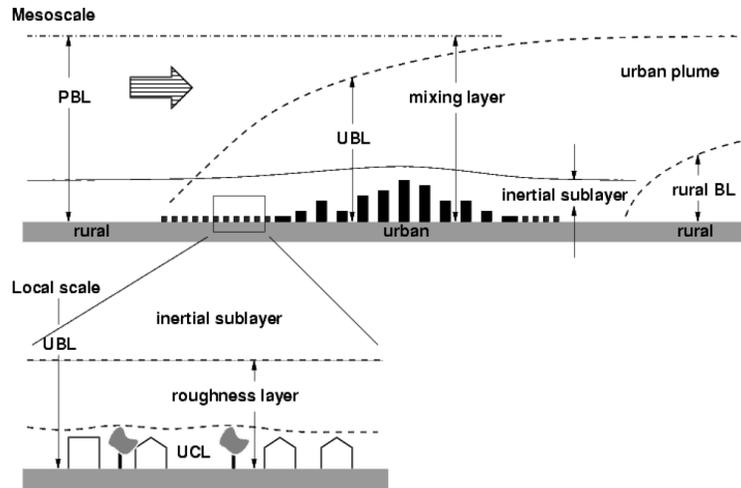


Figure 5: The layers of the atmosphere and the urban plume,
PBL = planetary boundary layer,
UBL = urban boundary layer,
UCL = urban canopy layer

Figure 4-1: The development of the surface boundary layer an urban setting, image

source: reference [19]

4.2 Optimum placement

Small wind turbine placement in urban settings has a significant effect on performance. The power output goes up with the cube of wind speed; therefore, finding the best mounting location is critical. Unfortunately, modeling local aerodynamics around structures in urban settings is very difficult, primarily due to the unsteady flow field that is a function of surrounding geometry, wind speed, wind direction, time dependence, and temperature. Collecting wind data with a wind anemometer is the best way to determine the optimum location for maximum sustainable wind; however, data collection is costly both in time and money.

There are; however, empirically derived rules of thumb for setting wind turbines on and around structures. Figure 4-2, Figure 4-3, and Figure 4-4 show several small wind

turbine setting scenarios with the best placement highlighted with circles. In general, these rules-of-thumb are for buildings and tower mounted wind turbines in urban areas; however, they can also be applied to non-traditional mounting structures, such as: street lights, flag poles, side of buildings, and roof tops.

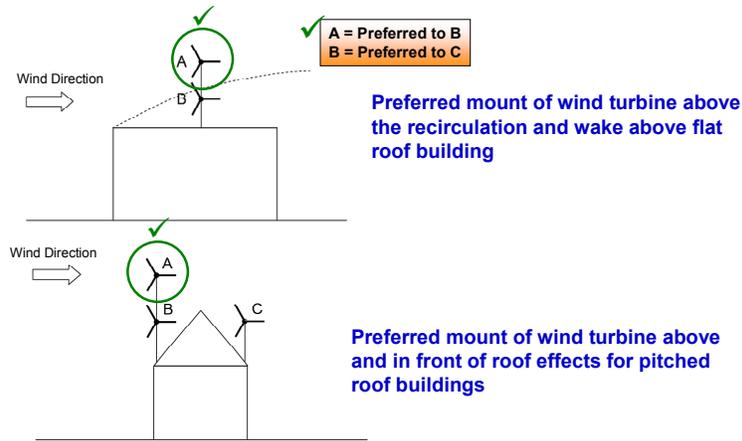


Figure 4-2: Each building has a unique boundary layer, for best performance the small wind turbine should be placed above this boundary layer [19]

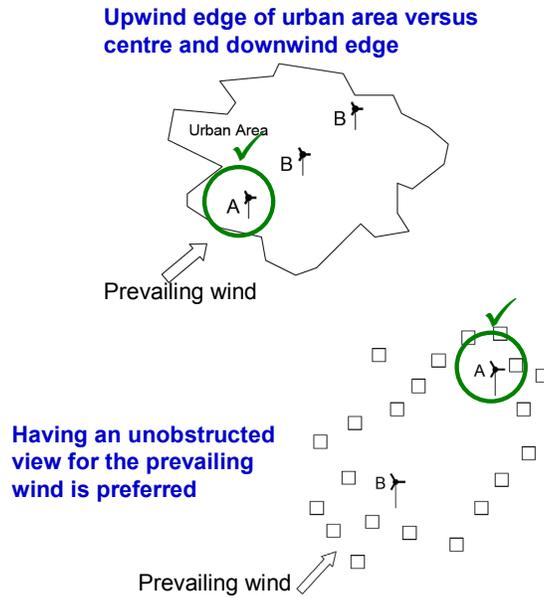


Figure 4-3: Wind turbines mounted on the leading edge of an urban areas is preferred; however, wind turbines mounted with an unobstructed view of prevailing wind is an alternative [19]

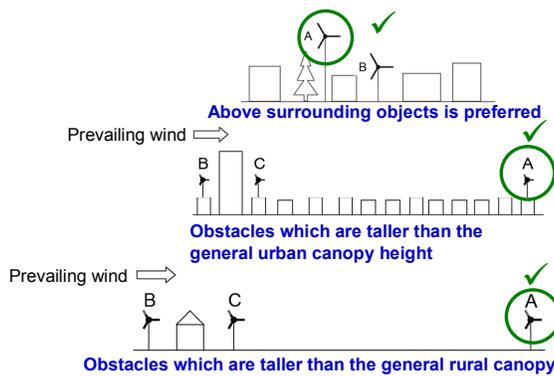


Figure 4-4: When wind turbines are near taller objects then separation from taller objects is preferred [19]

5. CURRENT URBAN WIND ASSESEMENT

Adopters of small wind turbines today have several tools available to them for predicting their average wind conditions. These resources include publicly available national and state wind maps (Figure 5-1), scaling factor charts (Figure 5-2), and local studies of small wind turbine performance (for example WWT, chapter 3). The wind resource maps provided in Figure 5-1 are particularly useful for larger turbines of 10 kW or greater, since they are based on data at 50 to 80 meters (160 to 260 ft); however, for most small wind turbines mounted to existing urban structures, these heights can be excessively high. Urban mounted small wind turbines are typically located at heights of 10 - 20 meters (30 to 60 ft). The wind resource data can, however, be corrected for these heights and surrounding structures with wind speed scaling factors, which are shown in Figure 5-2. Yet, most small urban wind turbine users do not have the knowledge that corrections are even need. Further, small wind turbines on existing urban structures operate in a lower wind speed environments, making predictions of average wind speed more critical to system viability. To highlight the criticality of average wind predictions: say a user of a small wind turbine system over predicts their average wind speed by 2 m/s (4.5 mph), a common occurrence today. This difference increases the expected pay off time from 5 years, up to 10 years for a \$2,500, 1 kW rated small wind turbine system.

To ensure that a small wind turbine is truly viable for a given urban location, local wind measurements are required. Figure 5-3 depicts a sample of a typical wind measurement

system mounted to a large dedicated pole. These systems include a wind speed anemometer (Figure 5-4), a data acquisition system, and some form of power supply (Figure 5-5). These systems are capable of measuring wind speed and wind direction, which is then stored in a data acquisition system. These systems typically cost \$600 and up [30]. A recommended investment for a potential small wind customer who is planning on buying a small wind turbine rated at 5 kW or more. These ‘larger’ small wind systems costing upwards of \$10,000 or more are a considerably higher investment compared to the typical small wind system mounted to existing structures. Micro wind turbines (rated less than 1 kW) typically mounted to buildings cost between \$1,500 and \$6,000, depending if the tower is included. For a potential customer of these small ‘micro’ wind turbine systems, spending \$600 dollars or more is not justifiable. This leaves potential small ‘micro’ wind turbine customers who want to mount to existing urban structures with little options. Today they must sort through the given resources, and try to make an educated assessment. And given the inherent difficulty of making corrections for urban aerodynamics, even for experts, there is little chance an urban small wind turbine customer will be able to make a truly rigorous assessment of their local wind resource.

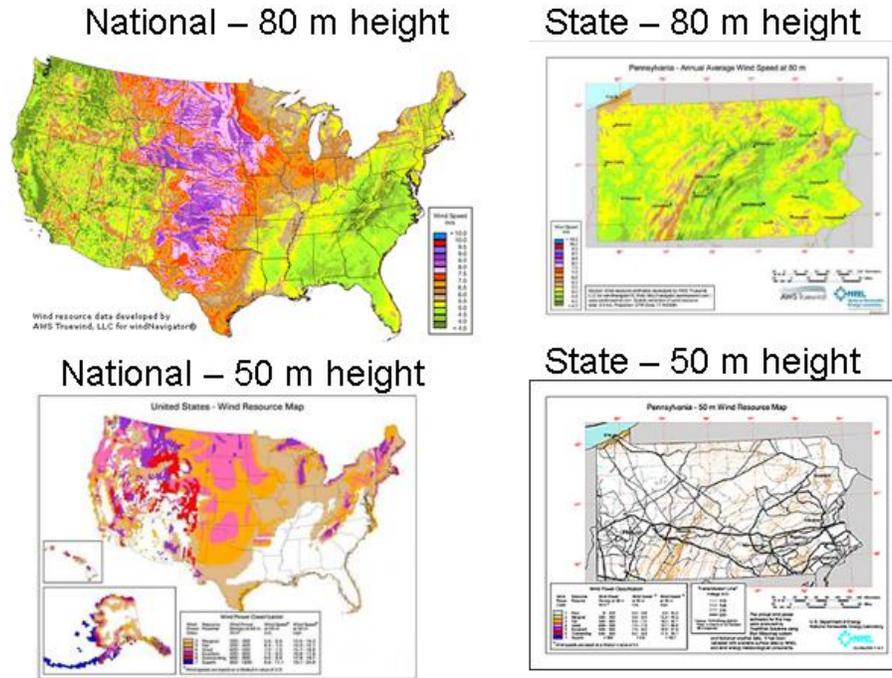


Figure 5-1: Publicly available wind resource maps for national and state typology, image source reference [31]

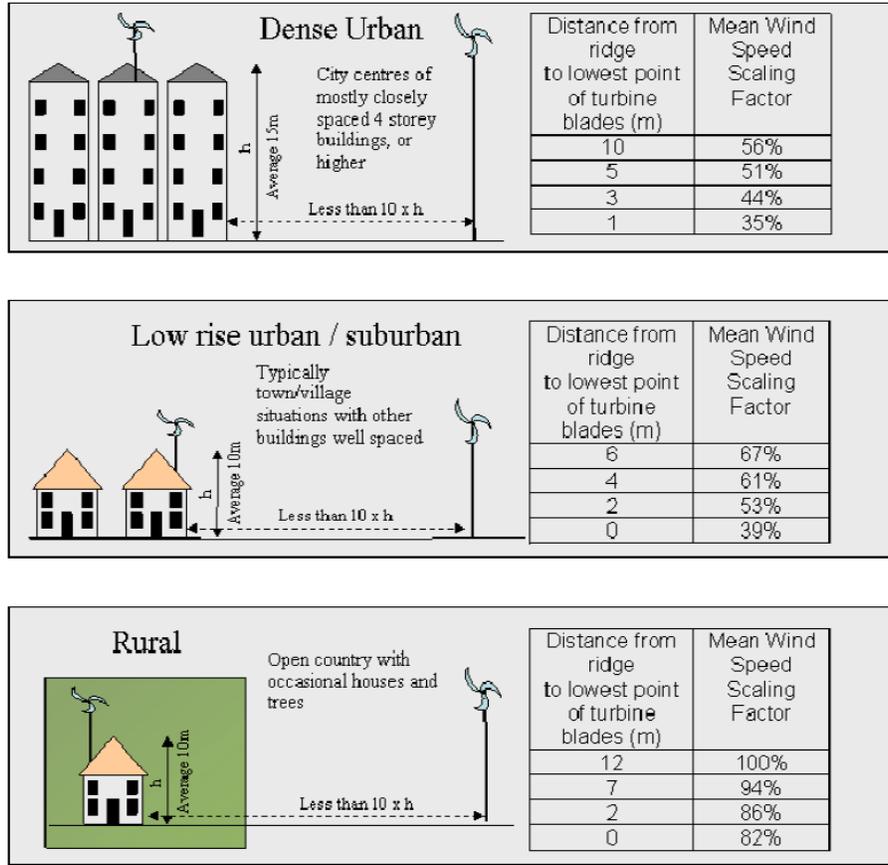


Figure 5-2: Wind speed scaling factors based on proximity to nearby obstructions, image

source reference [6]



Figure 5-3: Sample image of a currently available wind measurement system mounted atop a dedicated pole, image source reference [30]



Figure 5-4: Close-up view of wind speed anemometer and wind direction sensor, image source reference [30]



Figure 5-5: Sample of a data collection sensor with solar power supply designed by WindMonitoring.com, image source reference [30]

6. NOVEL WEB-BASED WIND ASSESMENT SYSTEM (WWAS)

There may be a better way for potential small wind turbine customers, who want to mount to existing urban structures, to assess their potential wind resource and power generation viability. Currently, wind resource data, correction factors, local government installation requirements, local tax incentives, and installation experts are scattered throughout the internet. Some government organizations have recently started collecting portions of this data into their own websites (example: <http://www.windpoweringamerica.gov>, <http://www.nrel.gov>) to help potential users make informed decisions. These resources are invaluable for potential customers who have intermediate knowledge of small wind turbine systems; however, for the greater number of potential customers, especially urban mounting customers, making an informed decision will require a simplified more economically viable approach.

A Web-based Wind Assessment System (WWAS) is a potential approach which could be developed. The WWAS works by amalgamating various wind resources into a single database and coupling it with algorithms that can correct the data for the local mounting environment. The user need not have any knowledge of small wind turbine systems to get a straightforward assessment of their local wind resource. This is because the data and algorithms, which calculate the predicted wind resource, would be transparent to the user. The user would only input simple known quantities into a web-based form like the one shown Figure 6-1.

This Web-based Wind Assessment System (WWAS) would accept inputs like zip code, mounting height, mounting location, and surrounding structures to name a few. Then based on the user input the WWAS would look-up local wind resources from a database and couple it with the necessary corrections based on all user inputs to output a predicted wind resource. A complete list of WWAS inputs:

- Zip Code
- Mounting type (select from images)
- Mounting environment (select from images)
- Mounting height
- Surrounding object height
- Surrounding object distance
- Number of surrounding objects
- Small wind turbine rated power (or select from list of manufacturers)
- Small wind turbine cost (or select from list of manufacturers)
- Number of small wind turbines

Notice in the sample input page of the WWAS shown in Figure 6-1, the user can select from images of potential alternate mounting locations and structures. The system would allow users to (optionally) upload photos of their potential mounting site. This would allow experts to survey the potential location and further correct the wind assessment.

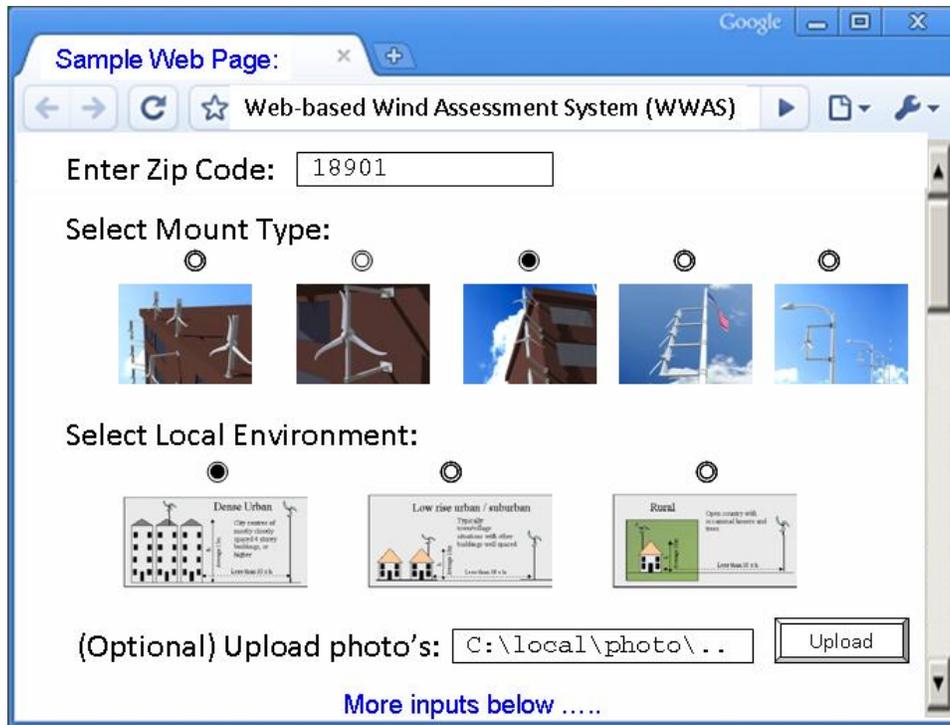


Figure 6-1: Example of input web page for Web-based Wind Assessment System (WWAS)

Sample outputs of the WWAS, listed below, and shown as a sample in Figure 6-2 would be simplified so that user could easily understand the predictions. The inputs would be repeated and summarized for clarity. A wind distribution based on the prediction would be shown, and viability of the site would be clearly indicated. Other optional outputs would be potential small wind turbines that match the resource, projected annual energy production if a wind turbine is selected from a list, projected number of years for return on investment. Local government and federal tax incentives would be automatically applied, and a list of qualified installers could potentially be listed as well. The WWAS would essentially become a one-stop-shop for any potential small wind turbine customer. The system could be sponsored by small wind turbine manufacturers, but would need to

be independently or government owned so that data was not skewed in favor of one manufacturer over another.

A final issue is the accuracy of predictions. Today, no algorithm to date can with absolute accuracy predict the actual wind resource for a given location, it is critical that actual data be taken. This is accomplished by using the most innovative feature of the WWAS, which is the modular wind measurement system. If the WWAS website determines, based on user input, that the given location is viable as a wind resource, the user can rent a modular wind measurement system. This wind measurement system is unique in that it allows the user to mount to any existing urban location to measure its potential wind resource. The system hardware is completely self contained and allows the data to be uploaded via a cellular connection to the WWAS website. Because the system is rentable, its expense to potential urban mounted small wind turbine customers is much lower than purchasing a wind measurement system. This allows it to be a viable means of collecting wind data for lower cost small wind turbine systems, specifically ones mounted to existing urban structures. In addition, the data is analyzed through the WWAS algorithms and translated into useful plots of average wind speed, return on investment, as an example. Greater detail about the wind measurement system is given in the next section, chapter 7.

The WWAS coupled with the modular wind measurement system, allows potential users to assess their wind resource with greater accuracy, and ease compared to today's fragmented resources. In addition, the data collected by the many users of the modular

wind measurement system can be fed back into the database and prediction algorithms in the WWAS to further improve its accuracy. The modular wind measurement system makes wind data collection economically viable for low cost small and micro wind turbines customers, which are most common in urban areas, where wind resources are particularly hard to predict.

A complete list of WWAS outputs:

- Wind map showing surrounding resources
- Predicted average wind speed
- Predicted seasonal variance
- Site viability for small wind
- Should wind measurement system be rented
- Wind measurement system rental cost
- Estimated wind measurement duration (based on local seasonal data)
- Projected Annual Energy Production (kWh)
- Projected number of years for return on investment
- Available local tax incentives
- Local government installation requirements/ordinances for small wind turbines
- Local installers

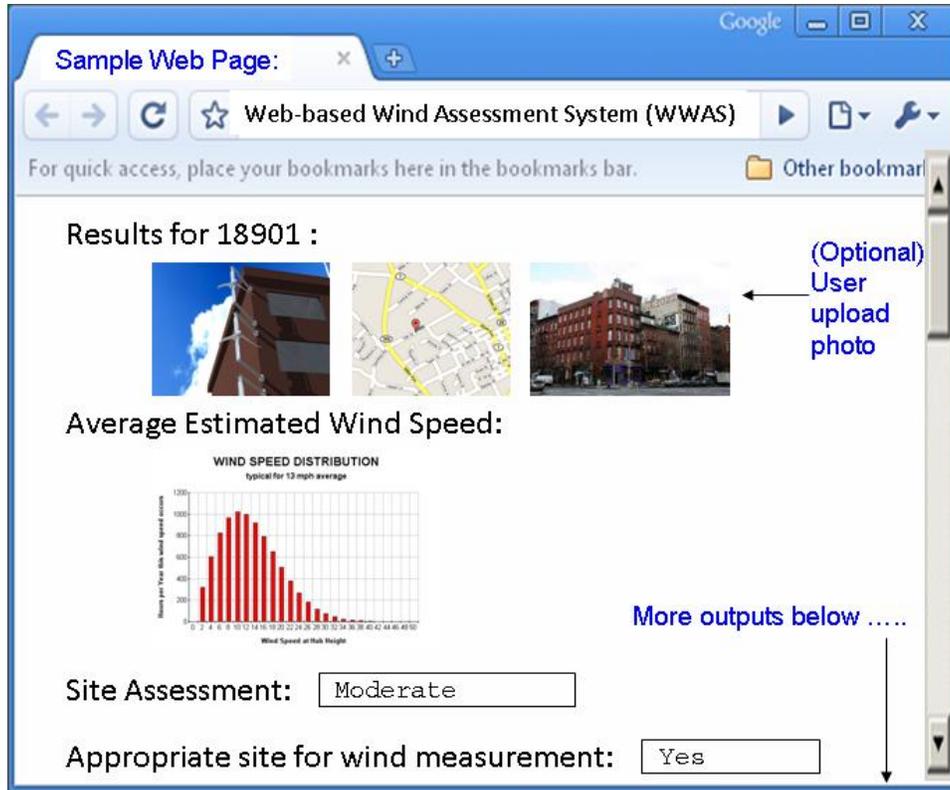


Figure 6-2: Example of output web page for Web-based Wind Assessment System (WWAS)

7. MODULAR WIND MEASUREMENT SYSTEM

Unlike today's wind measurement systems, which are expensive and require a dedicated pole, the modular wind measurement system depicted in Figure 7-1 can mount to various existing urban structures. The system is completely self-contained with the wind anemometer, power supply, data logger, and cellular communication system contained in one unit. This unit is then mounted using various interchangeable attachments, which are tailored for existing urban structures. The data collected is then sent through a cellular communications system to the Web-based Wind Assessment System (WWAS) discussed in chapter 6, where it is processed and displayed into easy to understand output that the user can access from any web browser. The modular wind measurement system can be rented for any duration of time, based on the WWAS recommended time period or by user discretion.

Because the system is rented (\$30-\$50 per month), wind measurement, data collection, and data analysis becomes affordable to most urban small wind turbine customers. Purchasing a small wind measurement system of similar capability would cost \$600 and up, and leave the user on his/her own to analyze the data [30]. This is a wise investment for small wind turbines costing \$10,000 and up; however, for small wind turbines mounted to buildings the usual cost to entry is closer to \$2,000 – \$6,000. This makes purchasing a wind measurements system prohibitive relative to the cost of the wind turbine system. The modular wind measurement system coupled with the Web-based

Wind Assessment System (WWAS) gives potential urban mounted small wind turbine customers an economically viable way to assess their local wind environment (Figure 7-2).

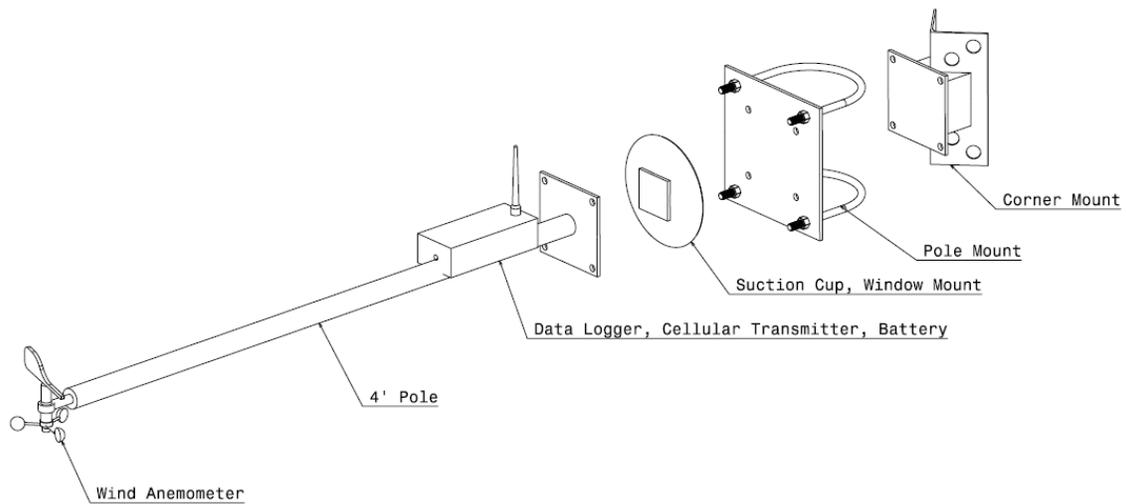


Figure 7-1: Drawing of modular wind measurement system. Details include an assortment of attachments, which allow it to be mounted on various existing urban structures.

