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Urban Wind Generation: Comparing Horizontal and Vertical Axis Wind Turbines at Clark University in Worcester, Massachusetts

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ABSTRACT

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Electricity production must shift towards carbon neutral sources such as wind power to mitigate the impacts of climate change. The wind resource in urban environments is challenging to predict but technologies, including computational fluid dynamics software, are making it possible. This software pinpoints suitable placement for wind turbines through models that show wind acceleration patterns over a building. Horizontal axis wind turbines (HAWTs) have dominated the wind industry but vertical axis wind turbines (VAWTs) offer potential to outperform HAWTs in urban environments. VAWTs can handle turbulent and unconventional wind and generate energy at slower speeds, which is beneficial for these areas. A case study at Clark University in Worcester, Massachusetts analyzes the functionality of a HAWT and a VAWT. The machines are compared by their efficiencies due to an imbalance of rated power outputs. The machines' average maximum power coefficients are similar. However, when the R^2 values of the turbine's power curves are compared the VAWT demonstrates greater capacity to track changes in the wind. This research is the first step in redefining the power systems employed at Clark University and the data will be utilized to find better locations for the wind turbines.

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Table of Contents

1 INTRODUCTION 1
2 BACKGROUND 4
2.1 History of Wind Turbines 4
2.2 Rooftop Shape and Urban Wind flow 6
2.3 What are turbines and how do they work? 7
2.4 HAWTs.. 9
2.5 VAWTs 10
3 METHODS..11
3.1 Literature.. 11
3.2 MicroGrid and Turbines 12
3.3 Measuring equipment.. 12
3.4 Analysis... 13
3.5 Calibration and Energy assumptions.. 13
4 RESULTS 15
5 DISCUSSION 21
5.1 Limitations.. 26
6 CONCLUSION 26
7 REFERENCES 28

1 Introduction

67% of the county's electricity is produced by carbon heavy fossil fuels and only 4.7% is generated from zero emission wind power [1]. To mitigate the effects of climate change, a shift towards sustainable forms of energy such as solar and wind power is necessary. Wind energy is the fastest growing energy source in the United States [2][3]. Large-scale wind operations both on and off-shore will generate significant amounts of energy, but with global energy demand expected to grow by 48% by 2050 from standards, it is necessary to investigate all avenues for energy generation [4]. Urban wind generation and the application of vertical axis wind turbines have recently gained attention because of their potential to harness wind power in new locations and reduce energy loss through transmission.

Urban wind generation involves installing wind turbines in the urban environment. These can be mounted on freestanding poles such as a light post, or on a rooftop. Less attention has been given to wind generation in the built environment because wind patterns are more difficult to measure in urban areas [5]. Buildings obstruct and deflect the wind, leading to increased turbidity and decreased intensity of the wind. Turbines work best in environments with strong and consistent winds, such as over an open field or off-shore [6]. However, research demonstrates that turbines may have a place in the urban environment as well. Computational fluid dynamics (CFD) software has been used to expand the knowledge of wind patterns around buildings [7][8][9]. This information can help developers more accurately estimate wind resources and locate the most effective sites for wind generation.

Rooftop wind projects are advantageous because they bring energy production closer to the end user [10]. Transporting energy from distant commercial wind farms and fossil fuel plants results in energy loss through transmission. The EPA estimates that 5% of electricity is lost through transmission every year [11]. Rooftop wind turbines generally serve those in the building where they are located, so minimal energy is lost in transport. The efficiency of a turbine can be enhanced when it is coupled with a battery storage and distribution system as it stores energy for use when there is no wind [12].

Clark University has an experimental microgrid project that intends to eventually power the physics building with renewable energy. A microgrid is a small-scale electricity distribution system. Electricity is gathered from many sources and stored in batteries, which can be used to power classrooms. When the renewable sources do not produce enough power, electricity can be drawn from the conventional grid. Clark's microgrid currently collects power from 10 solar panels. Rooftop turbines could prove to be a useful addition to the system. They are able to produce power at times when the solar panels are inactive, such as at night or on cloudy days. An ideal microgrid energy system utilizes multiple energy sources to build resilience against intermittency [13].