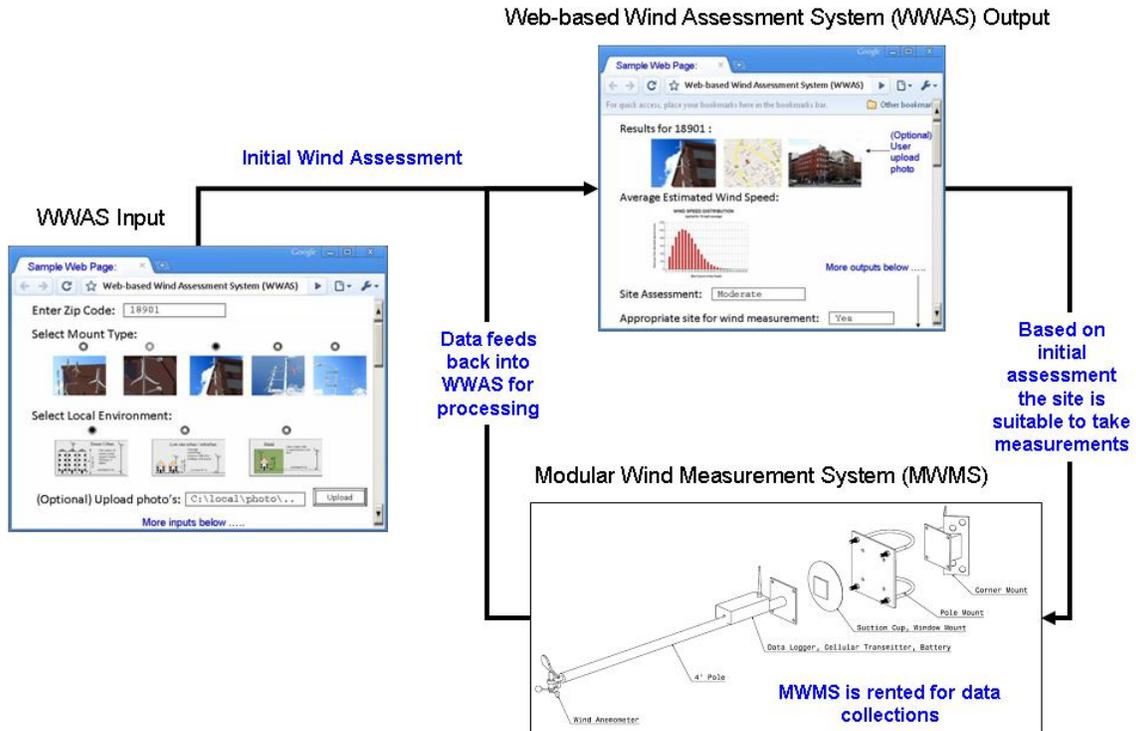


Figure 7-2: Flow diagram of how the Web-based Wind Assessment System (WWAS) works

8. ALTERNATIVE MOUNTING FOR SMALL WIND TURBINES

In a low wind speed environment, placement is the single most important factor for successful operation of small wind turbines. Mounting flexibility allows for placement in the highest wind velocity locations available. Figure 8-1 and Figure 8-2 show several small wind turbines mounted to the corner and outside of a building wall. This is unlike the traditional roof mounting seen on most of today's urban small wind turbines. Given the right conditions, mounting between buildings can also take advantage of airflow that gets accelerated, also known as a venture effect (Figure 8-3).

In addition to building mounted wind turbines, there exist various other structures offering suitable mounting conditions for small wind turbines. Figure 8-4 thru Figure 8-6 depicts additional alternate structures for mounting small wind turbines, like: flag poles and street lights. These already existing poles offer additional real estate for mounting small wind turbines and offer the added benefit of being high off the ground. An example would be to mount small wind turbines on street light poles in an open parking lot. Parking lots offer an unobstructed view of the wind, as well as offering a conduit through the lights for transferring the power generated to the grid. When the winds are high, the small wind turbines could power the lights and excess power would be delivered to the grid; when winds are low the lights would be powered by the grid itself.

The focus of this project will be to design the next generation of small wind turbines to take advantage of this concept by providing a simple, flexible design that allows for commonality even with various mounting configurations.



Figure 8-1: CATIA V5 render of building corner mounted small wind turbines



Figure 8-2: CATIA V5 render of building wall mounted small wind turbines

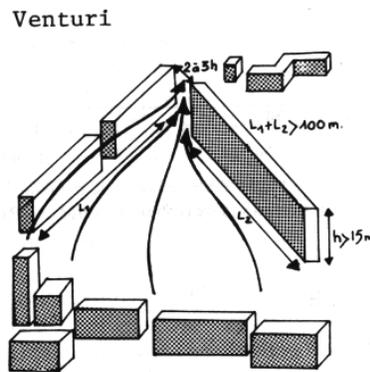


Figure 8-3: Wind between buildings can become accelerated causing an increase in airflow velocity. A properly placed small wind turbine could be mounted here to take advantage of this accelerated airflow. Image source: reference [2]



Figure 8-4: CATIA V5 render of flag pole mounted small wind turbines



Figure 8-5: CATIA V5 render of street light pole mounted small wind turbines

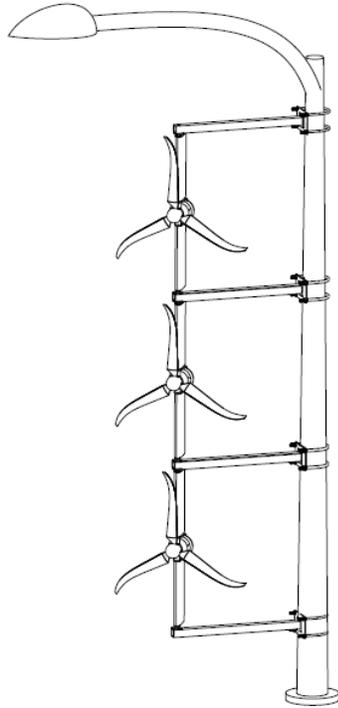


Figure 8-6: Multiple small wind turbines mounted to a single street light pole

9. SMALL WIND TURBINE DESIGN WITH MODULAR MOUNTING

CONCEPT

The small wind turbine designed for this project is focused on the concept of mounting to various existing urban structures using an easy to install interchangeable mounting system. This design uses off the shelf components where possible, for example: the generator is an off the shelf 0.5 – 1 kW permanent magnet generator (PMG), designed for low starting torque. The low starting torque accommodates the lower than average wind speeds. In addition, the blade design will be aerodynamically tailored for the low wind speed urban environment. CAD (Computer Aided Drawing) models and drawings are created using CATIA V5.

The design is influenced by the lessons learned from recent testing of small wind turbines in the urban environment (Warwick Wind Trials [8, 9, 10]). It incorporates technologies that make it more urban friendly. For example: optional swept tip blades for reduced noise and improved aesthetics, a set of optional rubber mounting shims to isolate vibrations from transferring into the building, an interchangeable motor to customize power generation for lower than average wind sites, and an optional netted duct to keep out wildlife. All added technologies are modular to the same baseline design so that the user can customize the turbine to his/her requirements.

9.1 Review of urban mounted small wind turbine locations

The small wind turbine designed for this project is tailored for mounting to various existing urban structure including buildings, poles, and tall structures. Figure 9-1 reviews the examples of where small wind turbines can be mounted in an urban environment.

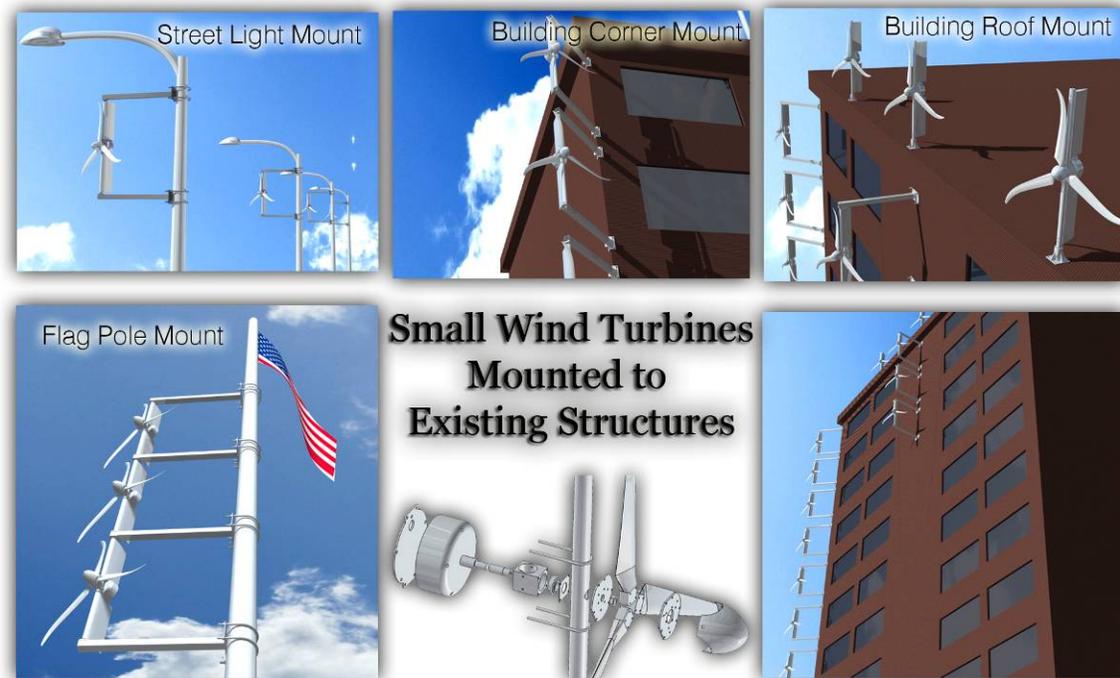


Figure 9-1: Examples of existing urban structures that small wind turbines can mount.

9.2 Blade radius

Blade radius was chosen to be small enough to ensure that the turbine would fit on most urban structures; but large enough to capture a reasonable amount of energy. Six foot diameter provides 28.3 sq.ft. (0.3 m^2) of disk area, which can produce 523 W of power at 15 mph wind speed, and almost 700 W of power at 20 mph wind speed. For

comparison, **Figure 9-2** shows a 6 foot man standing next to a 6 foot diameter small wind turbine.

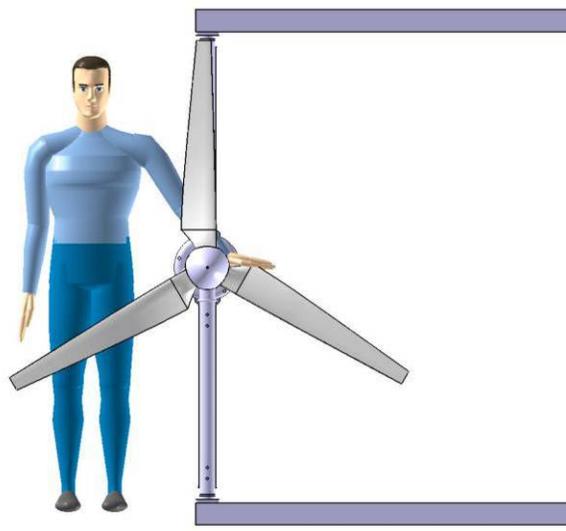


Figure 9-2: A comparison of a 6 foot man with the 6 foot diameter small wind turbine

9.3 Airfoils

For small wind turbines, airfoils are not as critical for performance as they are for large wind turbines; however, manufacturing and structural properties are critical. The SG605X series designed by Selig/Giguere from the University of Illinois at Urbana-Champaign were used because of their good low Reynolds number performance [24]. The SG6050 has a thicker cross section (t/c - 16%) and therefore, is used inboard from 20% to 50%. This provides additional stiffness at the root. The SG6051 is used from 51% to the tip because of its improved L/D and thinner cross section (t/c - 12%). Additional thickness is added to the root airfoils to further stiffen the blade to account for root bending moment. Figure 9-3 shows the SG6050 and SG6051 airfoil cross sections. The 2-D low Reynolds number C_l , C_d data are shown in Figure 9-4 and Figure 9-5.

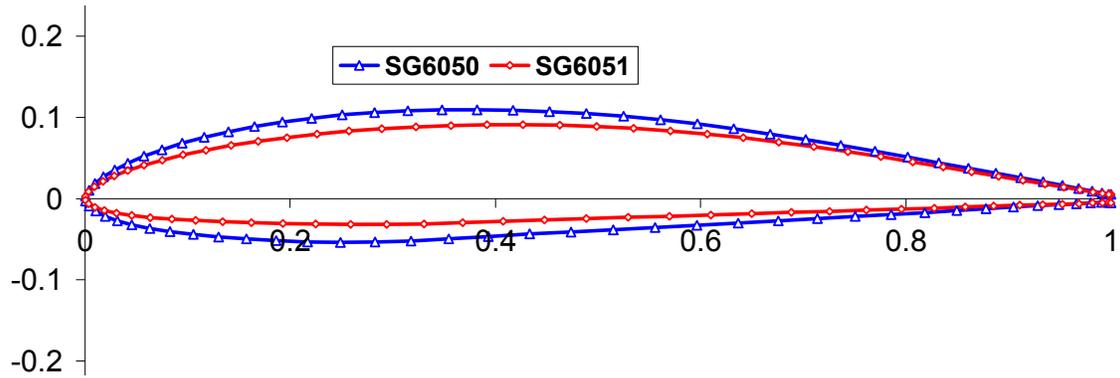


Figure 9-3: The SG605X airfoil series designed by Selig/Giguere are specifically tailored for low Reynolds number performance [24]

9.3.1 Airfoil Wind Tunnel Data

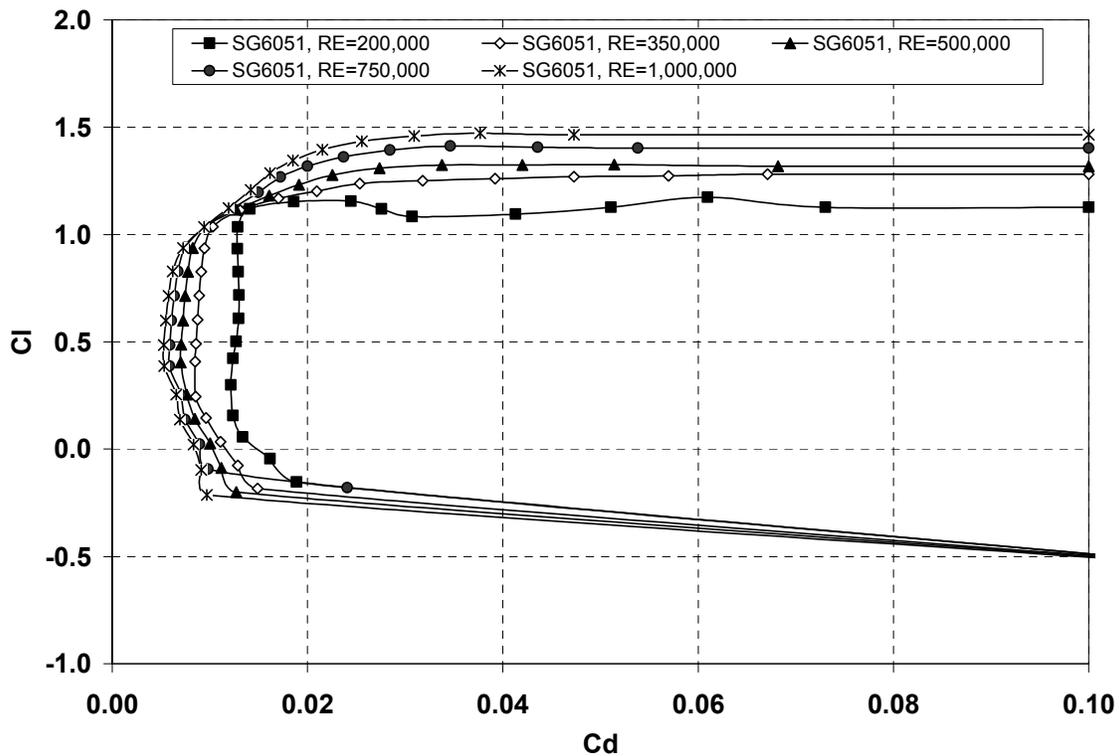


Figure 9-4: C_l vs. C_d for the SG6051 airfoil section. Data collected from University of Illinois at Urbana-Champaign LSAT [24]

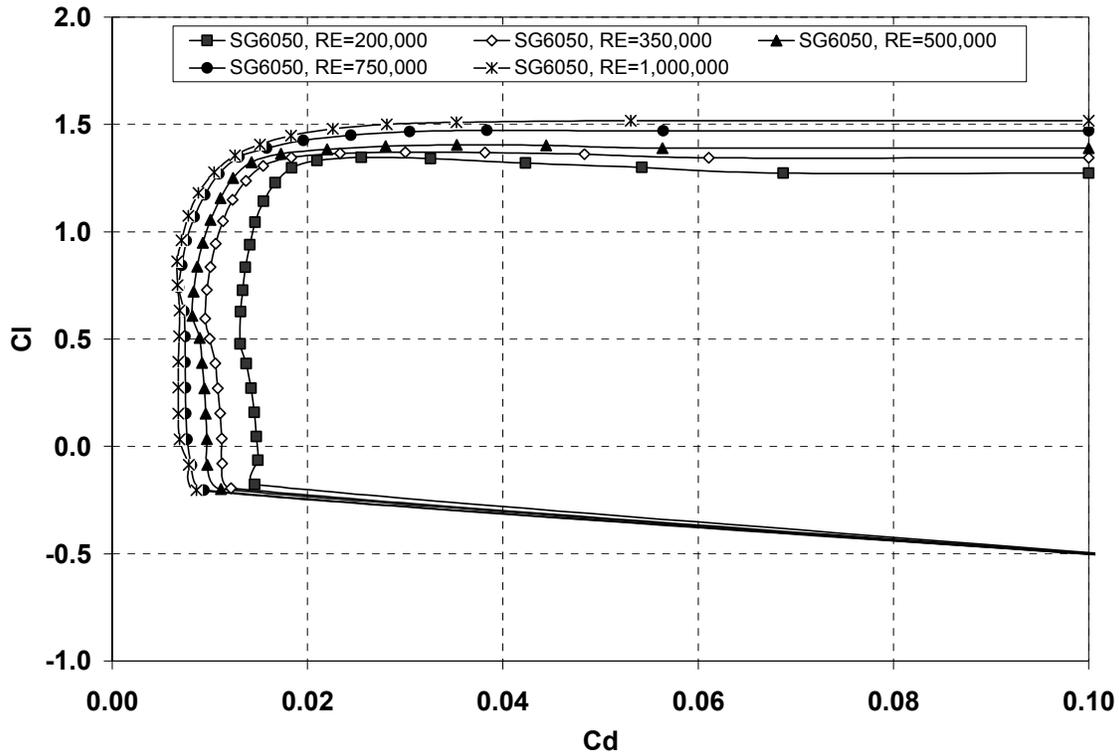


Figure 9-5: C_l vs. C_d for the SG6050 airfoil section. Data collected from University of Illinois at Urbana-Champaign LSAT [24]

9.3.2 Design C_l & Angle of Attack

The optimum angle of attack (AOA) between 5° - 6° is chosen to correspond to the SG6050/SG651 airfoils optimum lift over drag (L/D) ratio. To avoid stall the lower AOA of 5° is chosen for this design. Figure 9-6 shows the L/D and lift curve for both airfoils. The design sectional AOA and corresponding optimum lift coefficient C_l are used to define the optimum twist and taper ratio for best performance.

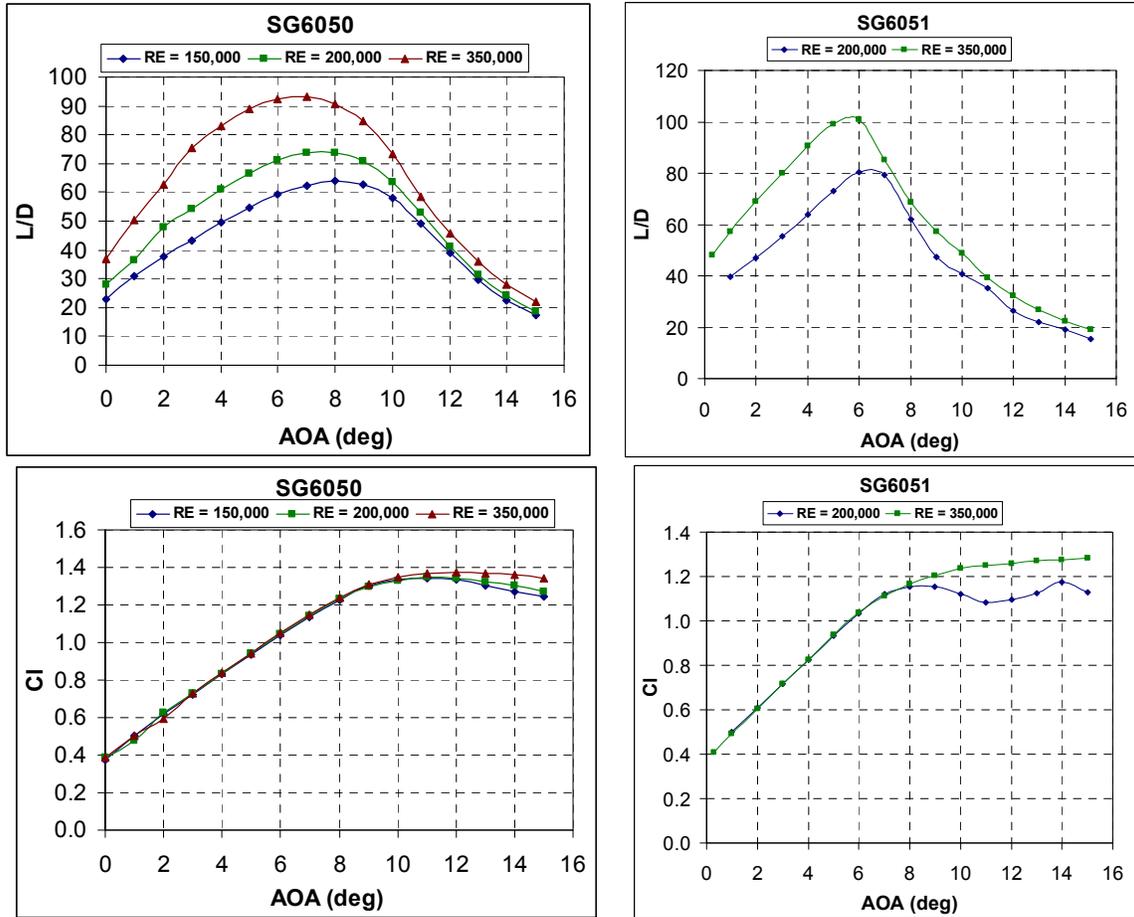


Figure 9-6: L/D and lift curve for SG6050/SG6051 airfoil section.

9.4 Planform

Planform is governed by design tip speed ratio (λ). The tip speed ratio was defined by the rotational tip velocity (ΩR) divided by the free stream wind velocity (U_∞). The equation below defines the optimum chord for a given tip speed ratio, where R defines the blade radius, N defines the number of blades, and r is the sectional blade radius [3, 22].

$$\lambda = \frac{\Omega R}{U_\infty} \quad c(r) = \frac{16\pi R^2}{9C_l N r \lambda^2}$$

For this design a tip speed ratio of 5.6 was chosen by taking the desired design wind speed of 10 mph and maintaining a relatively low 262 RPM to reduce noise and match the generator operating RPM. For manufacturing purposes, and because the root does not provide much torque performance, a linear taper was chosen and matched to the tip chord, shown in Figure 9-7. The airfoil coordinates, chord, and twist were put into CATIA V5 and a drawing of planform was made (Figure 9-8).

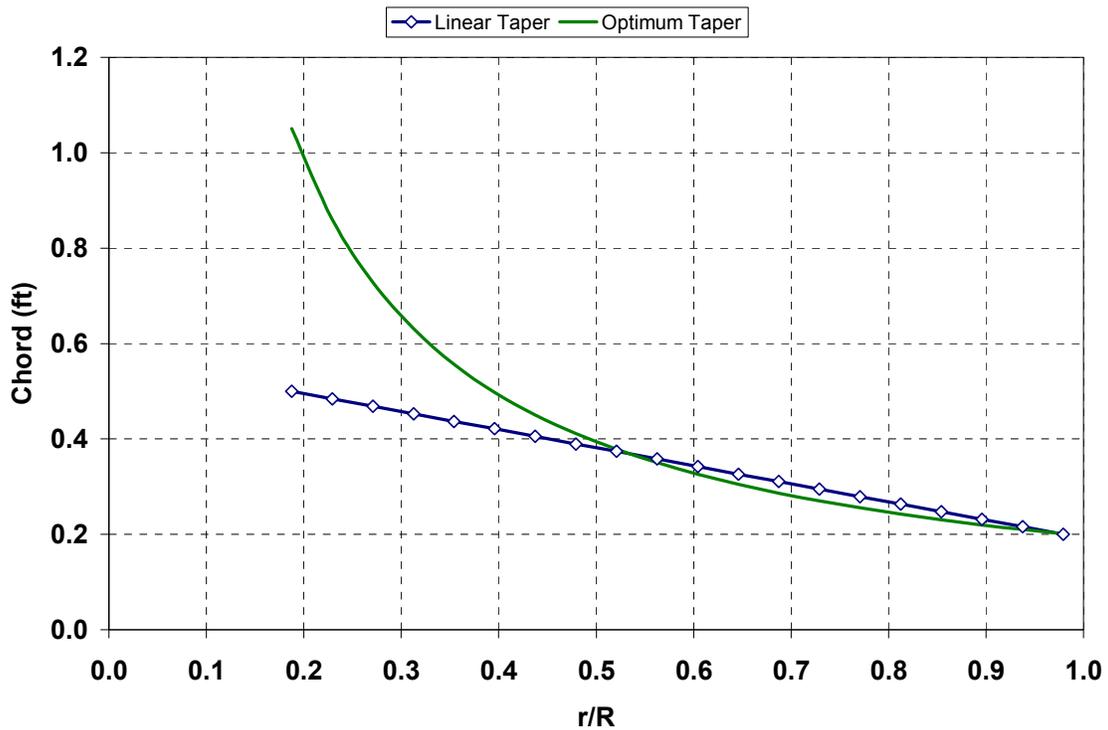


Figure 9-7: The optimum chord distribution vs. the actual chord used for design

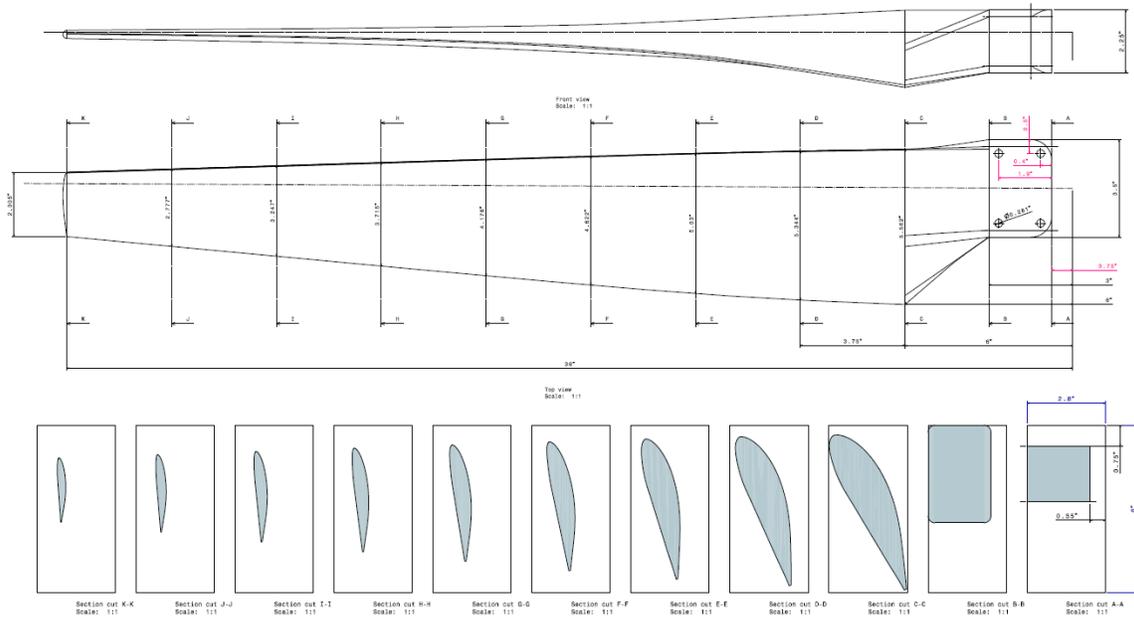


Figure 9-8: The blade planform, and section cuts from CATIA V5 CAD model

9.4.1 Cutout Radius

The blade cutout was determined based on the required blade attachment geometry. For the 3.0 foot radius blade, a 6.0 inch cutout, or 20% blade radius was chosen. Figure 9-9 is an isometric view of the blade showing the blade root, and hub attachment geometry.

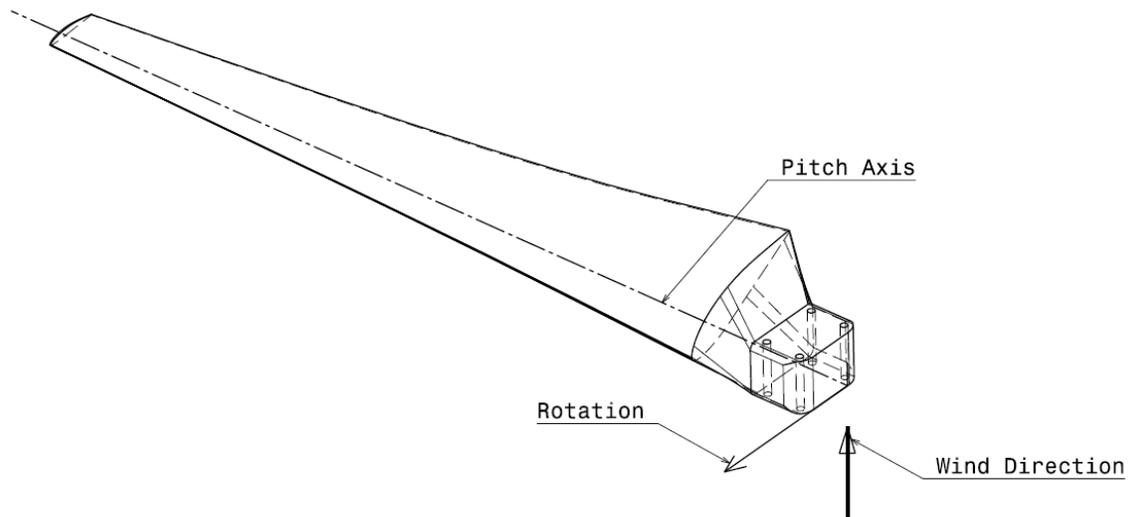


Figure 9-9: Isometric view of the blade showing root geometry

9.4.2 Swept Tip Blades for Low Noise

Swept tip blades can reduce the blade tip noise by reducing the interaction of the tip vortex with the blade trailing edge [4, 20]. For this design the baseline design is an un-swept blade; however, an optional set of swept tip blade provides slightly reduced noise for the same performance with improved ascetics. The swept tip blades come at a higher cost to manufacture; therefore, are optional. The current hub design allows for interchangeable blades so that the user can chose which blade type fits their needs. Figure 9-10 shows both swept and un-swept blades.

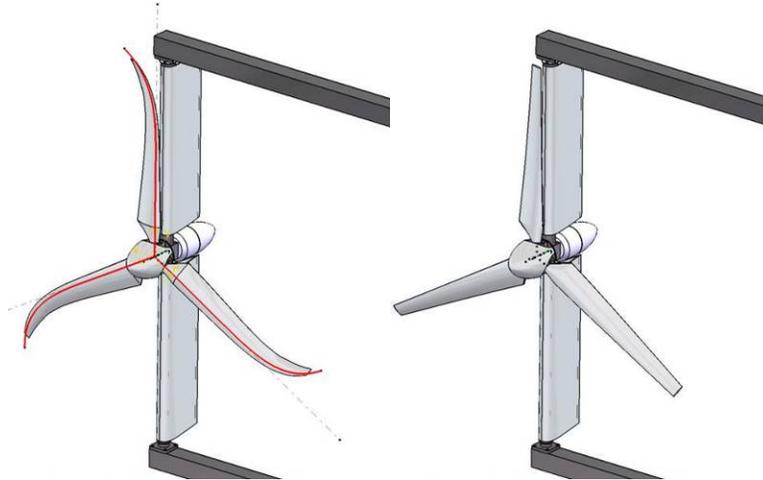


Figure 9-10: Interchangeable blades allow the user to choose between swept and un-swept blades. The wind turbine on the left has a swept tapered tip blades, and the right has a traditional linearly tapered blades.

9.5 Twist

Optimum twist was defined by tip speed ratio and airfoil optimum operating AOA. For this low wind speed design, a tip speed ratio of 5.6 was chosen, and the optimum operating AOA for the SG6050/SG6051 was 5° . The equation below defines the optimum twist distribution as a function of blade radius, where β is the local blade pitch as a function of blade radius (defined as positive away from the wind) and α is the airfoil optimum operating AOA [3, 22]. Blade twist is shown in Figure 9-11.

$$\tan(\beta + \alpha) = \frac{2}{3} \frac{1}{\lambda} \left(\frac{r}{R} \right)$$

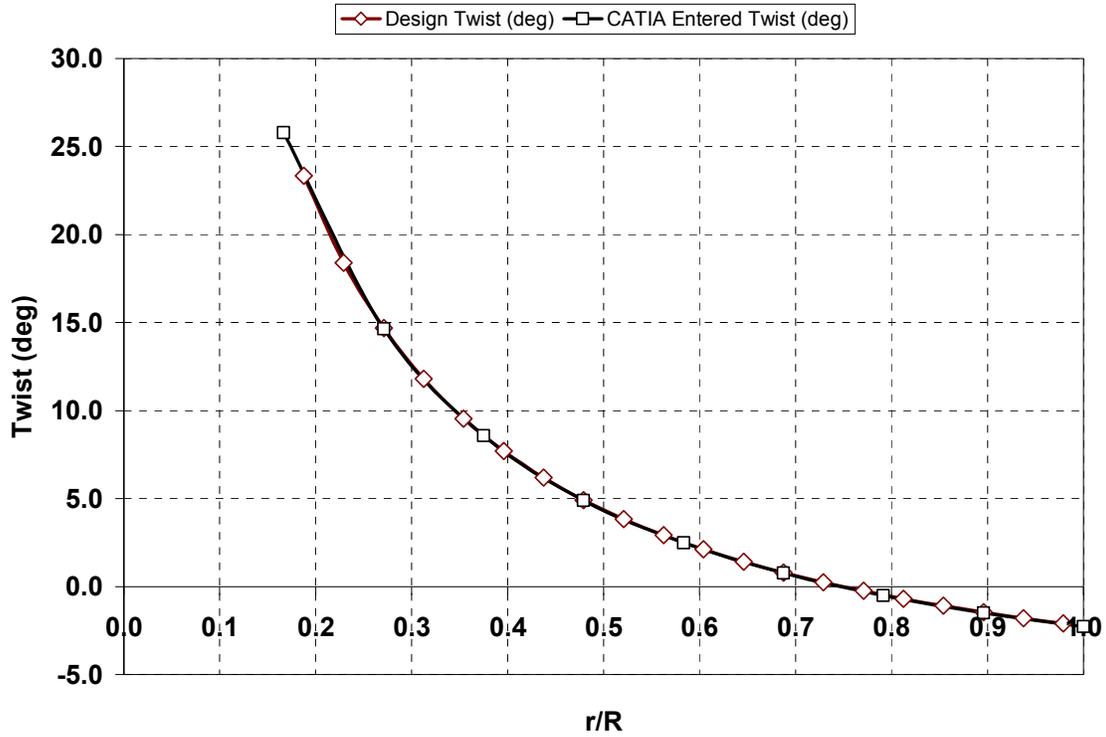


Figure 9-11: Twist distribution as a function of blade radius

9.6 Blade fabrication:

Large scale production blades will be fabricated from compression molded plastic. Compression molded plastic is more cost effective for high volume production. Foam core with fiberglass skin, shown in Figure 9-12, is used to make one-off prototypes, since tooling cost for hand lay-up fiberglass is much lower for low volume production.

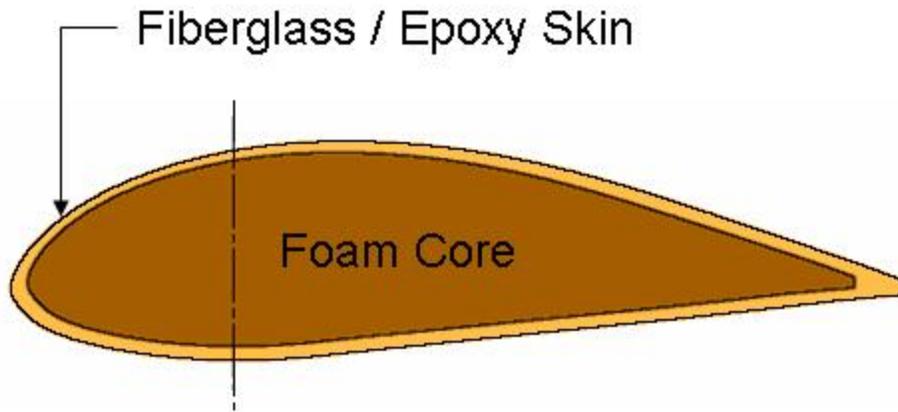


Figure 9-12: Cross-section cut of a blade showing the foam core and fiberglass skin for a prototype blade.

9.7 Blade pitch (fixed vs. variable)

The wind turbine designed for this project is classified as a small wind turbine (under 100 kW of power). Small wind turbines are typically fixed pitch, stall regulated systems because they do not benefit much from variable pitch systems. Variable pitch requires expensive more complex hub systems, which drive up cost. Cost is typically the largest driver for a successful small wind system; therefore, a fixed pitch blade was used for this design. The blade pitch for this design is 0° into the wind at the 75% span location. This is because the twist was optimized with blade pitch set to zero.

9.8 RPM (fixed vs. variable)

The RPM for this wind turbine is variable to allow for peak power tracking. Peak power tracking is used to vary the RPM for a given wind speed so that the optimum tip speed ratio of 5.6 can be maintained. Figure 9-13 shows the power output for varying RPM values. The peak power for each wind speed occurs at an RPM that corresponds to

the design tip speed ratio of 5.6. The generator power curve should go through the peak power produced by the aerodynamic loads of the wind turbine for various RPM's and wind speeds.

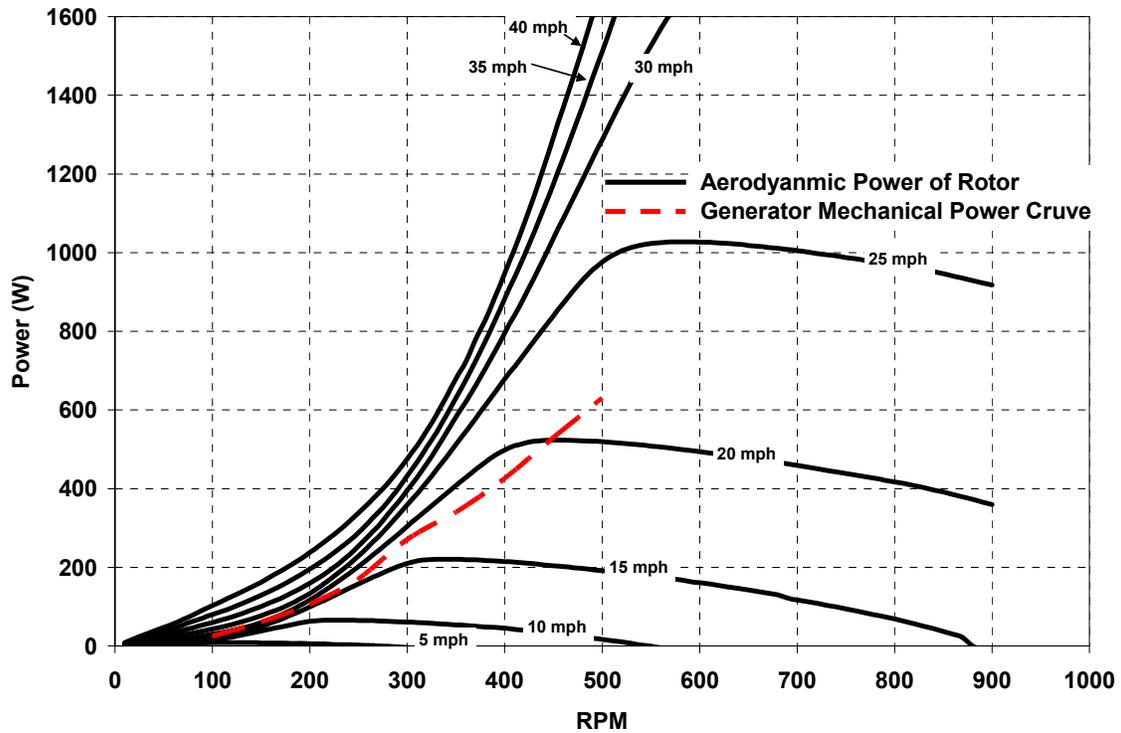


Figure 9-13: Power vs. RPM for various wind speeds

9.9 Hub height

The wind turbine designed for this project can be mounted to a variety of urban structures; therefore, the hub height varies. Figure 9-14 shows the mounting arms for the small wind turbine designed for this project. It can be mounted to a variety of structures, including poles and buildings.

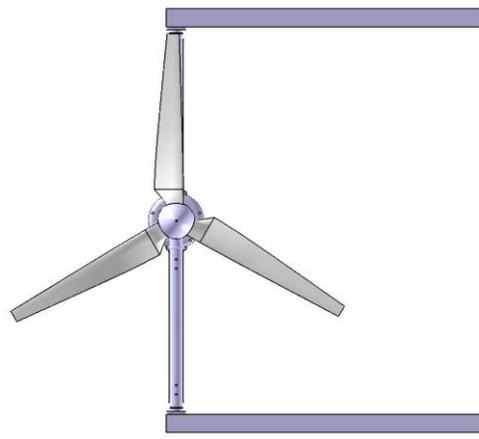


Figure 9-14: Front view of the small wind turbine designed to be mounted to various existing urban structures

9.10 Hub design

The hub design is meant to be simple and inexpensive. The hub consists of two aluminum plates, which are bolted together to hold the blades in place. The shaft is bolted to the aft plate. Figure 9-15 depicts the disassembled view of the rotor hub with blades in place to show how assembly is completed. A four bolt pattern is used to attach each blade to the hub. Figure 9-16 is a drawing of the forward and aft hub plates dimensioned for a machine shop construction. Figure 9-17 shows an image of the prototype hub completed. The aluminum blocks between the two plates will be removed and the blades will take their place.

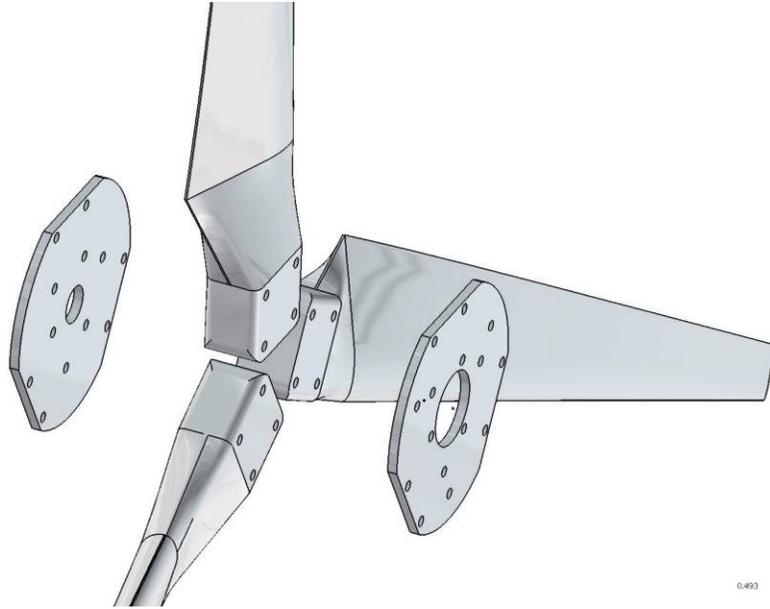


Figure 9-15: A disassembled isometric view of the hub and blades

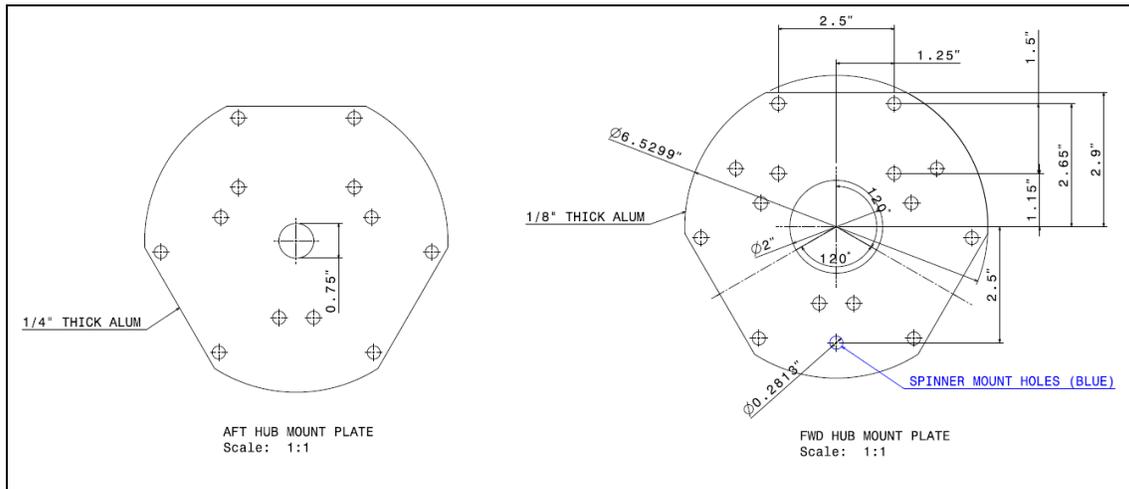


Figure 9-16: A dimensioned front view drawing of hub design for part machining

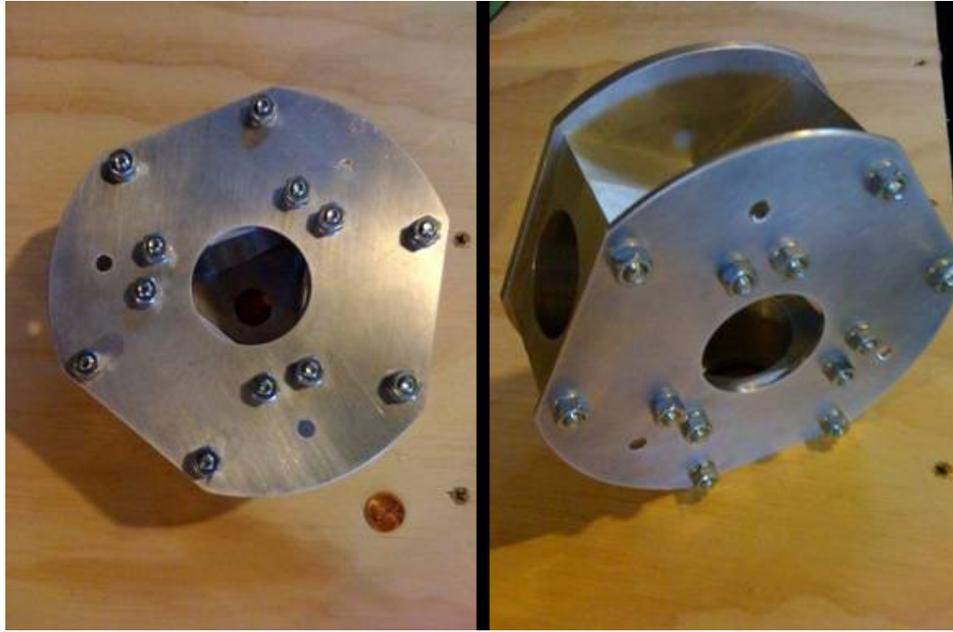


Figure 9-17: Image of a prototype machined hub

9.11 Yaw system

The design of the yaw system is tailored for mounting onto existing structures by fairing the center yaw pole into an airfoil shape. This produces a lift vector behind the yaw axis, which creates a yaw moment. This yaw moment aligns the wind turbine into the wind. Figure 9-18 shows a cross section of the fairing that is shaped like an airfoil. This airfoil shape acts like a vane to turn the wind turbine into the airflow direction. Figure 9-19 demonstrates this concept by depicting a top view of a turbine mounted onto a flag pole with the rotor axis yawed into the wind direction. The yaw fairing is constructed of a foam core covered in fiberglass. Mounting hardware is attached to the airfoil shaped upper and lower aluminum plates, which define the cross section of the fairing. This hardware is used to fasten the yaw fairing to the yaw pole, shown in Figure 9-20.

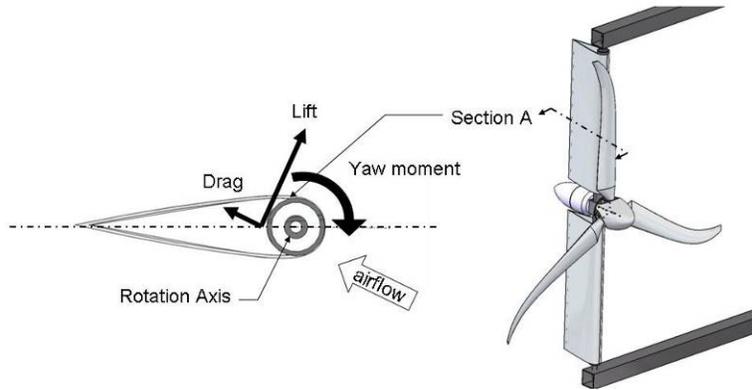


Figure 9-18: The left hand view is a cross sectional cut of the wind turbine yaw axis. The yaw moment is provided by the lift force from the airfoil fairing, which is located behind the rotational yaw axis.