The advancement of urban wind resource mapping opens the field for investigations into different kinds of turbines and their effectiveness. Effectiveness can be determined by examining the efficiency, cost, noise level, and maintenance requirements of each type of turbine. Horizontal axis wind turbines (HAWTs) are the dominant wind gathering technology because they have higher efficiency ratings [14]. Their main advantage is that their blades move perpendicular to the flow of wind so energy can be generated the entire way through a rotation [14]. Another type of turbine, the vertical axis wind turbine (VAWT), is not as common. VAWTs have been in operation longer than HAWTs but have not been given much attention because of their efficiency deficit. However, they are not useless. VAWTs have several features that make them attractive in the urban environment, such as the ability to operate under omni- and multidirectional winds [6][15], slower cut-in speeds [16], and reduced maintenance [6]. These specific advantages might make VAWTs the dominant technology for urban wind generation because of the slower, more turbulent wind found in cities [17][13].

This paper explores a case study at Clark University in Worcester, MA to explore the effectiveness of urban wind generation and to compare horizontal and vertical axis wind turbines. The paper addresses the following research questions: 1) Are vertical axis wind turbines more efficient than horizontal axis wind turbines in the urban environment? 2) Does Clark University have adequate wind resources to add turbines to its microgrid power sources?

2 Background

2.1 History of Wind Turbines

Humans have utilized wind energy as early as 5000 BC, when it was recorded that wind propelled boats on the Nile River [18]. Windmills are machines that harvest wind energy and convert it directly into mechanical energy which can be used to power heavy machinery [18]. The origins of the windmill are not known, but it is believed to have first been used in the area of Sistan and Khorasan in eastern Iran during the 9th century AD [17]. These early windmills had rectangular wings that rotated around a vertical axis perpendicular to the ground [17]. The Sistan mills were generally 6 meters tall with a 6-meter diameter [17]. The use of windmills to perform tasks spread through the ancient world to pump water and grind grains [17].

Windmills appeared in Western Europe between 1300 and 1875 AD [18]. Interestingly, these windmills had horizontal axes that were parallel to the ground. The axis faces into the wind and the blades rotate perpendicular to the flow of air. It is unknown why the switch from vertical to horizontal axis windmills was made. However, they could have been influenced by the design of the European water wheel [18]. These mills had more diverse functions, including the pumping of water, grinding of grain, saw milling, and the processing of such commodities as spices, dyes, and tobacco [18]. Mills declined in use during the 19th century with the advent of steam engines in the industrial revolution [15].

The next important development in wind power's history was the creation in the late 1800's of wind turbines, machines that convert wind energy into electrical energy. A wind turbine operates in a similar way to a windmill except instead of directly driving a mechanical operation, it rotates a generator which produces electricity. The first wind turbine was created by James Blyth, Professor of Natural Philosophy at Anderson's College in Glasgow (now Strathclyde University) in July, 1887 [19]. The next year the feat was duplicated by American engineer Charles Brush at his mansion in Ohio [20]. This machine was almost double the height of Blyth's and supplied his home with energy for 20 years [20].

Electric generation from wind power was developed in the late 1800's but did not receive significant attention until the 1970's due to the 1973 Oil Crisis [18]. During this time, the United States government began to research large commercial wind turbines. In 1980, the world's first windfarm was constructed on Crotched Mountain in New Hampshire. The farm consisted of twenty 30 kW turbines [21]. Unfortunately, the developers overestimated the wind resource and the project was ultimately a failure [19].

2.2 Rooftop Shape and Urban Wind flow

Utility scale windfarms are usually located in regions that are generally flat and have fast and consistent wind. Estimating the wind potential for a region with flat surfaces is easy and reliable because the wind faces no obstructions. Buildings increase the surface roughness, which slows down wind speeds and creates turbulence [22].They can also cast wind shadows, which block the wind from reaching certain areas that might otherwise be suitable locations for a turbine [23]. These factors make wind resource estimation challenging.

Computational fluid dynamics (CFD) simulations have been used to model the wind flow through urban environments. These models track how wind interacts with buildings, including where it goes after encountering a structure and how fast it moves. Wind is generally slower in urban environments – however, CFD reveals locations that are suitable for wind turbines. Models show that there is an acceleration effect when wind encounters a building and passes around it [8]. Height plays an important part in the effectiveness of a turbine because more consistent wind can be found at higher elevations [24]. As a result, rooftop turbines are most suited for buildings three stories tall or more, or at least 20 feet high [25]. An analysis of roof shape found that curved roofs generate the highest concentrations of high velocity wind due to the acceleration effect and are the most suited for turbines [8].

2.3 What are turbines and how do they work?

Wind turbines are similar to windmills, but they capture wind energy and convert it into electricity. Turbines types can be divided into two broad categories based on the orientation of the central axis: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). While both types have strengths and weaknesses HAWTs have received most of the funding for research and development and account for all utility scale projects because they offer the greatest efficiencies under consistent wind and do not suffer from the backtracking effect [26], which occurs when a blade rotates in the same direction as the wind and must travel into the wind before being pushed back around.

Turbines can operate on a combination of the two aerodynamic principles: lift or drag, which removes kinetic energy from the wind by spinning the turbine blades. Lift is a force that that moves in a direction perpendicular to the direction of wind [27]. This is the same force that keeps an airplane aloft while moving through the air. Drag is a force that operates in the same direction as the wind and is less efficient. The rotating turbine then powers an electric generator, which produces electricity. The amount of energy in the wind is given by equation 1.

$$Power = \frac{1}{2}\rho A v^3 \quad (1)$$

Where ρ is the density of the air, A is the area covered by the wind turbine and *v* is the velocity of the wind. The available power in the wind is highly dependent on its speed, which is why turbines are erected in areas with lots of wind. Unfortunately, the amount of power that can be generated from the wind is even less due to mechanical inefficiencies like friction. The Power coefficient (C_p) represents the turbine's efficiency and signifies the percentage of the wind's energy that a turbine can extract. In 1919, German physicist Albert Betz determined that the theoretical maximum efficiency a turbine could achieve is 59.3% [10]. The power a turbine can extract from the wind is given in equation 2.

$$Power = \frac{1}{2}\rho A v^3 C_p \quad (2)$$

The three most common types of wind turbine are the modern HAWT, the Savonious VAWT, and the Giromill/Darrieus VAWT [15]. The modern HAWT and the Darrieus VAWT operate on the force of lift while the Savonious VAWT uses drag. Generally the Savonious VAWT is the least efficient and the HAWT is the most efficient.

2.4 HAWTs

Horizontal axis wind turbines have blades that rotate on an axis that is horizontal and are parallel to the ground. The axis faces into the wind and the blades use aerodynamic lift to spin perpendicular to the direction of wind flow. HAWTs can have any number of blades, however an odd numbers of blades are preferred because they offer the optimal balance of energy efficiency and structural stability. Adding blades to a large turbine increases its cost and reduces the time each blade has before it encounters its wake; therefore, using the least number of blades is optimal. Turbines with an even number of blades cause significant stress on the structure holding the turbine because at the point when the blades are vertical the top is receiving the greatest amount of wind due to elevation and the bottom is receiving the least because it must cross in front of the pole or tower holding it up. This unequal distribution of force can wear away at the machine and eventually compromise it. Three-bladed turbines are the most prominently used because they have both an odd number and a small number of blades [28].

Because HAWTs generate energy through the full rotation of their blades due to their perpendicular motion, they are the most efficient type of turbine. However, one downside of HAWTS is that the blades must always face into the wind, which requires them to constantly change their direction for maximum efficiency. Smaller systems can utilize a weather vane-like tail to point the turbine in the correct direction. Larger systems require complex mechanical yawing systems which are costly and require maintenance [15]. HAWTs excel in locations with low turbulence and consistent wind so they do not have to change their direction as frequently.

2.5 VAWTs

Vertical axis wind turbines have blades that are perpendicular to the ground and rotate around an axis that is vertical. Vertical turbines use lift, drag, or a mixture of the two. The first known windmills were VAWTS. However, at some point in time horizontal mills appeared and became the norm. Brothers believe that this decision was random chance and that one technology is not inherently better than the other [29]. Because of this switch vertical axis turbines have remained on the fringe of development, while HAWTs received most of the attention. VAWTs tend not to be as efficient due to backtracking because their blades move in the same direction as the wind [27]. On every rotation a blade makes it must travel back into the wind before being pushed back around [27].

VAWTs have several advantages that make them ideal for an urban environment. Unlike HAWTs, which must face the direction of the wind, a VAWT is omnidirectional and can use wind coming from any direction [6][15]. The gearbox and other equipment can be located closer to the ground due to the turbine's vertical orientation, which reduces maintenance costs, whereas a HAWT must house all the mechanics at the top. Finally, VAWTs can generally start to produce power at lower wind speeds, which is ideal for the urban environment where wind is slower and more turbulent.

3 Methods

3.1 Literature

A database search of Google Scholar and GreenFILE was conducted to gather relevant literature. Many search terms were used, including "urban wind power," "small wind turbines," "urban wind flow," "turbine comparisons," "vertical wind turbine," and "horizontal wind turbine." An effort was made to locate articles written within the past 10 years to incorporate the most up-to-date information. Library resources were utilized to track down government documents. Sources cited within found literature were tracked down and catalogued. The documents were organized into a resources folder with subfolders titled "Vertical vs. Horizontal Turbines," "Urban Wind Flow," and "Case Studies." Articles were sourced from various journals including: "Renewable Energy," "Applied Energy," "Renewable and Sustainable Energy Reviews."