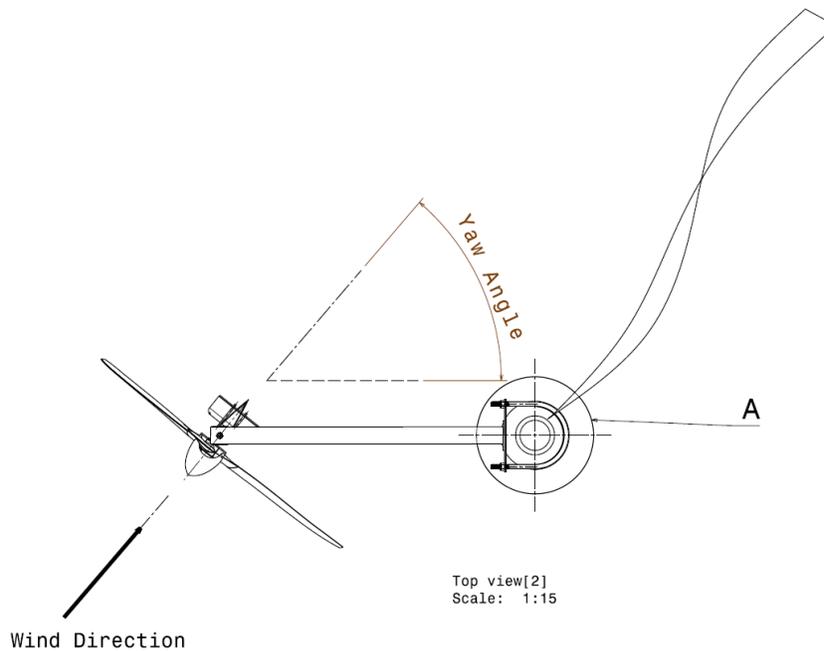


Figure 9-19: The design of the yaw system allows for the wind turbine to yaw into the prevailing wind direction.

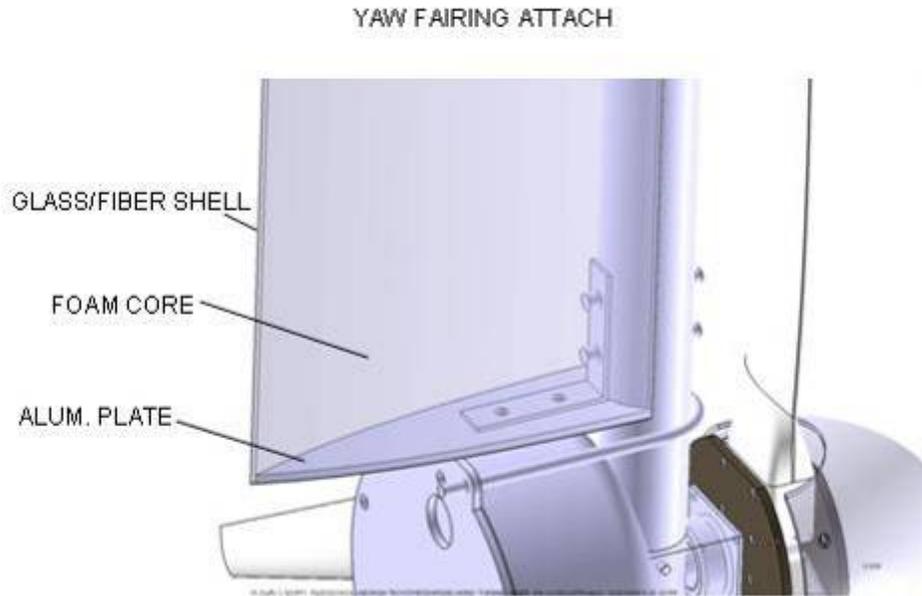


Figure 9-20: A detailed view of the construction of the yaw fairing

9.12 Generator selection

The majority of small and micro wind turbines today use three phase direct drive permanent magnet generators (PMG) [4, 27]. A direct drive PMG does not require a gear box to increase the shaft revolutions per minute (RPM) up to traditional DC motor RPM. The direct drive PMG operating RPM is customized by the number of poles mounted on the generators rotor [13]. The generator used for this design is an off the shelf PMG manufactured by Chinese manufacturer Ginlong [12, 27]. This PMG comes in two models: one rated at 0.5 kW (Figure 9-21) and the other rated at 1.0 kW (Figure 9-22). Both PMG are the same diameter; therefore, can both be mounted to the same baseline wind turbine design. This interchangeable design allows the user to select a 0.5 kW rated PMG for a lower average wind speed location or select a 1.0 kW rated PMG for a higher average wind speed location.

A direct drive PMG requires a rectifier (Figure 9-23) to convert the AC power into DC power for charging battery banks. For grid connected wind turbines, a power inverter is required to convert the rectified DC power into AC power at the correct grid frequency (typically 60 Hz). A sample of an off the shelf power inverter rated at 1000 W, 12V DC to 120V AC, is shown in Figure 9-24.

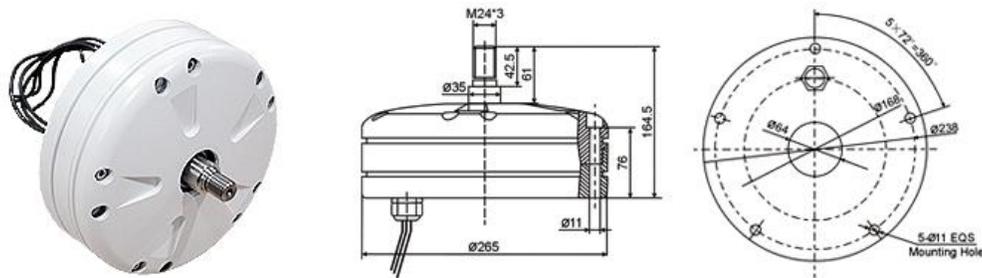


Figure 9-21: A sample image of an off the shelf 0.5 kW GL-PMG-500A permanent magnet generator (PMG) manufactured by Ginlong [12]

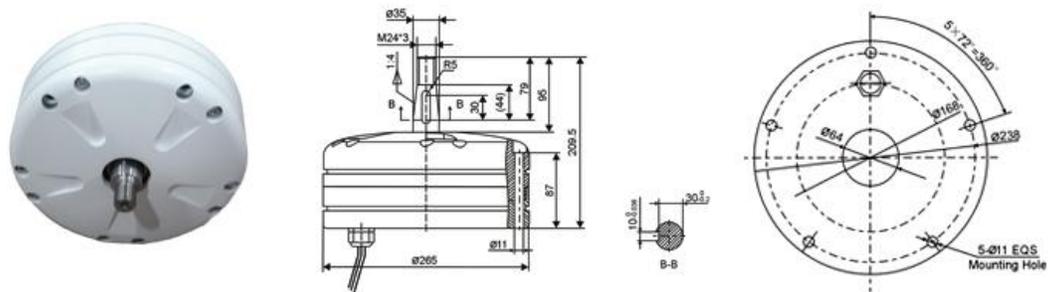


Figure 9-22: A sample image of an off the shelf 1.0 kW GL-PMG-1000A permanent magnet generator (PMG) manufactured by Ginlong [12]



Figure 9-23: A sample image of an off the shelf rectifier used to convert AC power to DC power for small wind turbines [27]



Figure 9-24: A sample image of an off the shelf power inverter used to convert rectified DC power into grid frequency matched AC power, manufactured by Sunway Power [14]

9.13 Permanent magnet generator and hub assembly

The permanent magnet generator (PMG) and hub are connected to the yaw shaft through the bearing housing. The bearing housing holds the PMG with shaft extension in-line with the hub using one bearing on the forward side of the yaw shaft. The PMG shaft with extension runs through the yaw shaft. The PMG is supported with two U-bolts, which force the PMG against the bearing housing. Figure 9-25 shows that the PMG uses a shaft

extension to travel through the yaw shaft and connect to the hub. The blades are attached using the forward mounted hub plate and the aft mounted hub plate attaches to the forward side of the bearing housing. When completely assembled, shown in Figure 9-26, the PMG rests against the aft side of the bearing housing, and the rotor hub rests against the shaft extension. The bearing takes the bending load, and the PMG transfers the thrust load into the yaw shaft.

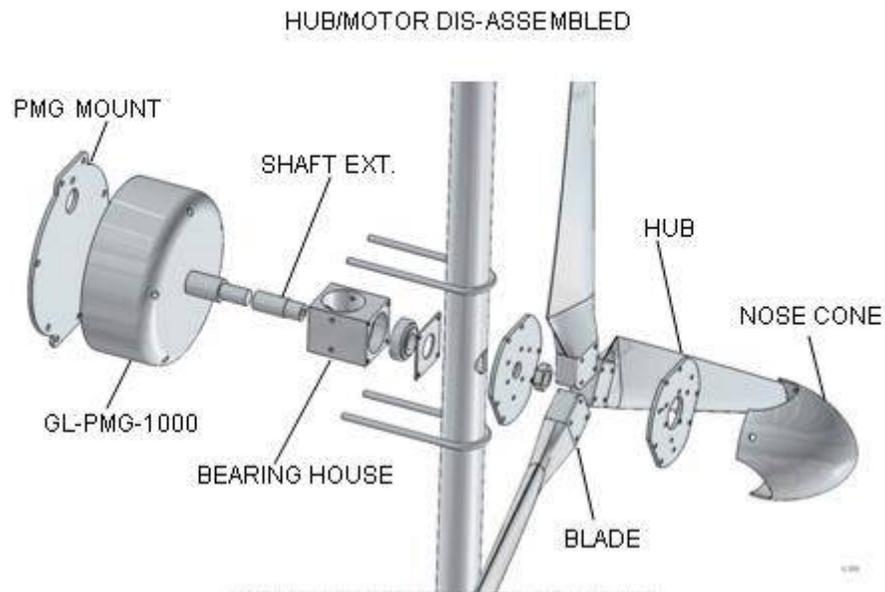


Figure 9-25: An isometric view of the disassembled PMG, bearing housing, hub, and blades

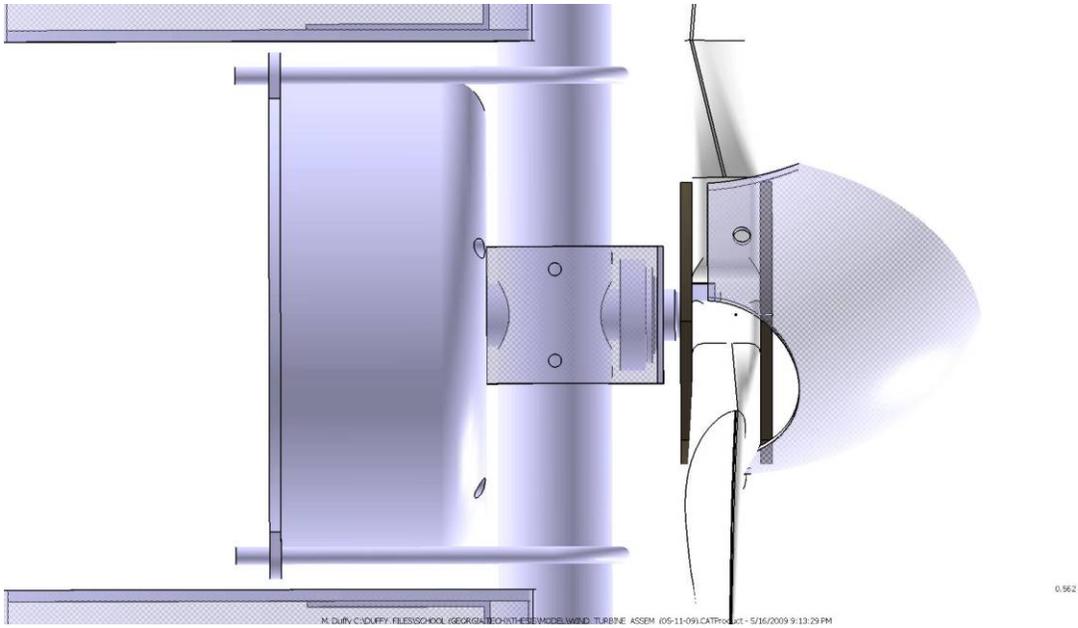


Figure 9-26: A side view of the assembled PMG, bearing housing, hub, and blades

9.14 Controller design:

The controller is used vary the load on the PMG to maintain the optimum RPM for various wind speeds. If the winds get higher then the rated wind speed or if the battery bank has reached full charge, the controller will short circuit the motor (which does not harm the motor) to slow the rotor to a near stop condition [27]. This prevents damage caused by high RPM. In addition the controller can be used to turn off the wind turbine for installation and maintenance. Figure 9-27 and Figure 9-28 show the torque and power vs. RPM for a six foot diameter micro wind turbine that is designed for low wind speeds. The controller will vary load to ensure that the rotor RPM is always at peak aerodynamic performance.

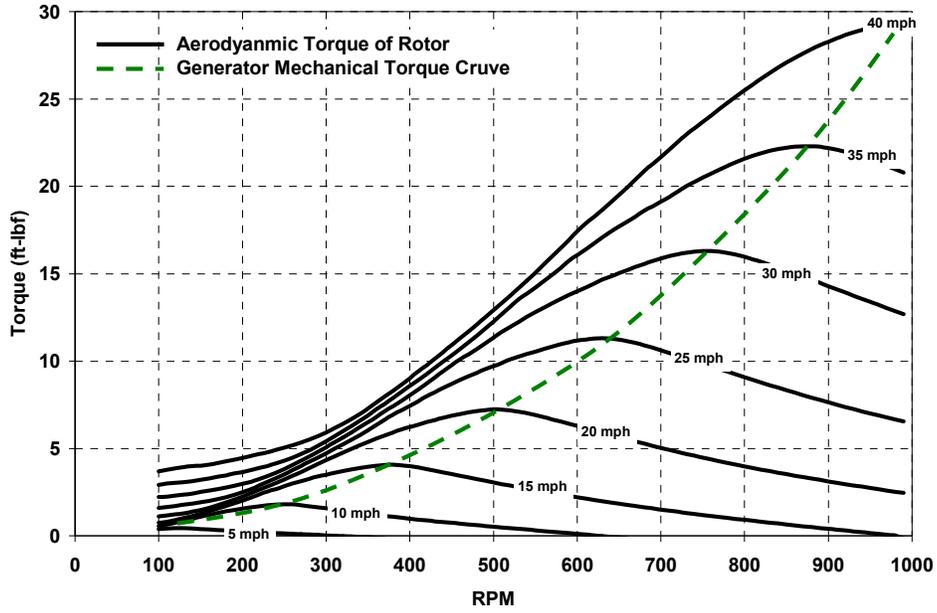


Figure 9-27: The motor torque is matched to the optimum aerodynamic torque by the controller

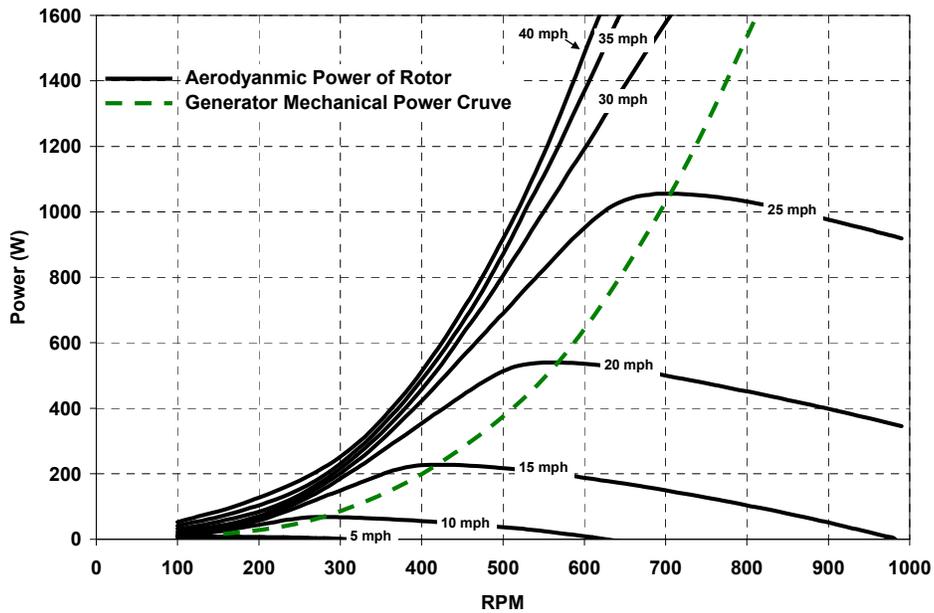


Figure 9-28: Power from the rotor is extracted at the optimum RPM for a given wind speed

9.15 Modular mounting design

In order to facilitate easy installation, yet still allow the capability to mount to various existing urban structures, a modular mounting system was designed. This design allows for various mounting hardware be attached to the same baseline wind turbine design. The basic design consists of the small wind turbine, which is mounted to a yaw-able shaft, depicted in Figure 9-29. The yaw shaft is then pinned between to mounting arms, which can then accept a variety of mounting hardware. There are two pillow block bearings at each end of the yaw shaft which allow for yaw rotation. Each interchangeable piece of hardware is tailored for the desired mount location (Figure 9-30). A CATIA rendered drawing shows the assembled view of the baseline small wind turbine design tailored for existing poles and building walls (Figure 9-31).

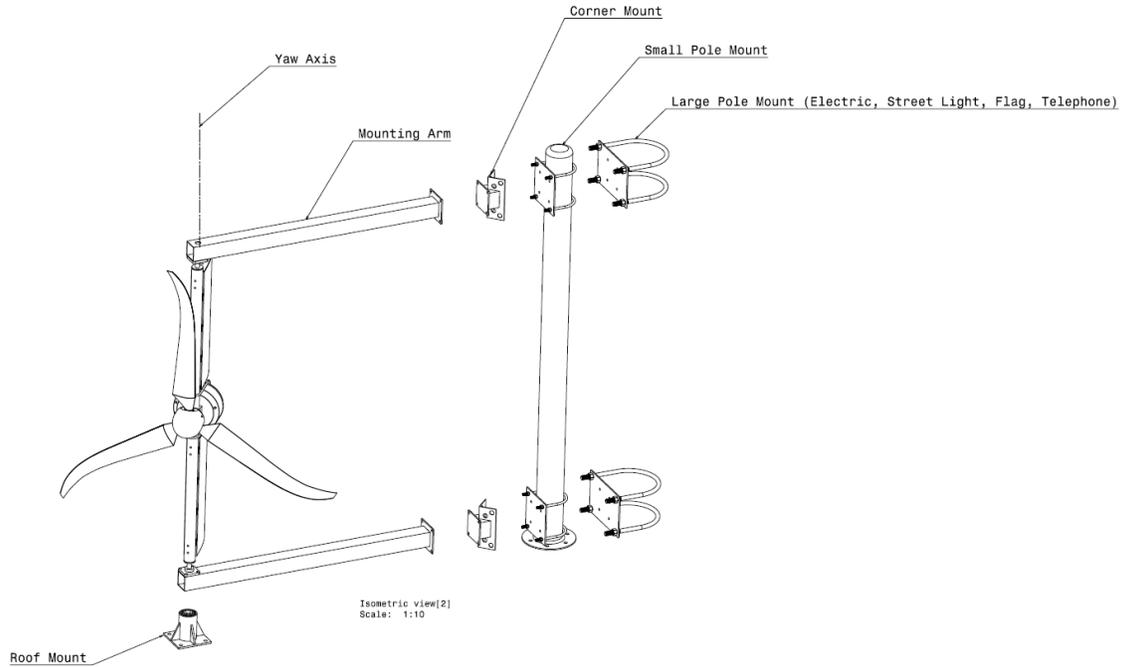


Figure 9-29: The modular mounting system allow for various hardware be attached to the baseline small wind turbine. This allows for mounting to various structures using the following hardware: building corners mounts, flag pole brackets, electric pole brackets, street light brackets, and wall mounts

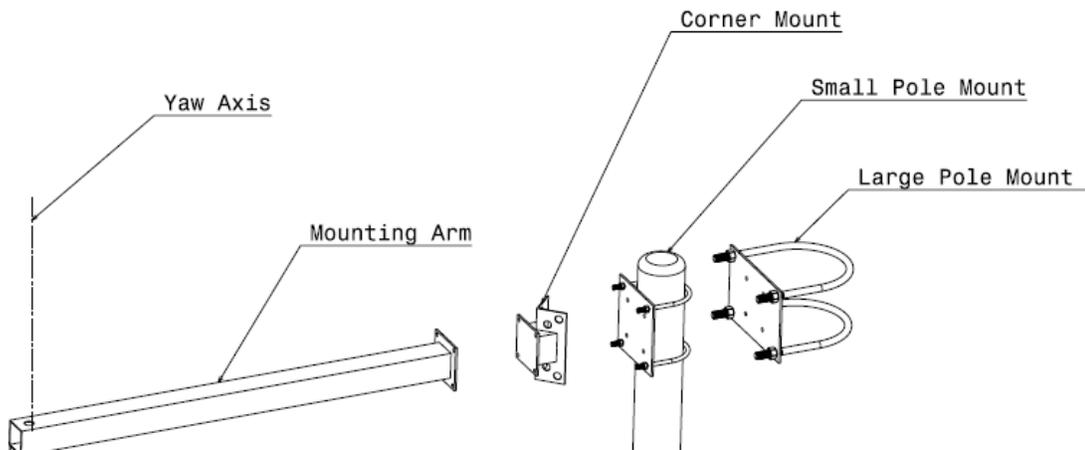


Figure 9-30: Zoomed view of the various modular mounting hardware



Figure 9-31: CATIA render of the baseline small wind turbine design with mounting arms for attaching to existing poles and building walls

For building rooftops, the mounting arms are not required. A simple mounting base, shown in Figure 9-32, is used to mount the small wind turbine to flat roof. Two bearings are used to take root bending where the yaw axis attaches to the roof. A pitched roof design can easily be tailored by changing angle of the hardware, or using angled shims with the current base plate design. Figure 9-33 shows a CATIA render of the baseline small wind turbine design with the rooftop base plate.

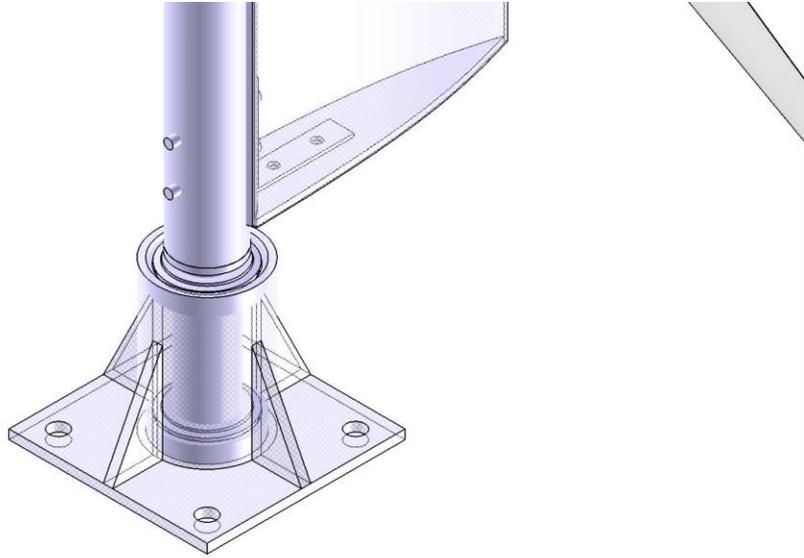


Figure 9-32: Zoomed view of rooftop mounting base for the baseline small wind turbine design



Figure 9-33: CATIA render of the baseline small wind turbine design with the rooftop mounting

9.16 Wire routing from the generator to the mounting structure

Power is transferred from the permanent magnet generator (PMG), down inside the center of the yaw shaft and into a slip ring, which enables power to go between the rotating yaw shaft system into the stationary mounting system. The power is then transferred through the center of the mounting arms and down into the structure (Figure 9-34).

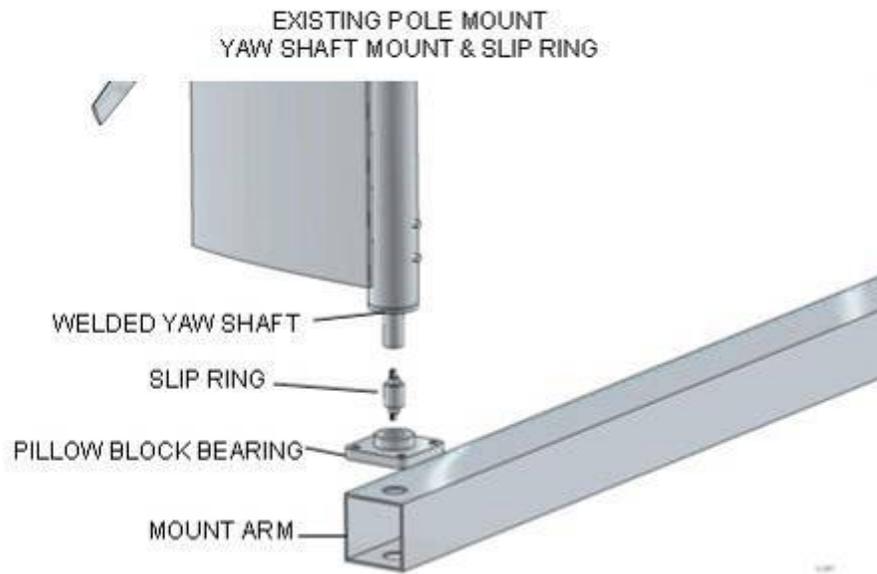


Figure 9-34: A detailed view of the slip ring location, which allow for the small wind turbine to yaw while transferring power to the non-rotating system

9.17 Duct to prevent Foreign Object Debris (FOD)

Ducted wind turbines have not yet proven their economic viability from a performance standpoint [3, 29]; however, ducts can be used protect wild life, specifically birds from flying through the rotor. Figure 9-35 illustrates the optional duct, which can be used to fasten a protective net. This protective net can keep foreign object debris (FOD) from entering the rotor system. This is especially important where local ordinances require protection for wild life. In addition, this net can protect the small wind turbine itself from being damaged by FOD.