3.2 MicroGrid and Turbines

Clark University is home to a microgrid project led by Professor Charles Agosta. This system was leveraged to gather data on different kinds of wind turbines. A student-made vertical wind turbine was recently mounted on the roof of the Sackler Science Center. This was used as our VAWT test subject. This machine has a rated output of 120 Watts (W) and costs about $400 to create. It is a Savonius style wind turbine. Savonius turbines have a simple construction and rely on drag to rotate. The VAWT covers a swept area of 1.1 m^2 and has 3 blades. The horizontal turbine was purchased for this study and to further the capacity of the microgrid. It cost $285 for the machine and $200 to design and build a mounting system. Its rated output is 300W and it has a swept area of 1.3 m^2 with 5 blades.

The turbines were placed on opposite ends of the roof to avoid interference. The VAWT is x meters above the roof and the HAWT is x meters. The turbines were positioned as high as possible to reach the faster winds at higher elevations.

3.3 Measuring equipment

A maximum power point tracker (MPPT) charge controller helps the turbines produce as much power as possible by constantly altering the electrical load seen by the turbine until it finds the best combination of variables.

To calculate the generated power, the wires from the turbines pass through a Hall effect current monitor which, along with a voltage measurement allow the product to be calculated in Labview. This value is then stored in an SQL database. Measurements of generated power were taken every one or two minutes. Wind speed was measured with an anemometer located near the turbines. Measurements of wind speed were taken every minute.

3.4 Analysis

The wind speed and power data was exported into an Excel spreadsheet for manipulation and analysis. Before analysis could be performed, the two data sets had to be put on the same time scale to account for the intermittent power measurements. An IF statement was used to sort the times and a VLOOKUP function was used to realign the measurements with their timestamps. Figures were generated to display power output, energy generation, efficiency, and wind frequency.

3.5 Calibration and Energy assumptions

The present power measuring sensors have a zero shift calibration error and thus the power data needed to be recalibrated for Excel. This calibration error means that the sensors treat a value other than 0 as 0. The sensors measuring the HAWT recorded power outputs of about 2.5W when the turbine was not producing anything. The VAWT was zeroed at about -0.31. Before analysis could be performed the data was recalibrated in Excel by subtracting 2.5 watts from each data point from the HAWT and adding 0.31 to data from the VAWT.

To estimate the amount of energy being produced by the turbines, the assumption had to be made that the wind blew at a consistent speed for a minute after it was recorded. This allowed the power data in watts to be converted into a quantity of energy in watt-hours (Wh) as given by equation 3 and 4.

$$Energy = Power\ x\ Time \tag{3}$$

$$Energy\ (Wh) = Power(W)\ x\ \frac{60\ seconds\ of\ consistent\ wind}{3600\ seconds\ per\ hour} \tag{4}$$

This method produces an overestimation of the energy produced because it is unlikely that the wind will remain constant for an entire minute.

4 Results

Day	HAWT Energy (Wh)	VAWT Energy (Wh)	Total Energy (Wh)
Jan			
27-Jan	122.34	65.81	188.15
28-Jan	53.85	35.53	89.37
29-Jan	4.41	6.03	10.44
30-Jan	2.33	9.48	11.80
31-Jan	4.94	3.74	8.69
Feb			
1-Feb	17.38	14.51	31.89
2-Feb	35.17	24.89	60.06
3-Feb	3.04	8.06	11.09
4-Feb	23.14	19.26	42.40
5-Feb	25.79	24.89	50.68
6-Feb	125.67	78.31	203.99
7-Feb	2.70	2.66	5.37
8-Feb	13.99	11.70	25.69
9-Feb	103.30	61.51	164.81
10-Feb	37.28	22.19	59.48
11-Feb	6.12	0.26	6.38
12-Feb	0.76	0.89	1.66
13-Feb	257.68	146.43	404.10
14-Feb	0.00	2.18	2.18
15-Feb	0.00	1.14	1.14
Grand Total	**839.88**	**539.47**	**1379.36**

Table 1 Daily energy generation in Watt-hours

Data collection for this project is ongoing and commenced on January 27th, 2017. 18 days-worth of data was extracted to run the following analyses. During this period the turbines produced a total of 1,379.36 Wh of electricity. These calculations represent an estimation of the energy produced because power is a rate, not a quantity. Each data point was multiplied by 60 seconds to represent the energy produced if the turbine generated the same amount of power for the minute between measurements as shown in equation 4. The day-by-day breakdown can be seen in Table 1. Although this represents a combined daily average of 69 Wh, it is apparent that some days produce nearly nothing while others are very productive. The HAWT had a daily production range of 257.68 Wh to 0.00 Wh. The VAWT's range was 146.43 Wh to 0.26 Wh.