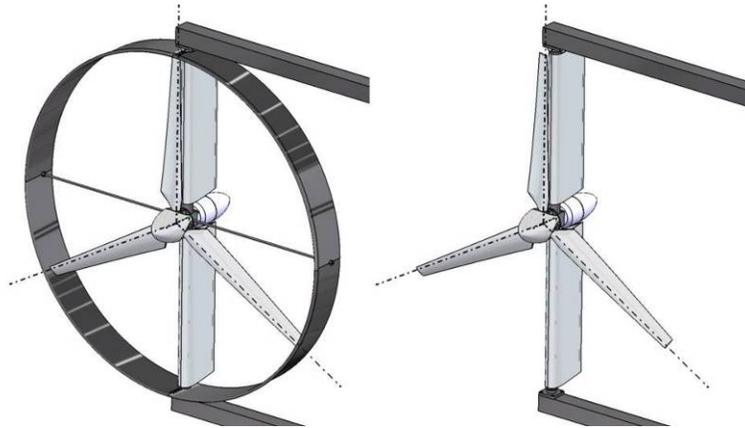


Figure 9-35: A duct can be used to fasten a net, which will prevent foreign object debris like wildlife from entering the rotor.

9.18 Complete wind turbine layout

A complete dissembled view of the baseline small wind turbine design is shown in Figure 9-36. The modularity and simplicity of the design is evident. There are only three machined parts. The permanent magnet generator (PMG), bearings, and major structural components are all off the shelf. A user of this small wind turbine system, can pick and choose, a le cart, the components and mounting hardware that matches their needs.

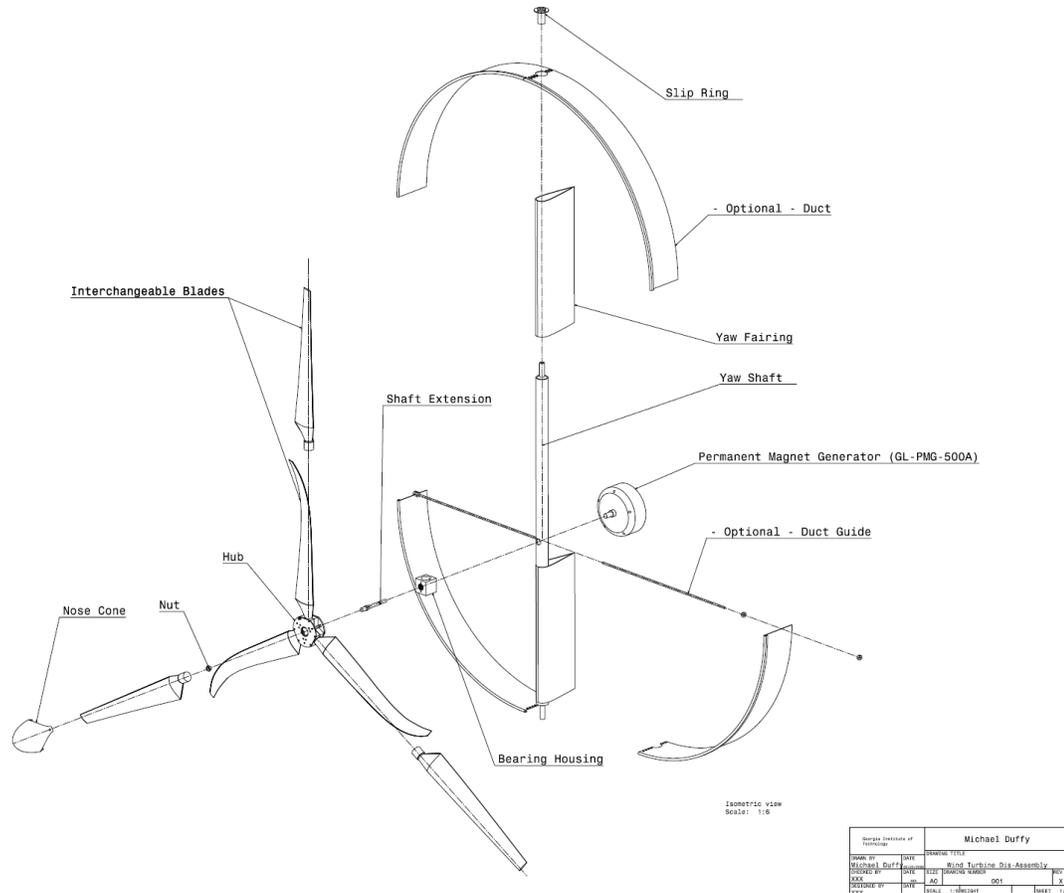


Figure 9-36: A detailed drawing of the interchangeable components, which make up the small wind turbine system that has been adapted for mounting on existing structures

9.19 System Architecture

From a macro view, a complete, installed and connected small wind turbine system is shown in Figure 9-37. This system architecture view depicts the core system, which is required for operation, and the connection options. The core system consists of the baseline wind turbine system, which is connected to the desired urban structure, say a flag pole. The wind turns the blades which generates power through the permanent magnet generator (PMG). The PMG produces varying frequency AC power, which is

converted to DC power by the rectifier. The rectifier sends the DC power to the controller which varies the load to control RPM and ensure peak performance. The rectified DC power then leaves the core system, and travels to the connection options. The connection options include a battery bank, which can take DC power directly, and is monitored by the controller. Or the power can be sent to a power inverter, which converts the DC power into a continuous frequency AC power to match the grid frequency.

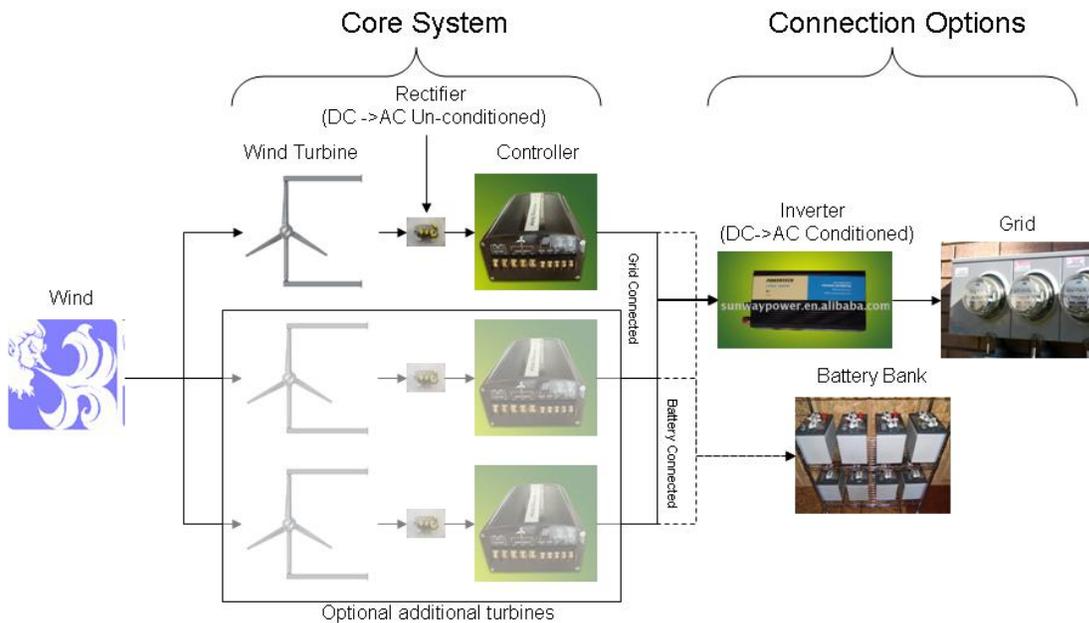


Figure 9-37: Complete system architecture, including connection options

10. SMALL WIND TURBINE PERFORMANCE

Wind turbine performance was estimated using WT_Perf 3.0, Marshall L. Buhl, Jr., National Wind Technology Center (NWTC), June 21, 2004 [17, 18]. The code is a blade element momentum theory code which uses 2-D airfoil data to predict performance and loads.

10.1 Power Prediction

The design wind speed for this wind turbine is 10 mph. At 10 mph this wind turbine is predicted to produce 65 W of power. This is not a significant amount of power; however, at higher wind speeds of 15 – 20 mph the performance improves to 200 – 500 W and at 25 mph the performance peaks at 1 kW. Figure 10-1 shows the performance of the 6 foot diameter wind turbine designed for this project. A curve showing the absolute best performance (59% efficiency, Betz limit), assuming momentum disk, is also shown for comparison. Figure 10-2 shows same data, but plotted differently. The power is now a function of rotor RPM, and can be matched up against the generator to ensure that peak aerodynamic power is being met.

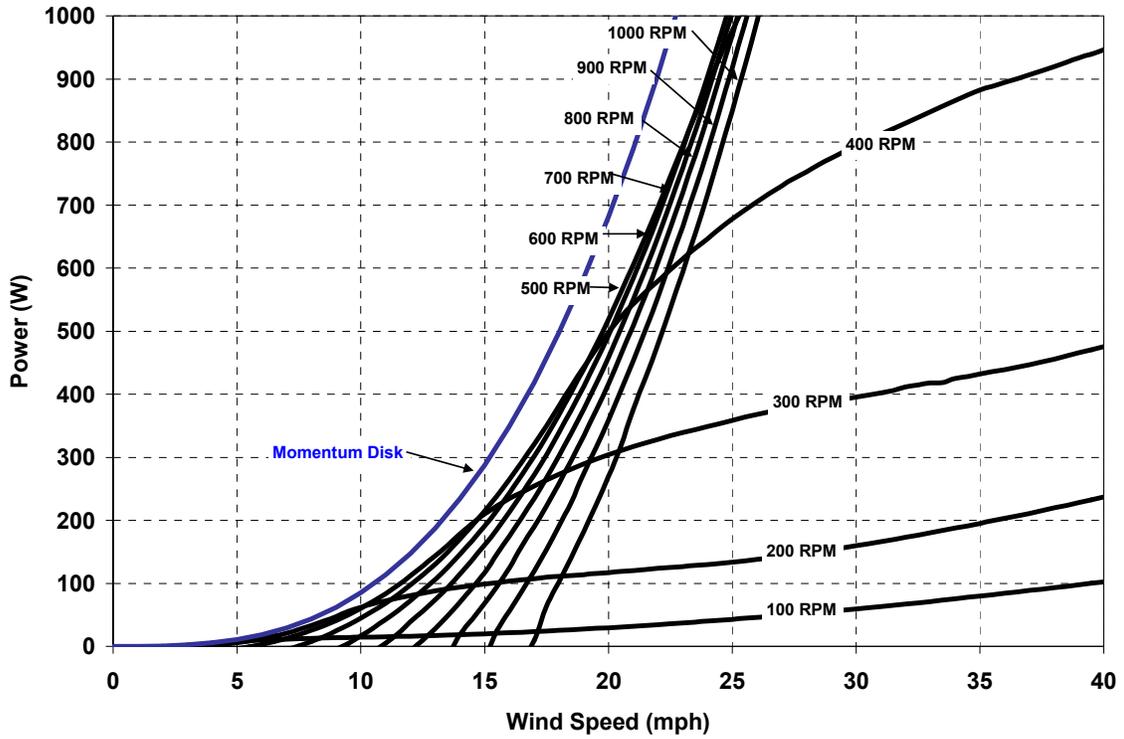


Figure 10-1: Power vs. wind speed for various rotor RPM

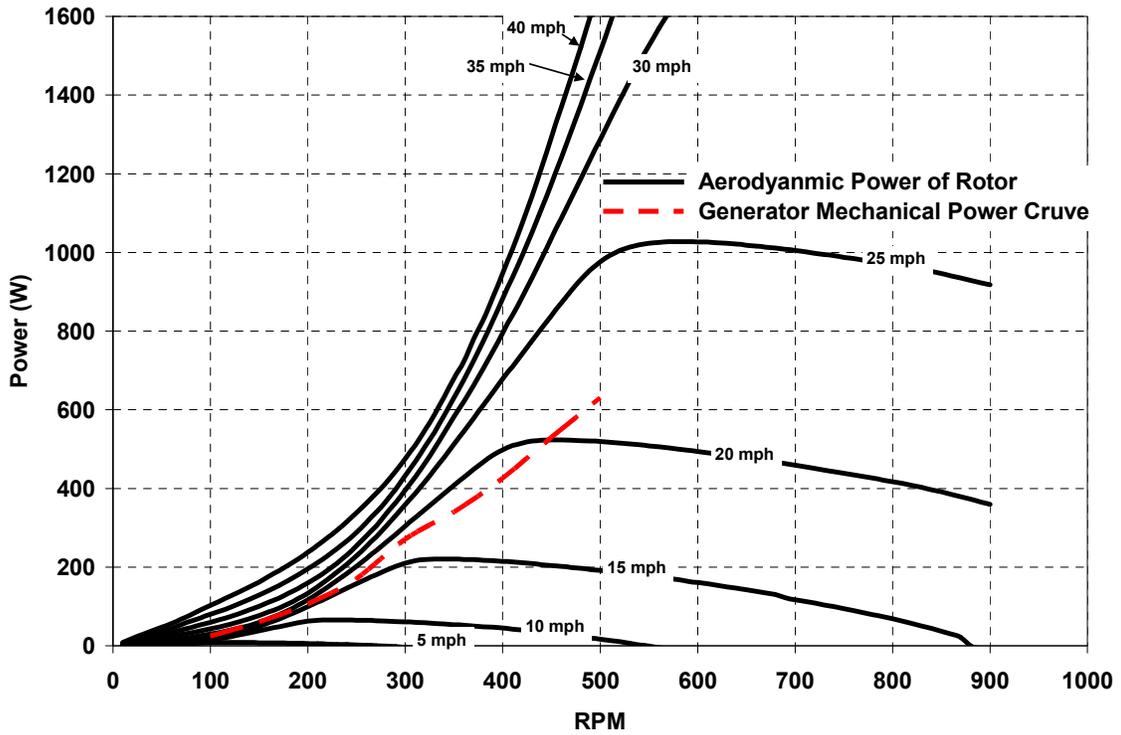


Figure 10-2: Power vs. RPM for various wind speeds

10.2 Coefficient of Power, C_p

Power coefficient defines the efficiency of the rotor. The maximum performance achievable for a given rotor diameter, assuming a perfect rotor, is the Betz limit, which is 59% [3]. For this rotor, Figure 10-3 depicts the predicted efficiency including tip, root, and swirl losses to be 46%. In addition, the optimum RPM for given wind speed can be seen. The peak efficiency for each wind speed is called peak power tracking, as described in the RPM section in chapter 9.

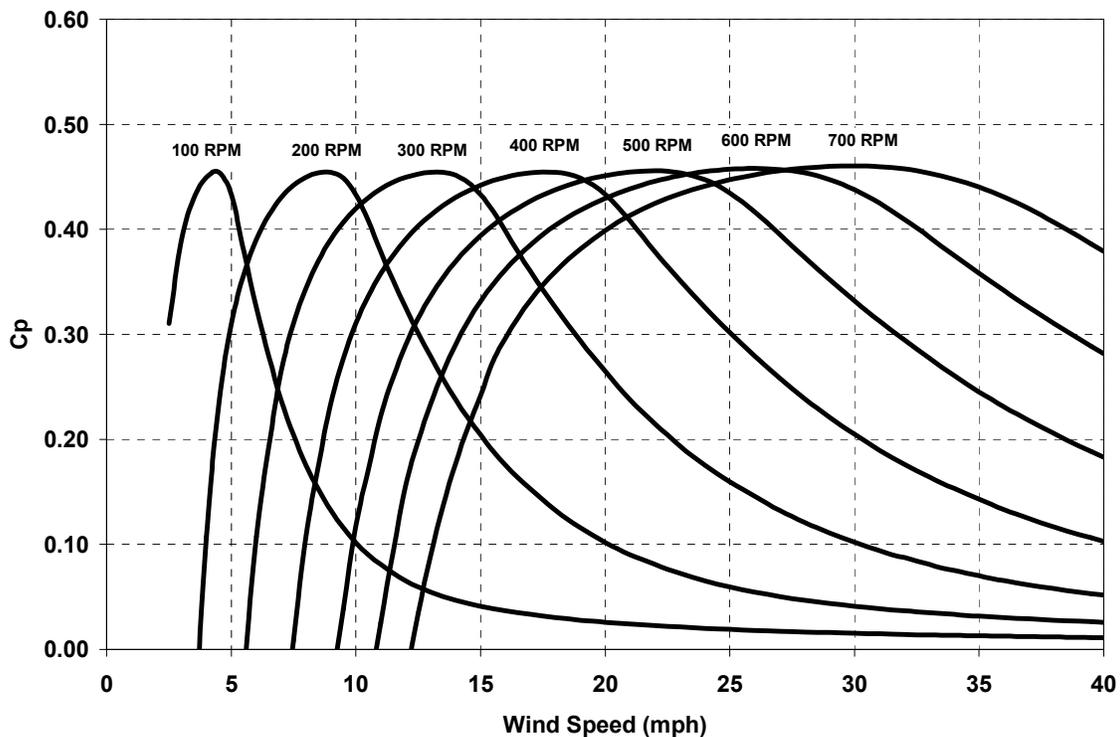


Figure 10-3: Power coefficient vs. wind speed for various rotor RPM

10.3 Torque

Torque is critically important for a low wind speed wind turbines. This small wind turbine was designed with a high solidity (the ratio of blade area to disk area). This provides the generator with high aerodynamic starting torque, and provides good efficiency at low wind speeds. Figure 10-4 shows the aerodynamic torque produced by the blades compared to the required generator torque.

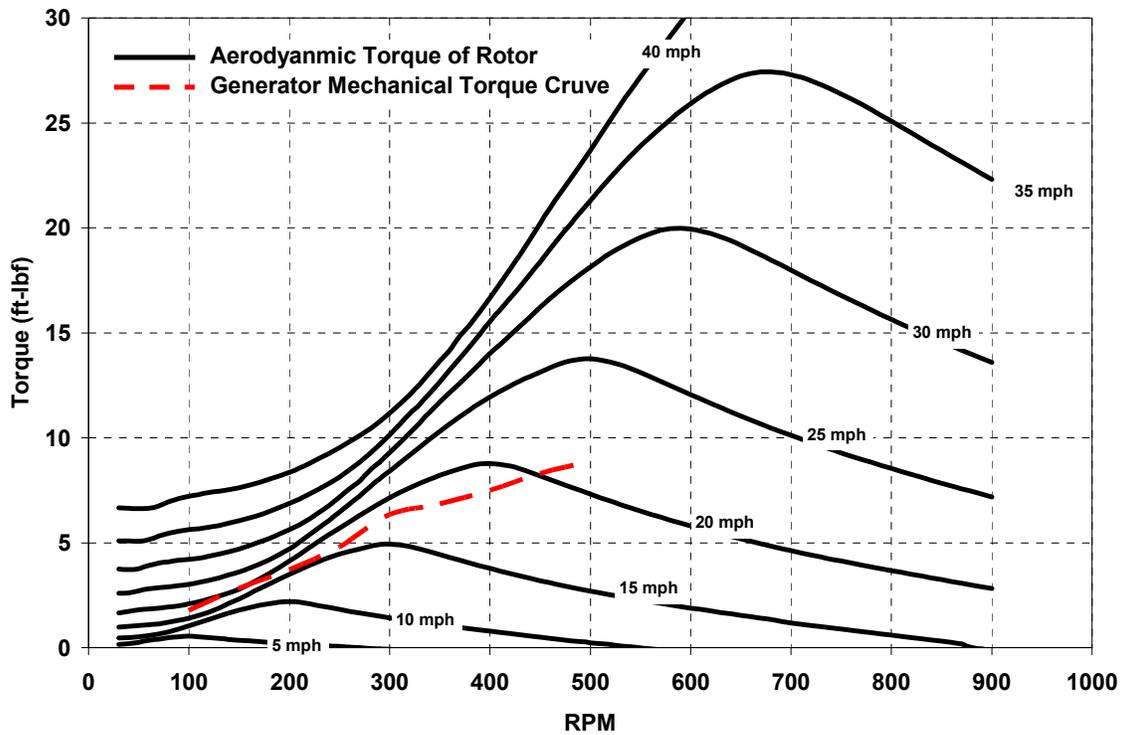


Figure 10-4: Aerodynamic and generator mechanical torque for a given RPM and wind speed

10.4 Blade Loading

Blade loading is shown in Figure 10-5 for the optimum tip speed ratio of 5.6. The wind turbine designed in this project operates at a C_l near or above 1.0, which corresponds to a

local airfoil AOA of 6° . As shown in the previous section, 6° AOA is at a high L/D ratio, which is desired for power efficiency.

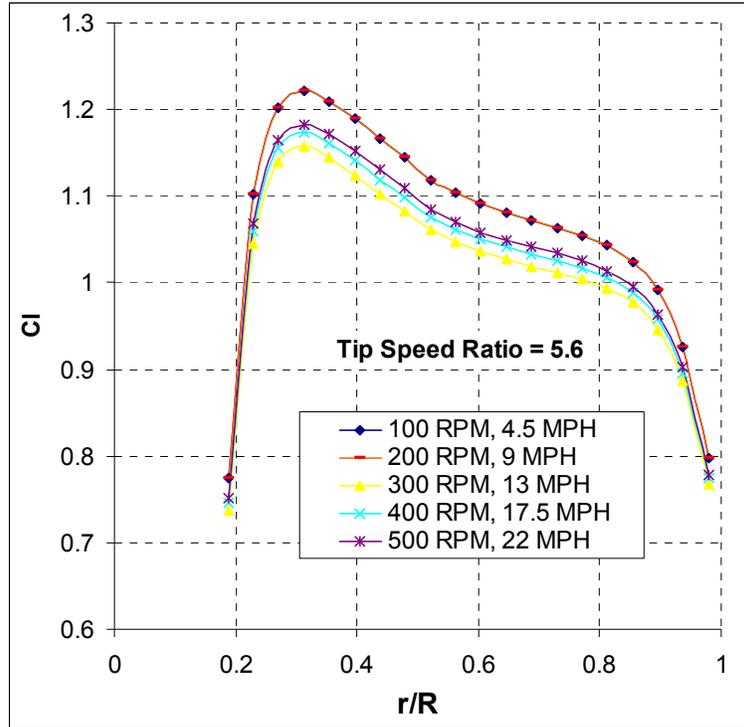


Figure 10-5: Blade loading as a function of blade radius

10.5 Annual Output

The annual energy output for this small wind turbine is shown in Figure 10-6. For low average wind speeds (< 8 mph) the annual output is below 1000 kWh/year. For wind speeds above 8 mph the annual output is over 1000 kWh/year, which is considered reasonable for a small 1 kW rated, 6 foot diameter wind turbine. Another valuable measure of performance is the capacity factor, which is depicted in Figure 10-7. The capacity factor is the measure of a wind turbines performance divided by the rated power.

A capacity factor greater than 10% is desirable for small wind turbines. For this design, that requires an average wind speed of 10 mph or greater.

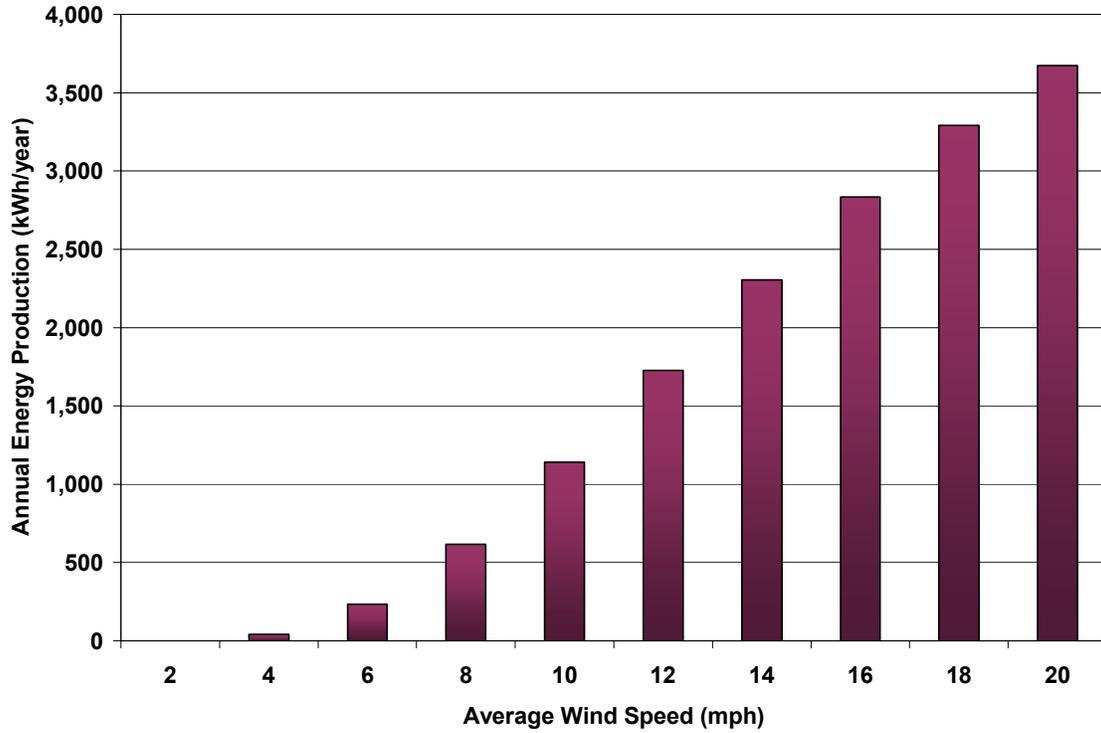


Figure 10-6: Annual energy output in kWh

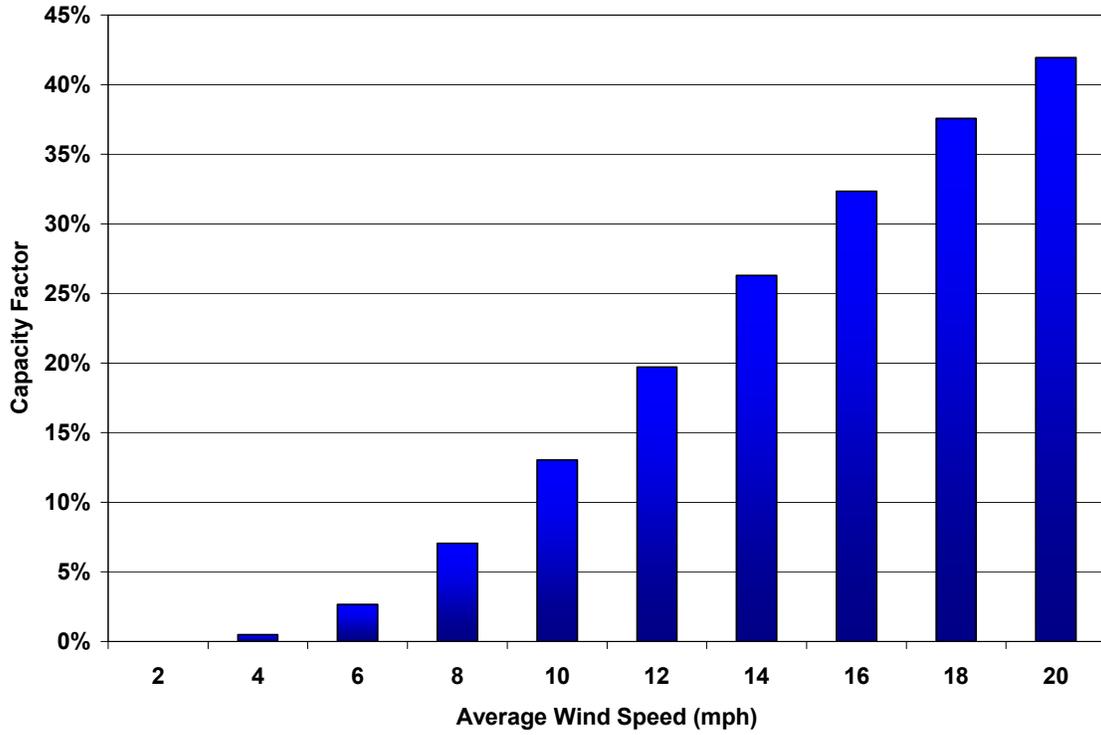


Figure 10-7: Capacity Factor for a given average wind speed

10.6 Performance summary

The small wind turbine in this project is designed for low wind speed performance. This design features a high solidity rotor with low Reynolds number airfoils. The twist and chord distribution are tailored for a 10 mph average wind speed at a tip speed ratio of 5.6. To further improve the low wind speed performance, peak power tracking is employed, which matches the optimum RPM for a given wind speed to ensure the design tip speed ratio is maintained. The size of the rotor was defined to be small enough to fit on existing urban structures, yet large enough to capture a reasonable amount of energy. This design is predicted to produce over 1,200 kWh of energy per year for an average wind speed of 10 mph.

11. COMPATIBILITY WITH EXISTING STRUCTURES

In order to be compatible with existing structures these small wind turbines must be capable of mounting to existing structures with little or no impact. In addition, details of how these turbines mount, where wires are run, and where supporting hardware is placed, must be addressed.

11.1 Pole mounting

11.1.1 Mounting hardware

Figure 11-1 depicts an example of how to cantilever a small wind turbine off the side of an existing pole. Two sets of U-bolts sized for the given pole diameter are used to fasten the mounting arm to the pole. A sample scene showing several light poles with small wind turbines mounted is shown in Figure 11-2



Figure 11-1: A U-bolt is used to attach the small wind turbine system to an existing pole



Figure 11-2: CATIA V5 render of sample installation on street light poles

11.1.2 Loads

The small wind turbine designed in this project produces no more than 100 lbs of thrust in the rotation axis direction and weighs less than 150 lbs. A street or flag pole must withstand thousands of pounds force produced by wind gusts. For example, a 30 foot street light, with a 1 ft diameter must withstand 120 mph wind gust to meet building code [21]. This equates to a drag force of 1,150 lbs, 11.5 times the value produced by one small wind turbine. The small wind turbine weight is taken up by the axial force of the pole. The pole compression strength is orders of magnitude greater than the small wind turbine

weight. A table of known poles or with generic parameters could be distributed to customers and used as a guide.

11.1.3 Pole dynamics

The predicted loads for these small wind turbines are an order of magnitude lower than most large diameter poles (> 1 ft) load limits. The dynamic vibrations caused by these small wind turbines should not effect any resonate frequencies as long as a safety factor of 5 or greater is maintained.

11.1.4 Wire routing and connection

Getting the generated power from the wind turbine to the ground can be a challenge. The wire needs to be protected from the elements as well as easy to install. In addition, the gauge of wire used depends on the distance from the turbine to the source. If multiple small wind turbines reside on one pole, each turbine system can be connected to each other, similar to Christmas lights, as they go down the pole (Figure 11-3). The turbine which is closest to the ground is then fed into a junction box, which contains the controller, or controllers if multiple turbines are present, and the inverter, if the turbines are grid connected. If the turbines are being used to charge a batter bank, no inverter is needed, and the turbines can connect directly from the controller into the battery bank. Figure 11-3 and Figure 11-4 show sample wiring schematics for multiple turbines mounted on two different pole types.

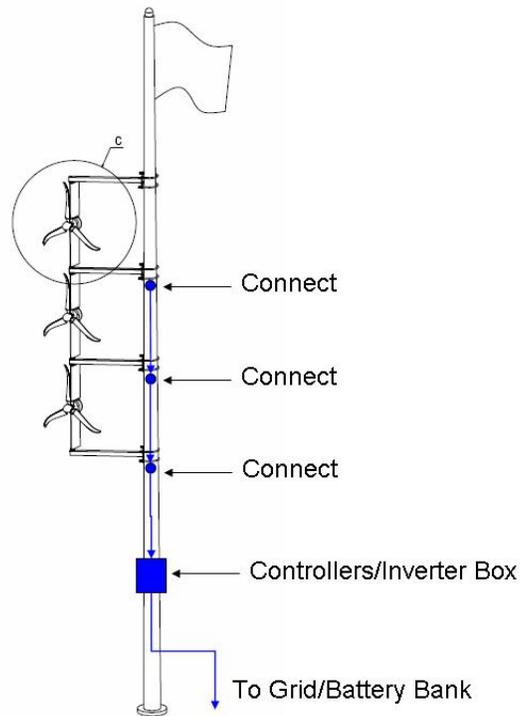


Figure 11-3: Wire routing configuration for three flag pole mounted small wind turbines

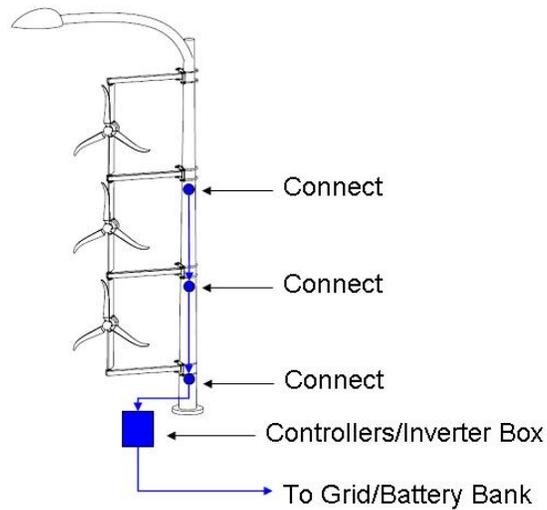


Figure 11-4: Wire routing configuration for three light pole mounted small wind turbines

11.2 Building mounting

11.2.1 Mounting configurations

Mounting small wind turbine systems to the corner or the side of a building may take advantage of the favorable flow between buildings. Roof mounted small wind turbine systems can take advantage of the building height. Figure 11-5 depicts several configurations that are possible for mounting small wind turbine systems to buildings. For clarity a CATIA render of the various alternative building mounting schemes are shown in Figure 11-6.

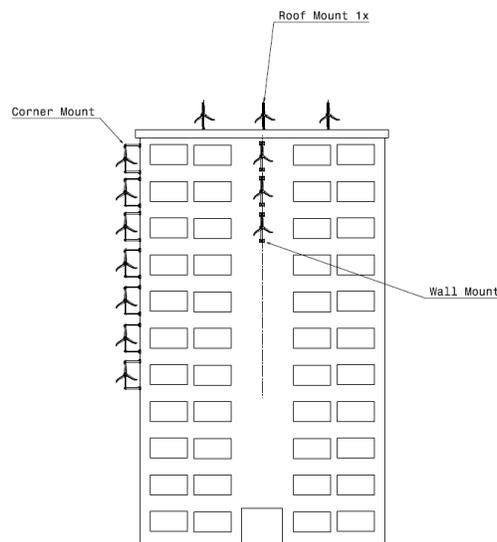


Figure 11-5: There exist alternatives to mounting small wind turbines on the roof. These alternatives include the building corner and sides

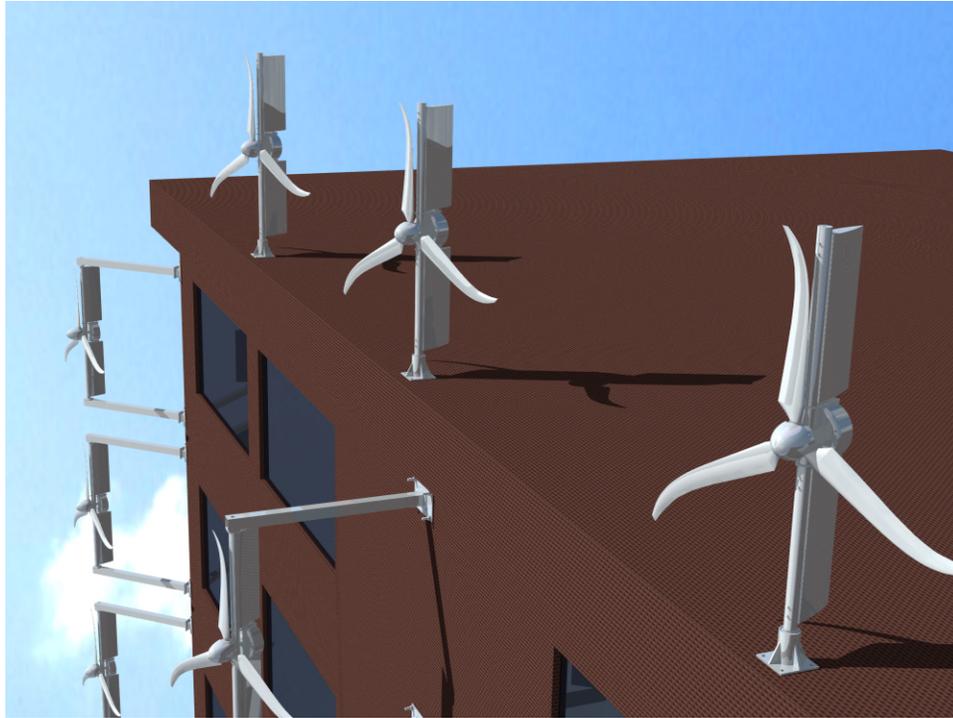


Figure 11-6: A CATIA V5 render of various mounting configurations for a small wind turbine on a building, including mounting to the walls and corners

11.2.2 Vibrations

Unlike pole mounted wind turbines, building mounted wind turbines are generally closer to people. Vibrations caused by small wind turbines mounted to buildings have already been known to cause issues [8]. During the Warwick Wind Trials (WWT), several small roof top mounted wind turbines had to be disabled due to excess noise and vibration being transferred into the building. One way to combat this issue is to use rubber mounting shims. These rubber shims would not alter the current design, rather, the rubber shims would be placed between the mounting arm and the mounting hardware. This isolates the load path of the small wind turbine from the building by putting a damper between the two. Figure 11-7 depicts a drawing of the rubber shims, which are

mounted between the mount arm and the mounting hardware. Notice the number of shims can be increased to achieve the desired level of vibration suppression.

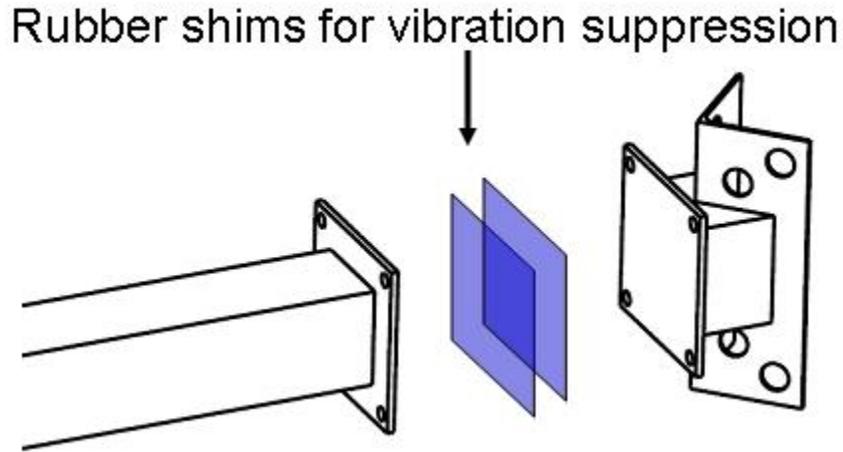


Figure 11-7: Rubber shims placed between the mount and connection hardware reduce vibration transmission into the building structure

11.2.3 Loads

Building structure, in general, can take the loads from these small wind turbines. A possible issue could be compatibility with the exterior material. Brick and mason should not present a problem; however, siding and other non-structural materials may require special mounting techniques. For example for a building with siding, a special mount might penetrate the siding into the building structure allowing the bracket to hover above the siding, so to not pinch the siding against the building, which might cause damage. For mason mountings, pre-drilled holes with metal inserts are required so to prevent material crumbling and falling off the wall. Each customized mount would still be

capable of attaching to the universal mounting arm, requiring no changes to the baseline mount design.

11.2.4 Wire routing and connection

Wire routing for buildings will be similar to wiring a satellite dish or antenna. Multiple turbines can be connected together, and the wires would be sent to a junction box located inside or on the roof for easy maintenance (Figure 11-8). Similar to the pole mounted wind turbines; these junction boxes will contain the controller and inverter (if grid connected). The wires are then sent to the grid conduit or battery bank.

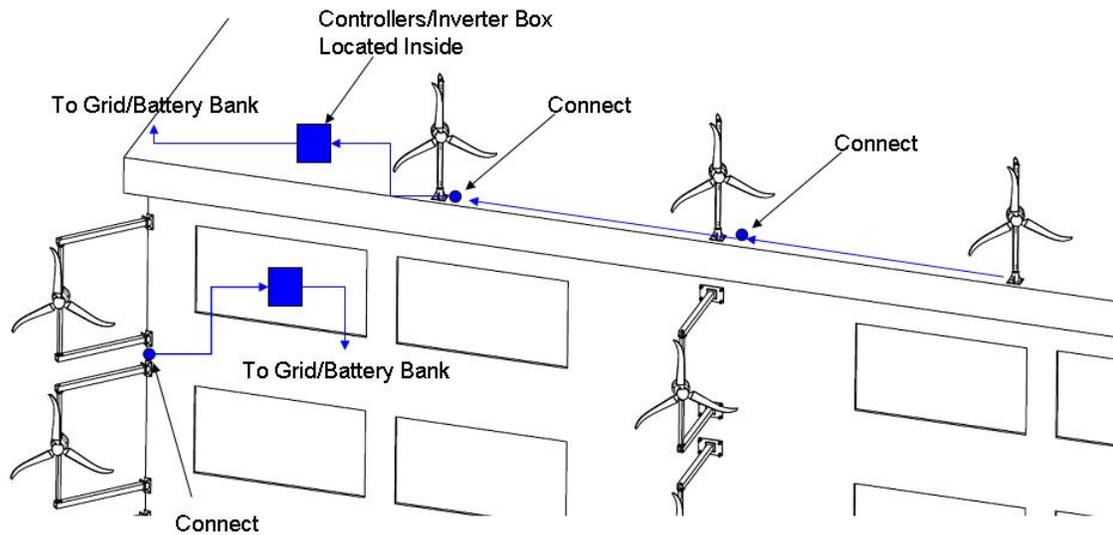


Figure 11-8: Wire routing configurations for various building mounted small wind turbines

12. COST

12.1 System cost

Cost is estimated using off the shelf components where possible. Figure 12-1 depicts the core components that are used to estimate cost. In addition to these core components, additional components, like the grid tie power inverter, rectifier, and mounting hardware, are also included. Table 12-1 summarizes the estimated manufacturing cost of the grid connected, six foot diameter, 1 kW rated small wind designed for this project to be \$1,899. An estimated customer cost is shown in

Table 12-2, and includes a mark-up for manufacturers operating cost and profit. The final estimated customer cost per unit, including the 30% federal tax credit, is \$2,051. This cost includes all the components needed for a grid connected small wind turbine that can be mounted to an existing urban structure. This does not include installation cost, as it is assumed that the customer will be able to do their own installation. This cost, based on the core system is on par with similarly sized small wind turbine core systems on the market today [1, 16], however, because this system does not require a dedicated pole, a savings of 40% (see section 2.6) for removing the dedicated pole is to be expected.

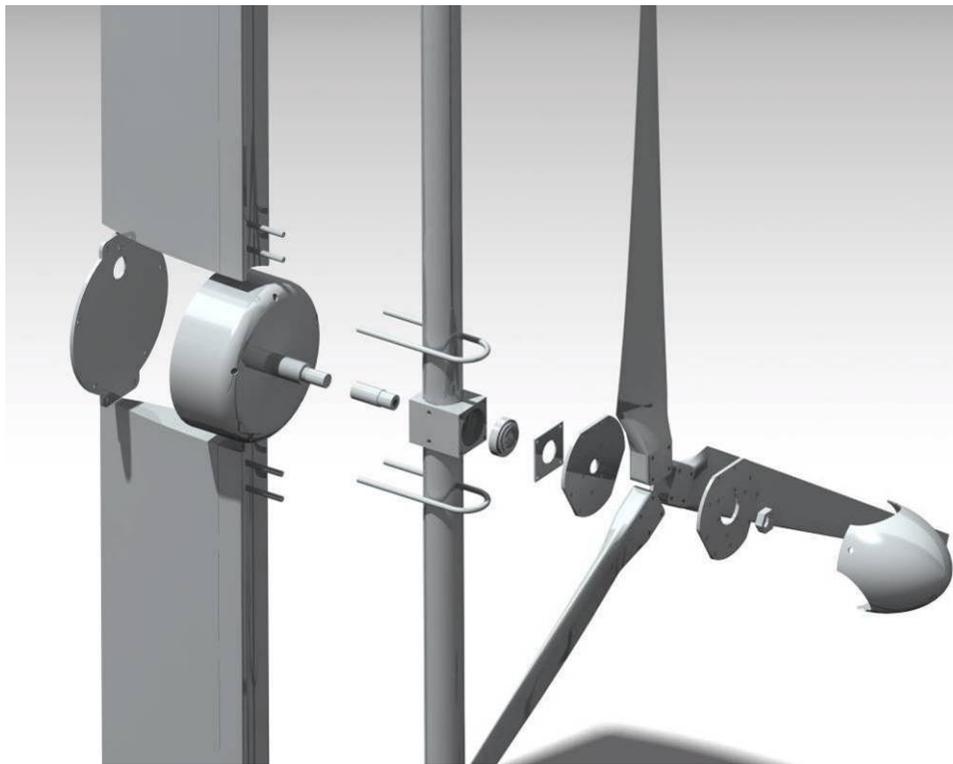


Figure 12-1: A CATIA render of the core components used for cost estimate (hub, motor, blades, bearings, and yaw system)

Table 12-1: Estimated manufacturing cost per unit for a 1,000 unit production run (2010

\$)

1000W - 6 Foot Diameter - Structure Mounted Wind Turbine	
Part	Price (Per piece)
Power Components	
Charge Controller	\$ 97.94
Inverter - Power converter 1000W 12Vdc to 120Vac pure sin	\$ 170.10
GL-PMG-1000A	\$ 722.50
Rectifier Kit	\$ 25.00
Generator Mount Hardware	\$ 30.00
Slip Ring	\$ 7.00
50 ft Wire	\$ 10.00
Machined	
Yaw Shaft (6', 2.5"OD, t=0.188	\$ 108.04
Alloy 4130 Steel Precision Shim Bushing Stock 1" OD, 1/2" I	\$ 54.40
1.00" Propeller Shaft Bearing (Square Mount, Derlin, No mai	\$ 32.41
0.75" Propeller Shaft Bearing (Square Mount, Derlin, No mai	\$ 32.41
Bearing Mount 2"x3" Aluminum Block	\$ 42.50
Hub - 2x 0.125" Aluminum Rounds	\$ 100.00
Zinc-Plated Steel U-Bolt W/Plate, 3/8"-16X1-1/4" L Thrd, for	\$ 17.14
Low-Carbon Steel Square Tube 3-1/2" X 3-1/2", .125" Wall T	\$ 57.92
Low-Carbon Steel Sheet 1/4" Thick, 12" X 12"	\$ 31.93
Low-Carbon Steel 90 Degree Angle 1/4" Thick, 4" Leg Lengtl	\$ 53.39
Blades / Fairings	
Blades (3x set)	\$ 189.00
Nose Cone	\$ 36.00
Blade Hardware	\$ 15.00
Yaw Fairing	\$ 66.00
Total Hardware (Turbine + Grid Connect) Cost	\$ 1,898.67

Table 12-2: Estimate of cost to customer for grid connected, 1 kW, 6 ft small wind turbine, including mark-up for operating cost and profit, then adjusted with 30% federal tax credit (2010 \$)

1000W - 6 Foot Diameter - Structure Mounted Wind Turbine		
Part		Price (Per piece)
Power Components		\$ 1,062.54
Machined		\$ 530.13
Blades / Fairings		\$ 306.00
<u>Total Hardware (Turbine + Grid Connect) Cost</u>		\$ 1,898.67
Operating Cost		
Engineering Support (5%)		\$ 94.93
Sales/Infustructure (15%)		\$ 284.80
Profit	Profit (15%)	\$ 284.80
<u>Total Cost</u>		\$ 2,563.21
Customer Cost		
Installation Cost (10%)		\$ 256.32
Tax Credit (30%)		\$ (768.96)
<u>Total Customer Cost (System Installed + Grid Connected)</u>		\$ 2,050.57

12.2 Choosing Weibull ‘k’ factor for cost estimates

Choosing the Weibull ‘k’ factor for cost estimates is critical because it determines the probability of wind distribution for a given location [3, 8, 9]. The urban environment does not produce the same average wind speeds as an open field. In the recent Warwick Wind Trials (WWT) study (Chapter 3), it was shown that the wind speeds, were on average, measured to be 67% lower than the government published database. Primarily, this is caused by the obstructions from surrounding objects such as: buildings, trees, and other urban structures. For context an example of a WWT location tested is shown in Figure 12-2. The Weibull distribution used for calculating the Net Annual Energy Production (AEP) in this project will use a k factor of 1.5, as opposed to 2.0, based on the recommendation given by the WWT. This k factor has been derived from the measured

data from the WWT. An example of this data is shown in Figure 12-3. For a more accurate estimate of wind probability for cost, the Web-based Wind Assessment System (WWAS), coupled with the modular wind measurement system is recommended (Chapter 6 and 7).



Figure 12-2: A wind turbine mounted to the roof of a building in the UK, source:

Warwick Wind Trials, 2009 [9]

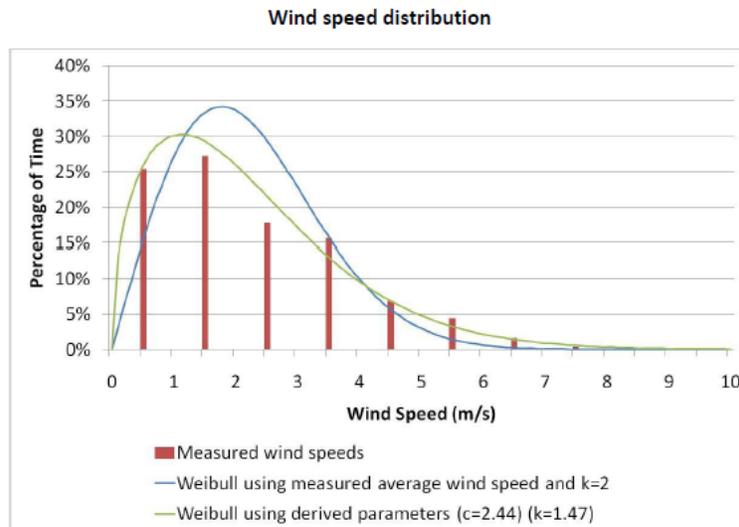


Figure 12-3: Measured wind speeds for the location shown in Figure 12-2, source:
Warwick Wind Trials, 2009 [9]

12.3 Net Annual Energy Production (AEP)

Based on the estimated performance calculated in Chapter 10, the Net Annual Energy Production (AEP) is shown in Figure 12-4. The AEP is an important input to the Cost of Energy (COE) and return on investment for a small wind turbine system. It uses the performance of the wind turbine combined with the predicted average wind speed distribution (Weibull) for a given location.

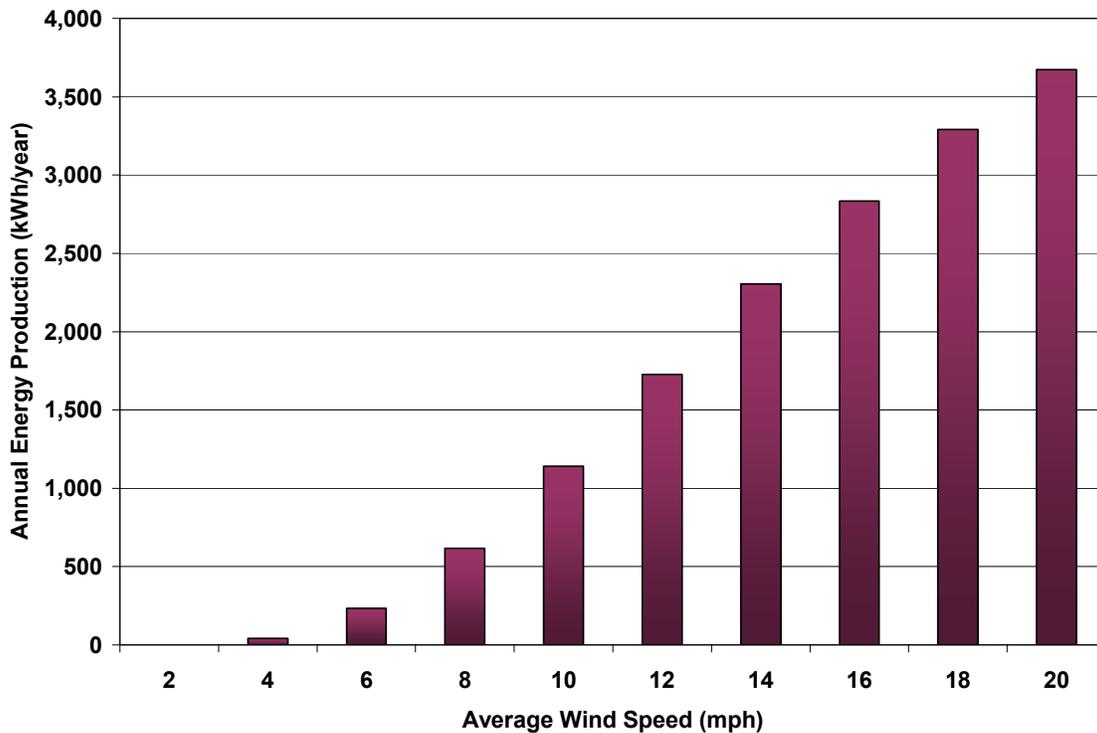


Figure 12-4: Annual Energy Production for a given average wind speed

12.4 Return on investment

Return on investment relies on several key assumptions. First, of course is the cost of the system, which was determined in section 12.1 to be \$2,050. Next, is the average wind speed data for a given location, which is best determined using measurements. The average cost of energy is used to calculate the revenue from the power generated. The current national average rate is \$0.11/kWh [7]. Inflation is used to adjust the cost of energy over time, which is estimated to be on average between 2-4%.

Once the inputs are gathered calculating return on investment becomes mostly dependent on average wind speed. Choosing a viable location is important, for example: a possible viable location could have an average wind speed of 14 mph (6.5 m/s). At 14 mph average wind speed the 30-year cash flow chart (Figure 12-5) reveals that this small wind turbine would pay for itself in 8.5 years. This leaves over 10 years of return on investment, yielding \$4,000 of profit over the 20 year design life [31].

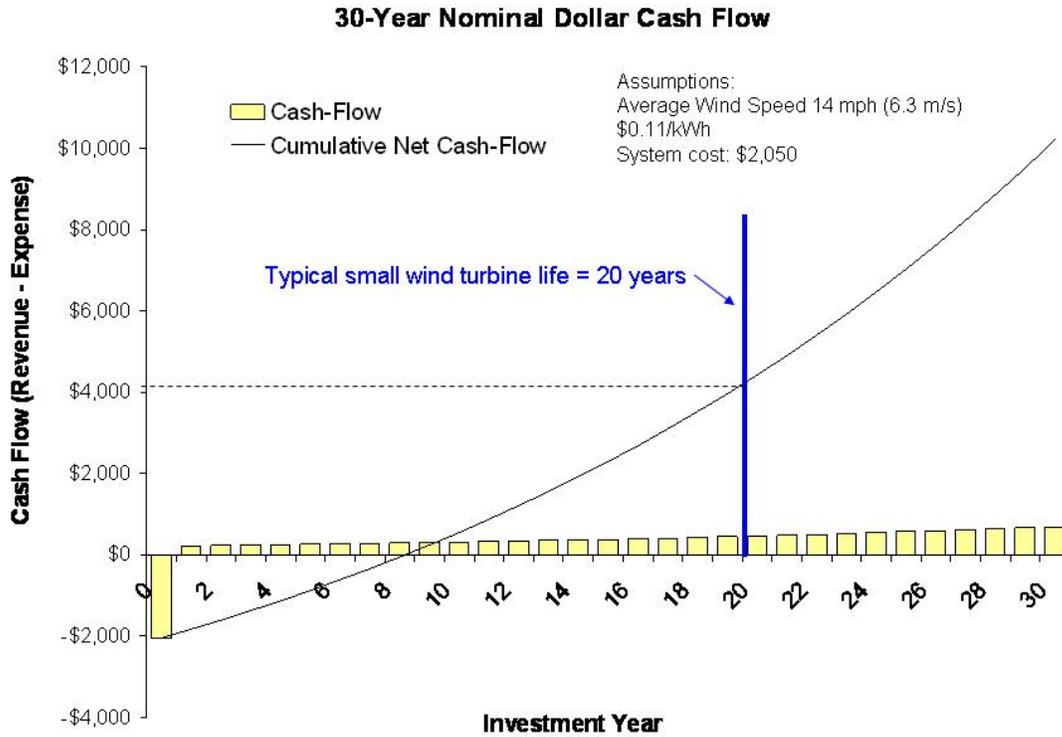


Figure 12-5: 30-year cash flow return on investment summary for the small wind turbine design for this project (assume 14 mph average wind speed), calculator source: Wind Powering America [31]

Again, to highlight the criticality of selecting a good setting location, Figure 12-6 shows the number of years till return on investment is achieved at different average wind speeds. For an average wind speed under 8.5 mph (3.8 m/s), this wind turbine would never pay for itself before its design life ran out (typically 20 year life). For locations with 9 mph average wind speed or greater, this wind turbine will have some period of time in which it pays for itself during its life and begin to return a profit. A very good site, with average wind speeds equal to or greater then 15 mph (6.7 m/s); this small wind turbine system will provide 12 or more years of profitable return.

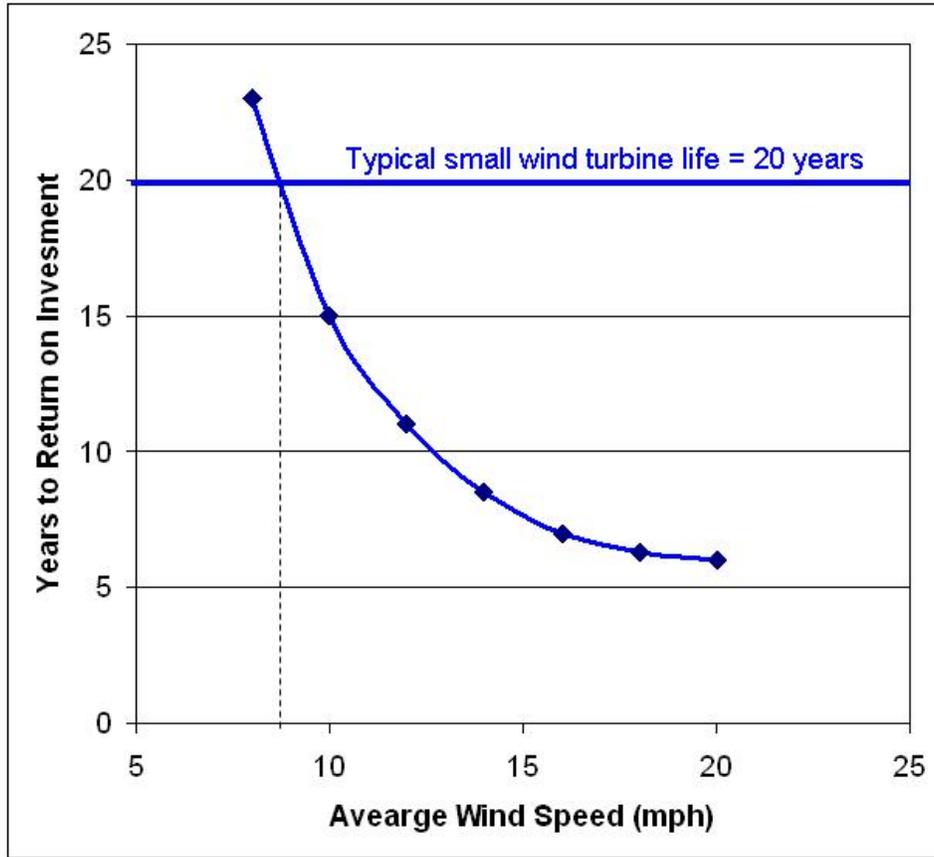


Figure 12-6: Years till return on investment for the small wind turbine designed for this project as a function of average wind speed [31]

13. CONCLUSION AND RECOMMENDATIONS

Despite existing inefficiencies in the mechanics and measurement of small wind turbine systems, this project illustrates how sites with viable wind resources (average wind speed > 10 mph) can be economically feasible in urban environments. To ensure such feasibility, a Web-based Wind Assessment System (WWAS) has been introduced and outlined. The proposed system prevents potential small wind turbine customers from over-predicting their local wind resource, thus saving time and labor. By implementing a system such WWAS coupled with the modular mounting system for small wind turbines, manufacturers, consumers, regulators, and members of the public can work more effectively toward shared conservation agendas.

To be fair, many challenges still face the developing market of small wind generating systems. Testing standards for small wind turbine manufacturers are still in the works, public perception of small wind systems is in its infancy, and local government installation regulations vary widely across communities. Yet, the future is bright for the small wind industry and its various stakeholders. As the public becomes more educated, and designers and manufacturers improve their technology, small wind has the potential to be as economically viable (for the right wind resource locations) as solar photovoltaic's (PV) is today.

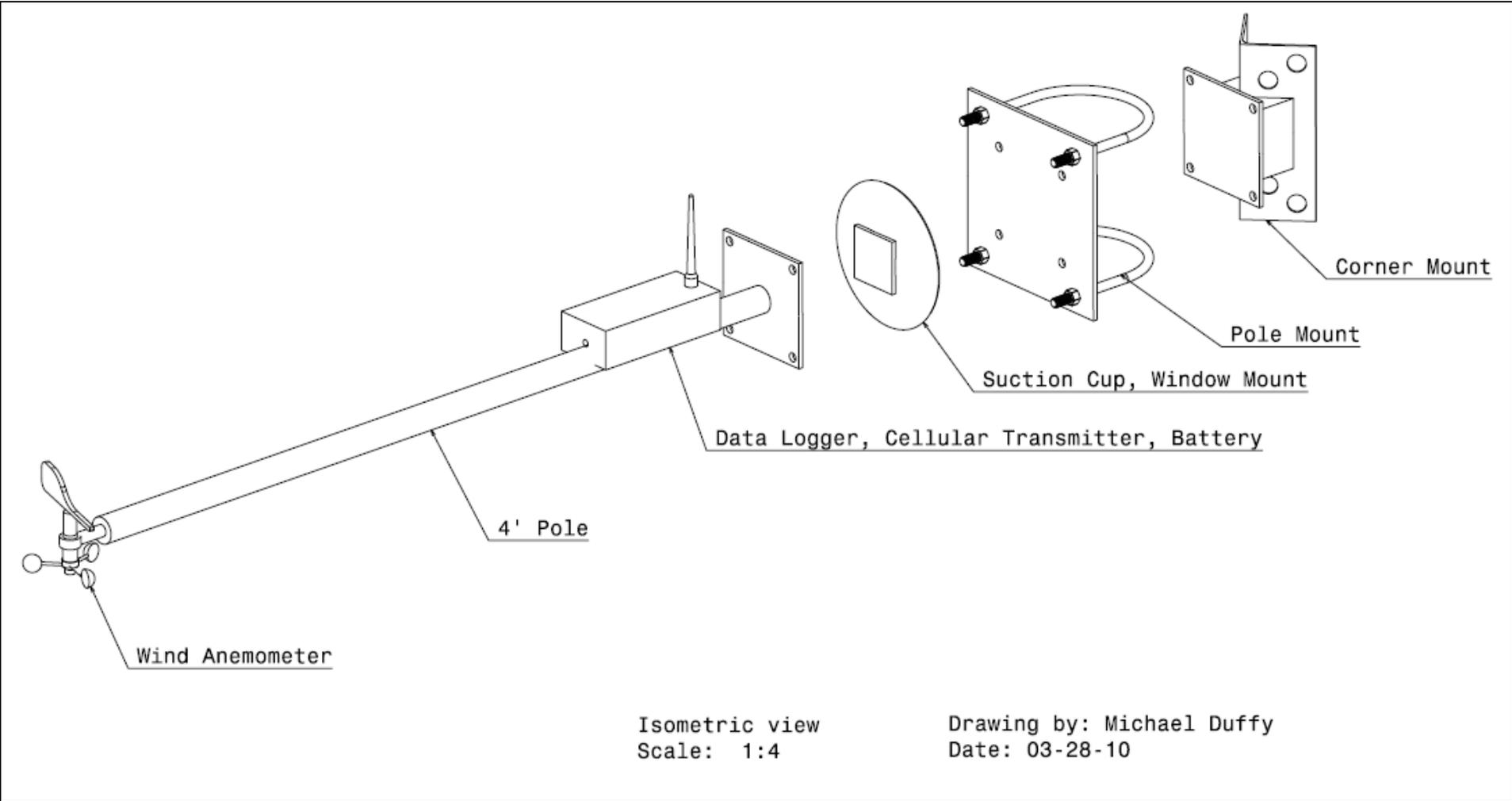
REFERENCES

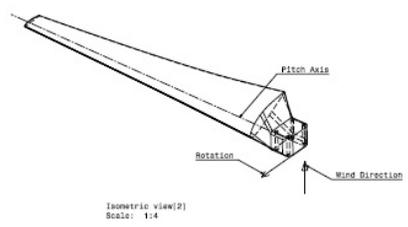
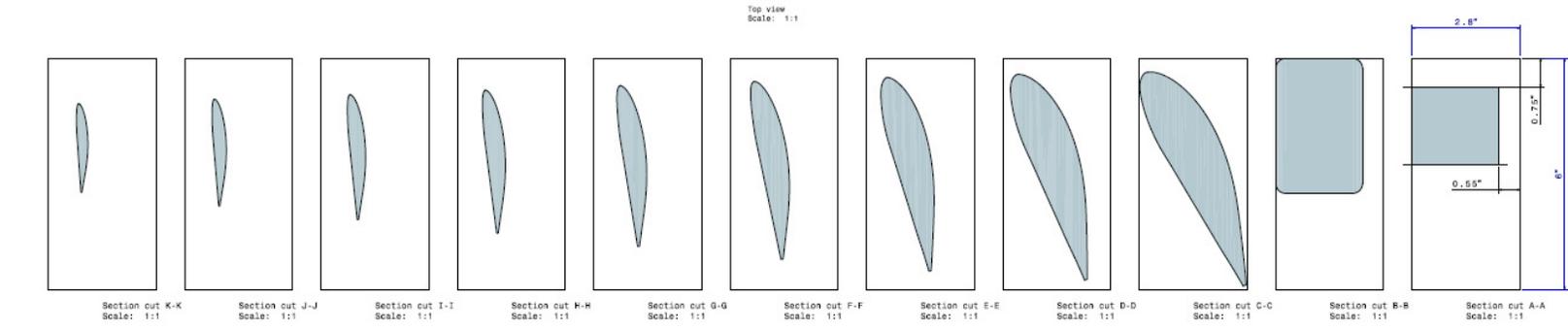
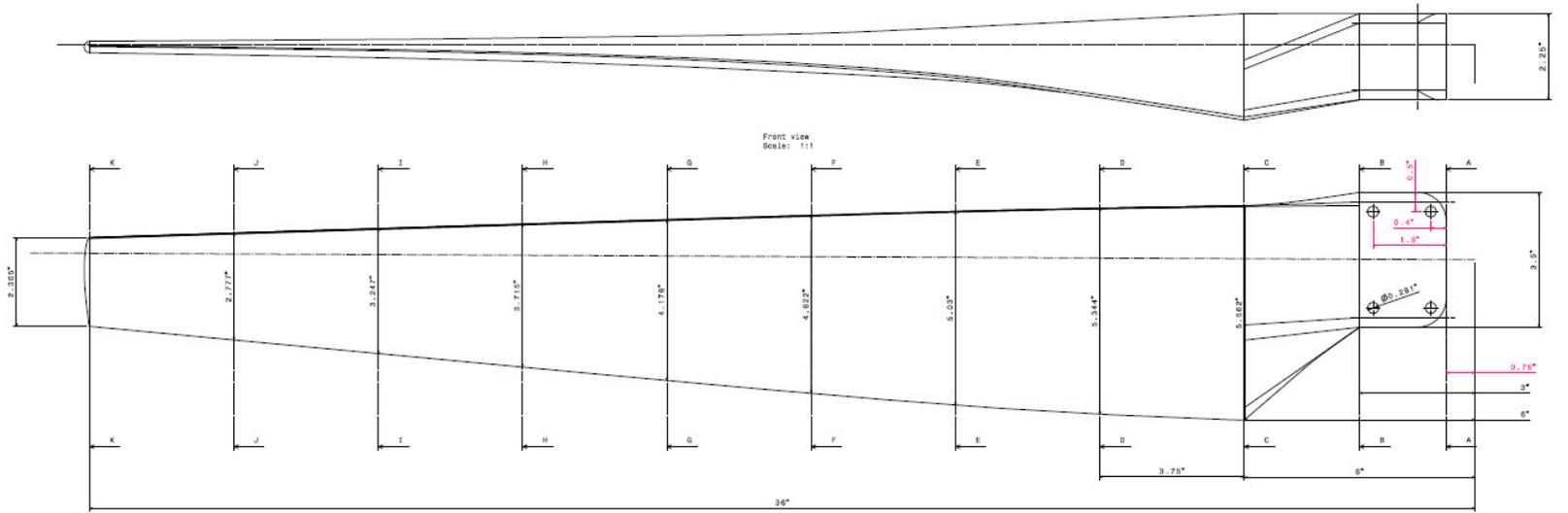
1. Bergey Windpower, “<http://www.bergey.com/Products/XL1.Comparisons.html>”, 2008
2. Blevins, R., “*Applied Fluid Dynamics Handbook*”, 2003
3. Burton, Tony, Sharpe, David, Jenkins, Nick, Bossayni, Ervin “*Wind Energy Handbook*”, Wiley, 2008
4. Crawford, C. & Stack, L., “*Optimal Rotors for Distributed Wind Turbines*”, AIAA 2009-1546
5. David Hailes, Encraft Ltd, “*Practical Challenges of Building Mounted Wind Turbines*”, Warwick Wind Trials Open Day, September 9th, 2008
6. Department of Business Enterprise and Regulatory Reform (BERR), “Microgeneration Installation Standard”, U.K., MIS 3003: Issue 1.2, February, 25, 2008
7. Electric Power Monthly, http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html, 2010
8. Encraft Ltd., “*Microwind – a catalyst for change in UK energy culture? - A report on the social and market aspects of the Warwick Wind Trials Project*”, April 2008
9. Encraft Ltd., “*Warwick Wind Trials Final Report*”, 2009
10. Encraft Ltd., “*Warwick Wind Trials Project – Interim Report August 2008*”, August 2008
11. Frede Blaabjerg, Zhe Chen, “*Power Electronics for Modern Wind Turbines – Synthesis Lectures on Power Electronics*”, Morgan & Claypool Publishers, 2006

12. Ginlong Technologies, "<http://www.ginlong.com/>", 2010
13. Hambley, A., "*Electrical Engineering – Principles and Applications, Second Edition*", Prentice Hall, 2002
14. Hefei Sunway Power Co., Ltd, "<http://sunwaypower.en.alibaba.com/>", 2010
15. James L. Tangler, University of Illinois at Urbana-Champaign, "*Steady-State Aerodynamics Codes for HAWTS – Selig, Tangler, and Giguere*" Power Point Notes – August 2, 1999 – NREL NWTC, Golden, CO
16. L. Fingersh, M. Hand, and A. Laxson, "*Wind Turbine Design Cost and Scaling Model*", Technical Report NREL/TP-500-40566, December 2006
17. Marshall L. Buhl, Jr., Alan D. Wright, and James L. Tangler "*Wind Turbine Design Codes: A Preliminary Comparison of the Aerodynamics*", [NREL/CP-500-23975](#), NREL-NWTC, December 1997
18. Marshall L. Buhl, Jr, National Renewable Energy Laboratory, "*WT_PERF USER'S GUIDE*", June 21, 2004
19. Met Office, accompany the Carbon Trust report, Small-scale Wind Energy – Policy insights and practical guidance "*Small-scale wind energy - Technical Report*", July 2008
20. Migliore, Paul G., National Renewable Energy Laboratory, "*Wind Turbine Aeroacoustic Issues*", California Wind Energy Consortium Forum, University of California, Davis, 17-18 December 2002
21. National Association of Architectural Metal Manufacturers, <http://www.naamm.org/>, 2010
22. Sankar, Lakshmi, "*AE8803 Lecture Modules 5.1 thru 5.4*", May 2009

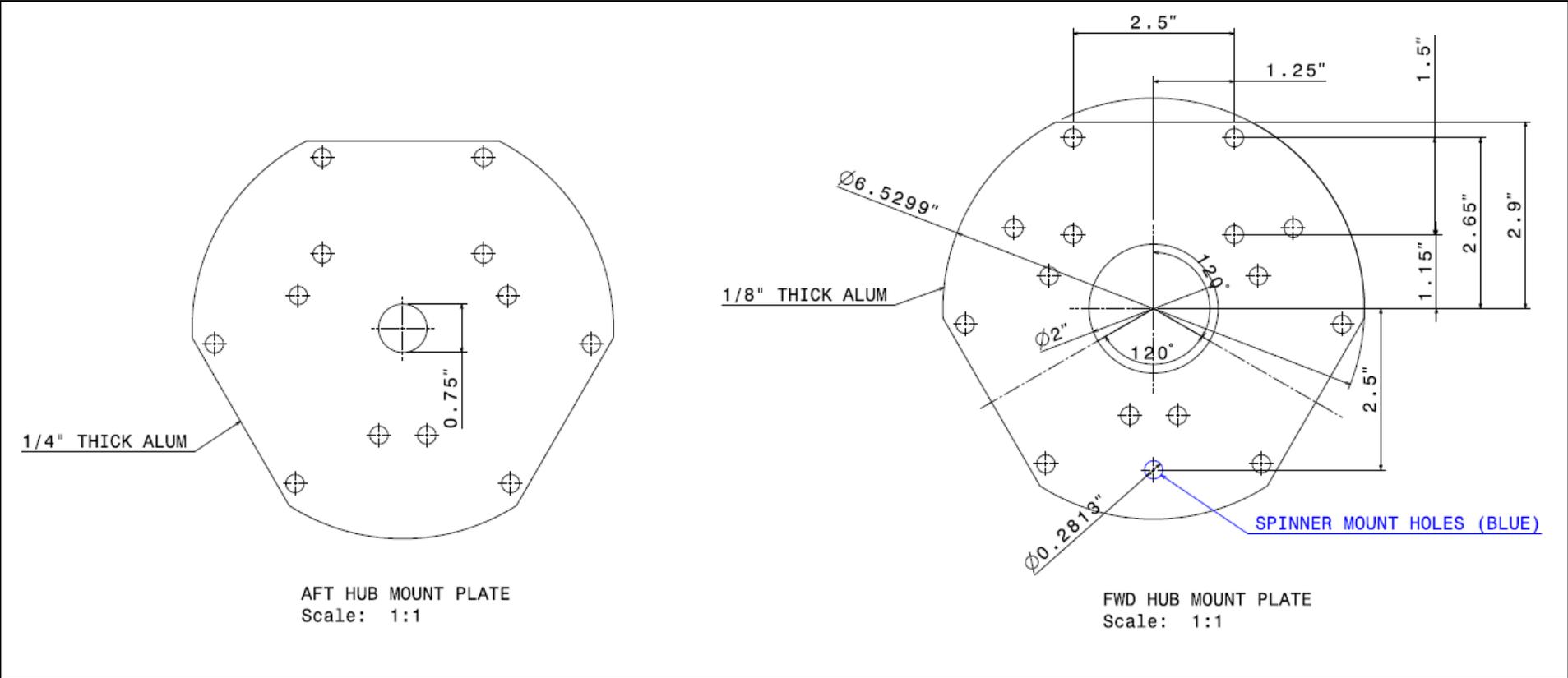
23. Sankar, Lakshmi, “*AE8803 Lecture Modules 6.1*”, May 2009
24. Selig, Michael S., McGranahan, Bryan D., “*Wind Tunnel Aerodynamic Tests of Six Airfoils for Use on Small Wind Turbines*”, October 31, 2002–January 31, 2003
25. Simmel, Ron, American Wind Energy Association, “*AWEA Small Wind Turbine Global Market Study 2007*”, July 2007
26. Simmel, Ron, American Wind Energy Association, “*AWEA Small Wind Turbine Global Market Study*”, 2009
27. Southwest Windpower, “*Air X Land Manual, Document #0056 REV D*”, 2002
28. TLG Windpower, “<http://www.tlgwindpower.com/>”, 2010
29. Werle, M. J. & Presz Jr., W. M., FloDesign Inc., “*Ducted Wind/Water Turbines and Propellers Revisited*”, *Journal of Propulsion and Power*, Vol. 24, No. 5, September-October 2008
30. Windmonitoring.com, 2010
31. Windpoweringamerica.gov, 2010
32. “*Wind Power Increase in 2008 Exceeds 10-year Average Growth Rate*”, <http://www.worldwatch.org/node/6102?emc=el&m=239273&l=5&v=ca5d0bd2df>
33. World Wind Energy Association, “*World Wind Energy Report 2008*”, http://www.wwindea.org/home/images/stories/worldwindenergyreport2008_s.pdf, March 2009

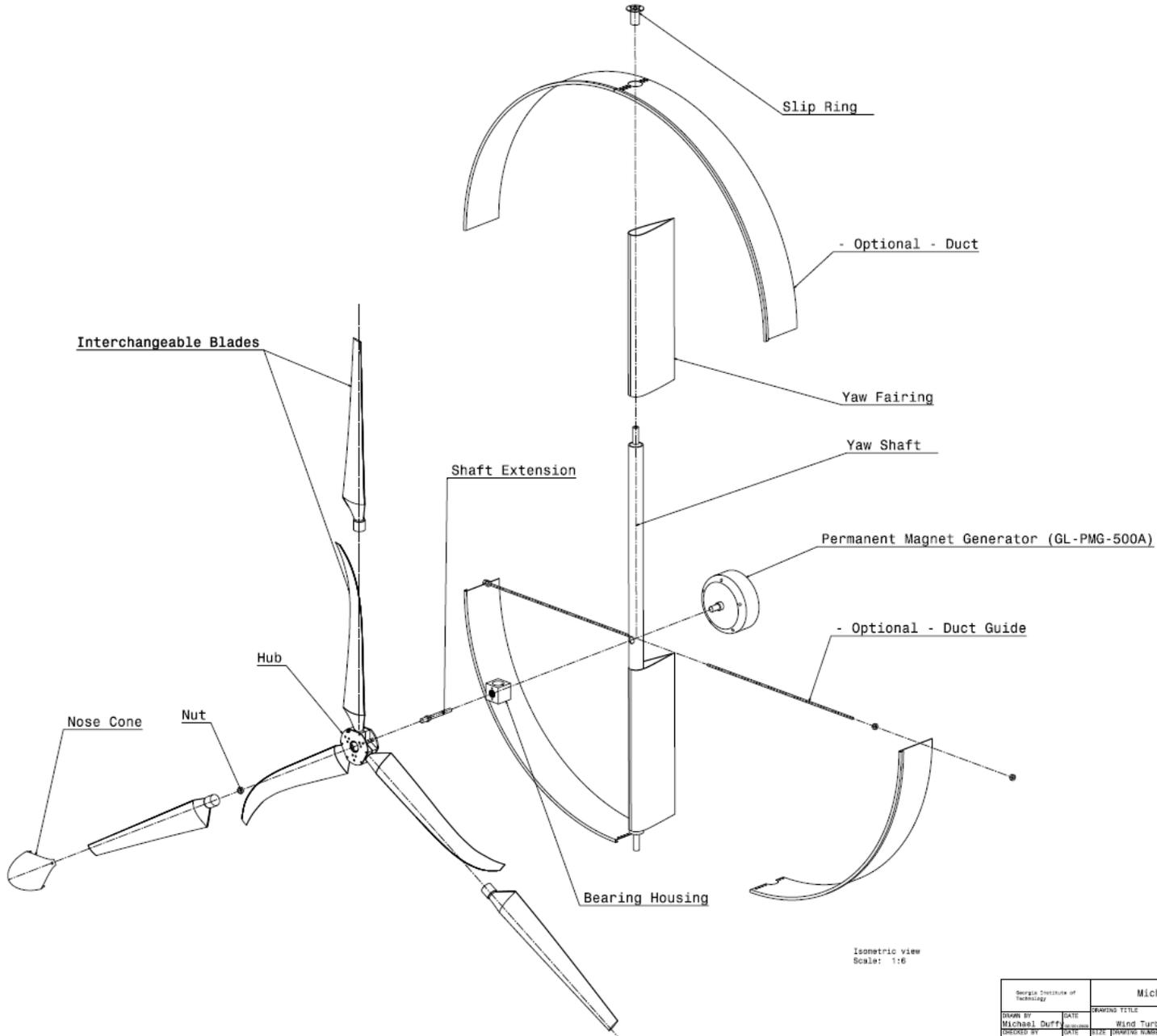
APPENDIX A: DRAWINGS





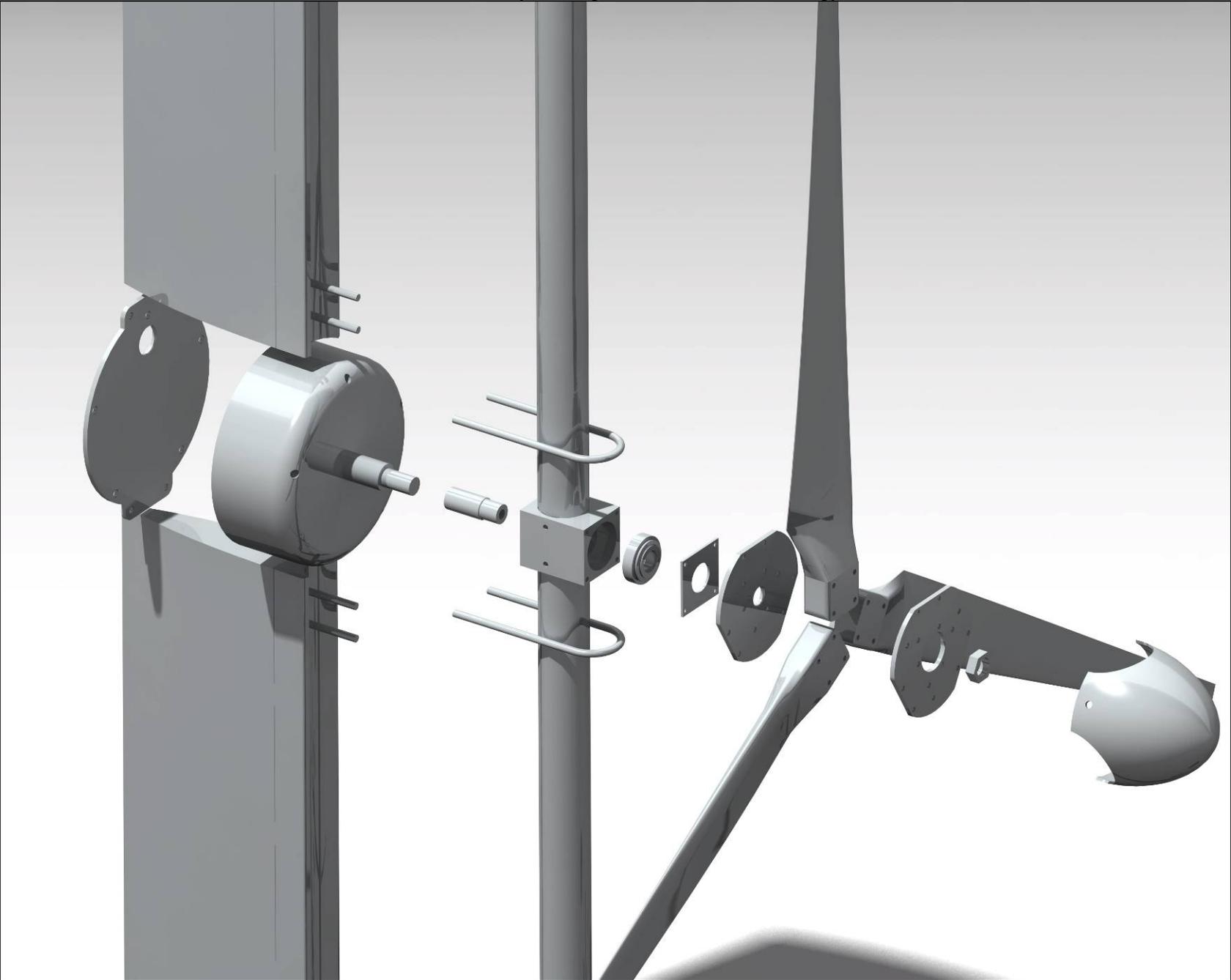
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PREPARED BY XXX	DATE 10/20/10	SCALE 1:1	SHEET 1/1

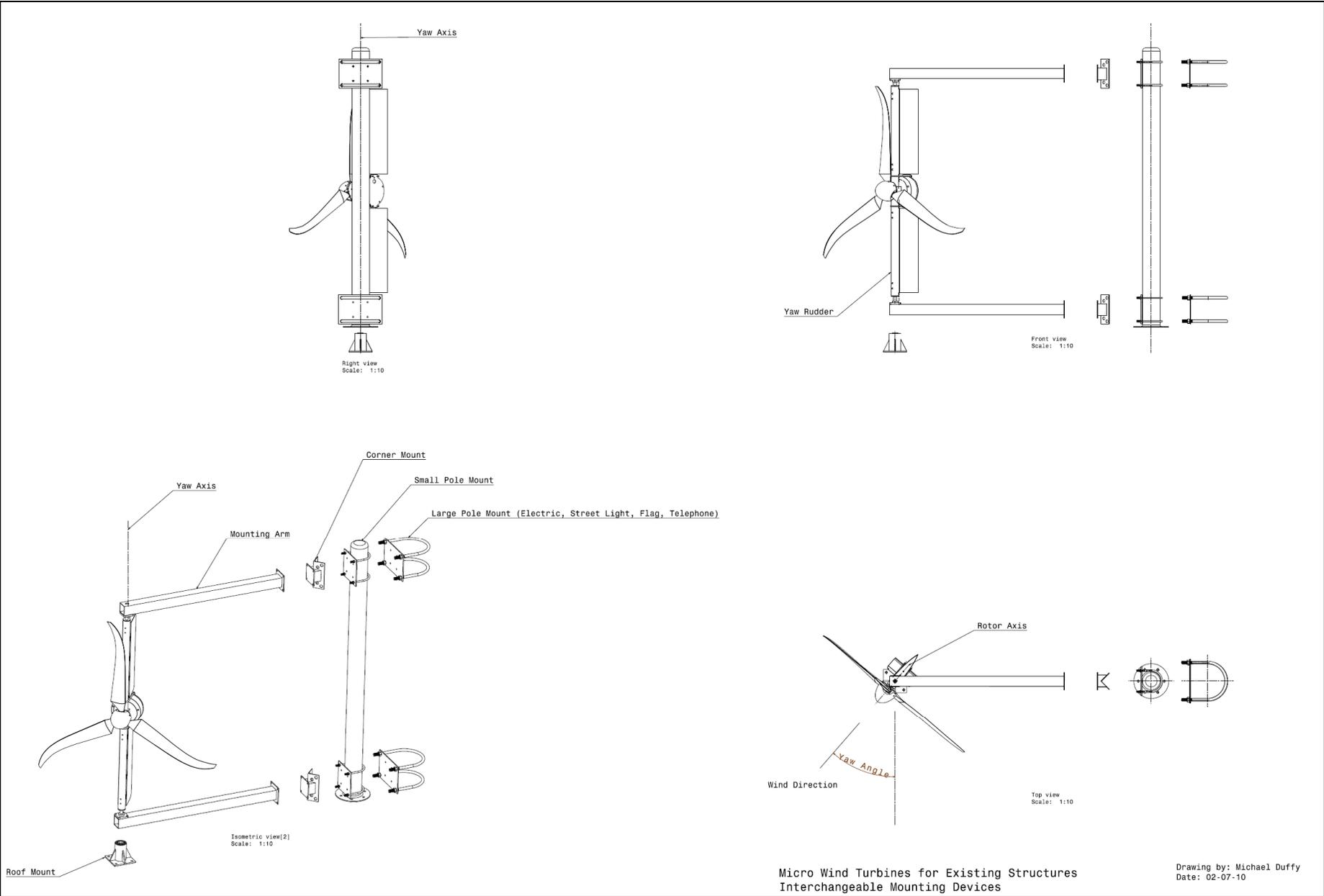


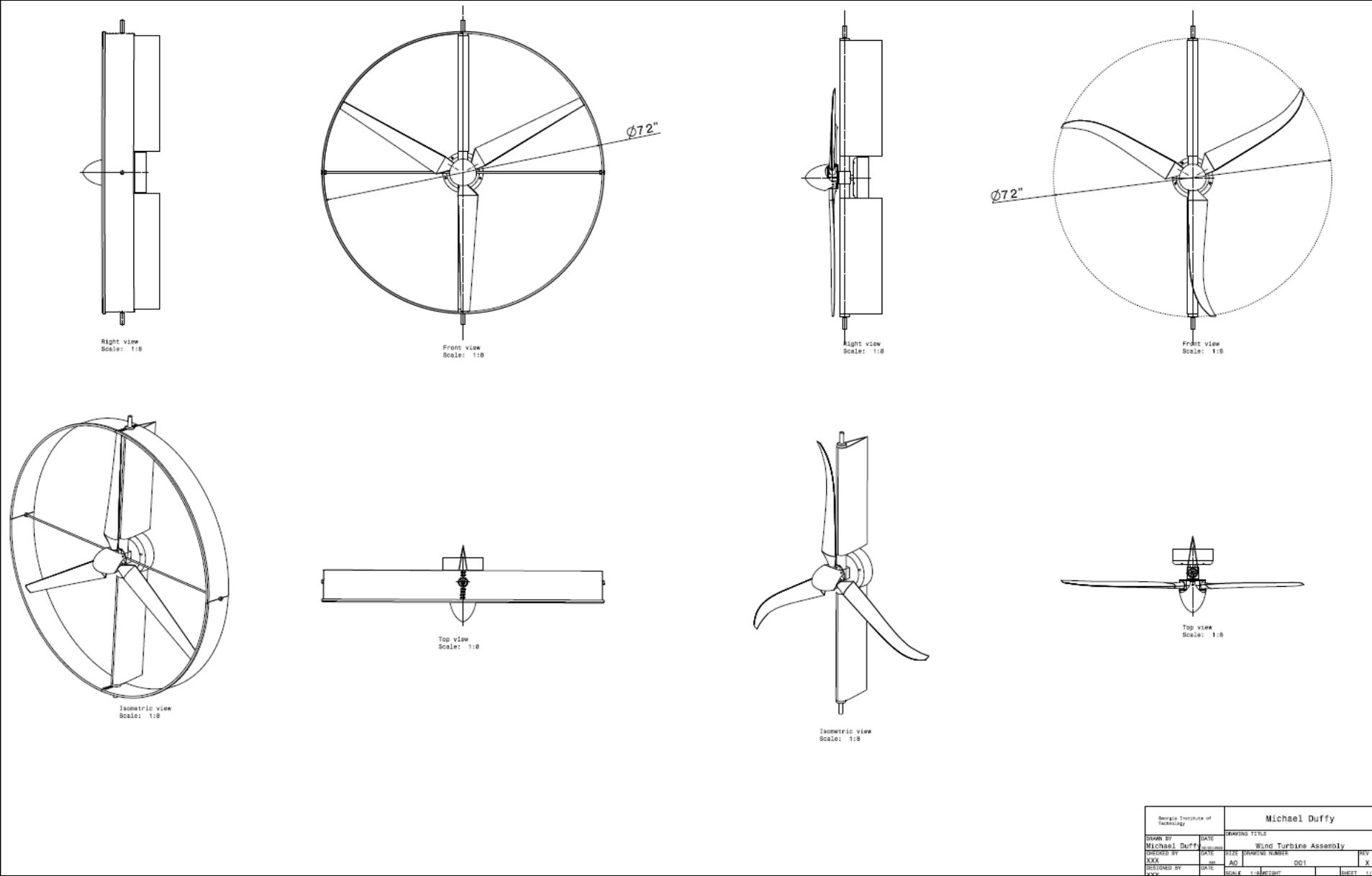


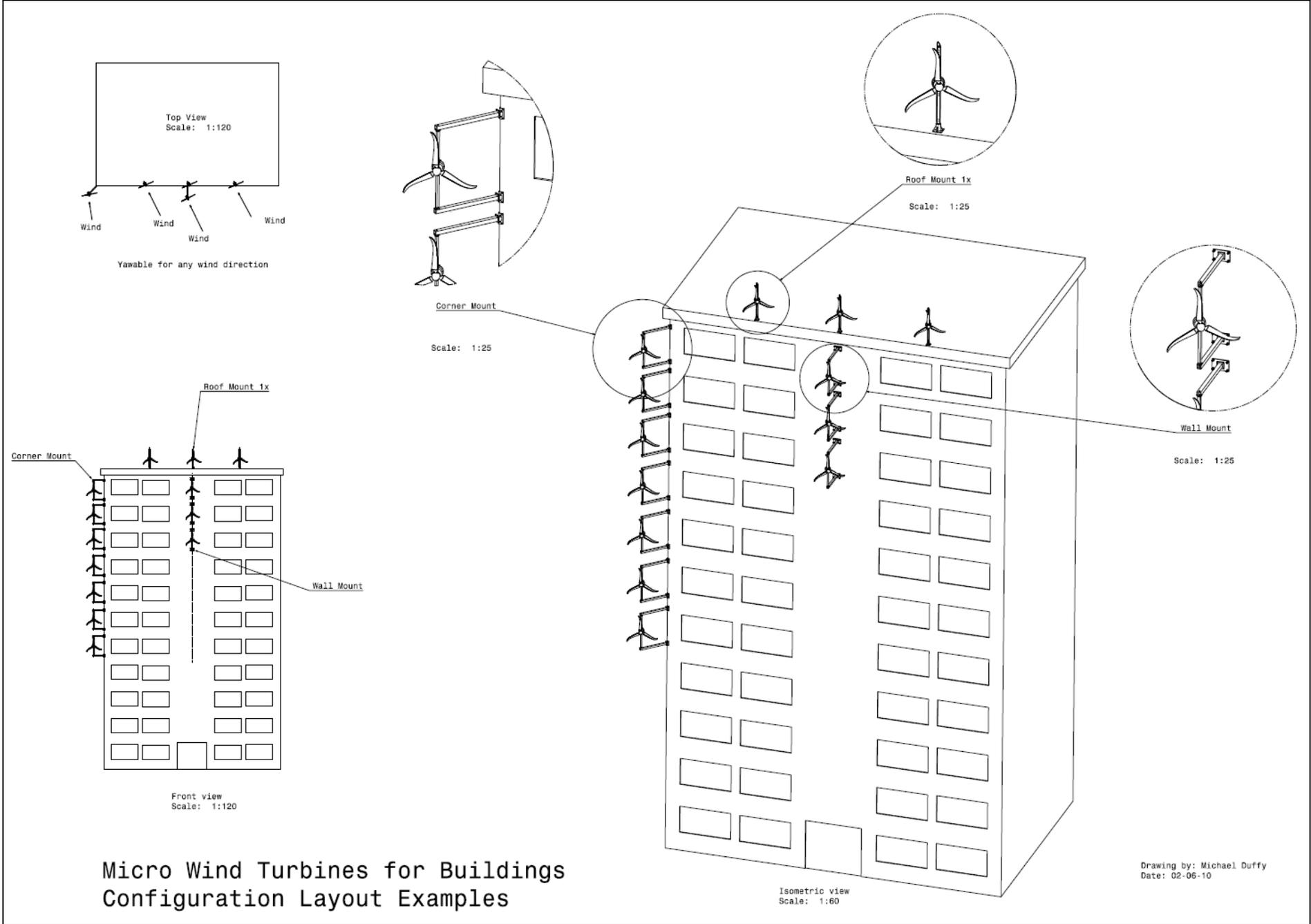
Isometric view
Scale: 1:6

Georgia Institute of Technology		Michael Duffy	
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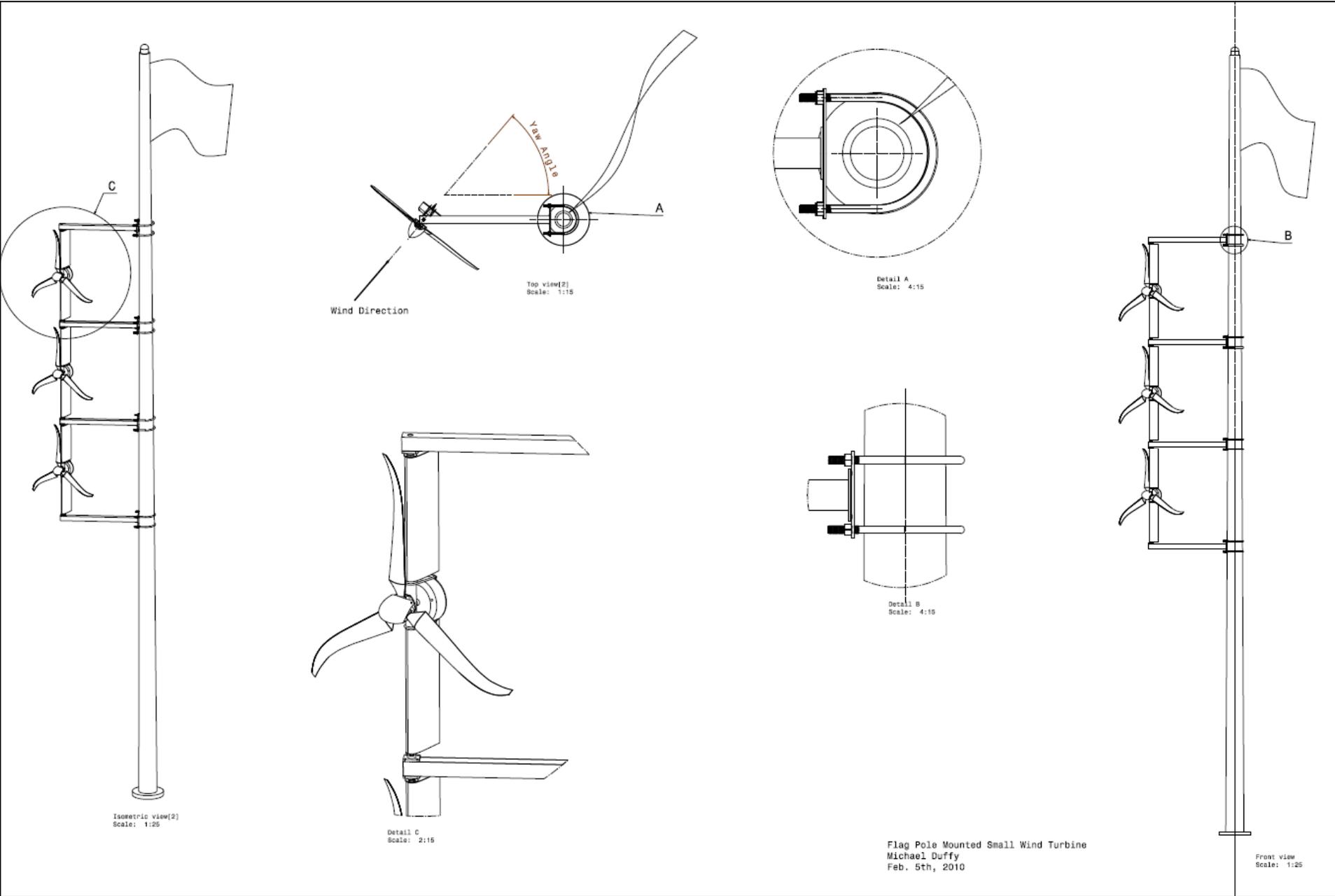




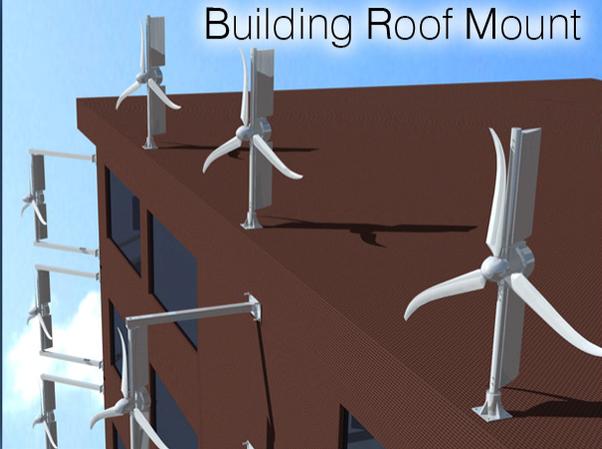


Micro Wind Turbines for Buildings Configuration Layout Examples

Drawing by: Michael Duffy
Date: 02-06-10







Small Wind Turbines Mounted to Existing Structures