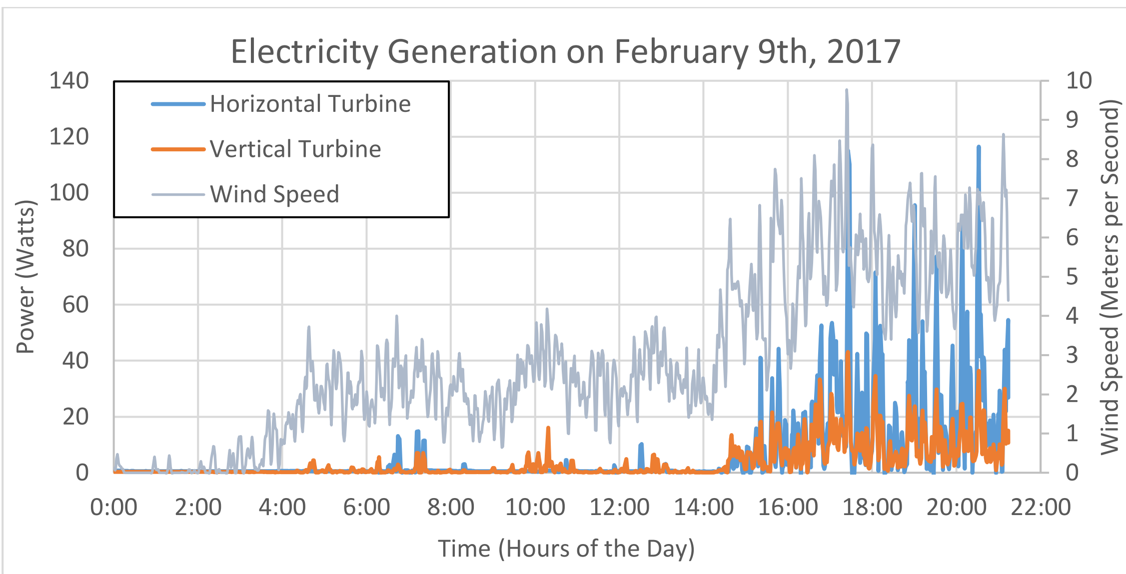

Figure 1: Power generation curves over the course of February 9, 2017

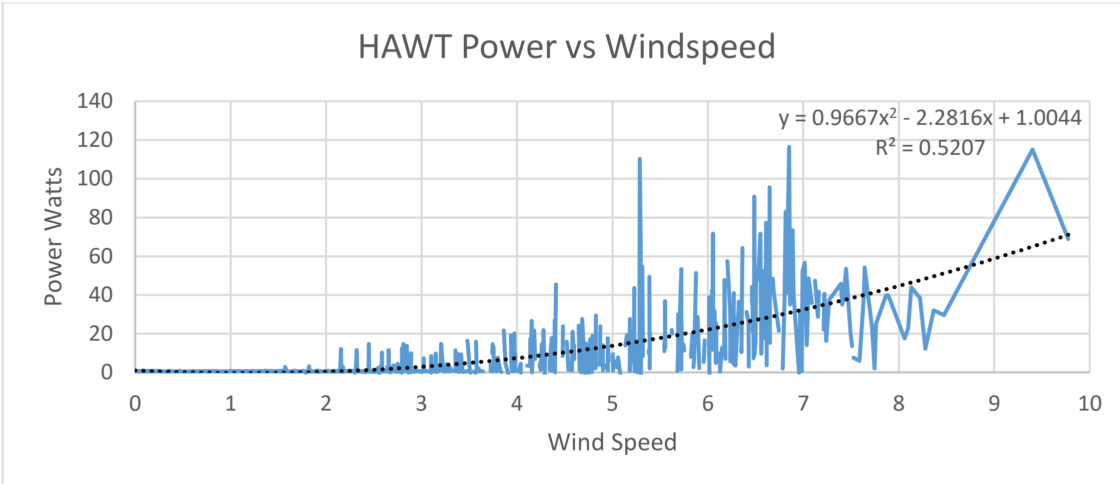

Figure 2: Power curve for the horizontal axis wind turbine. The R^2 value is 0.5207.

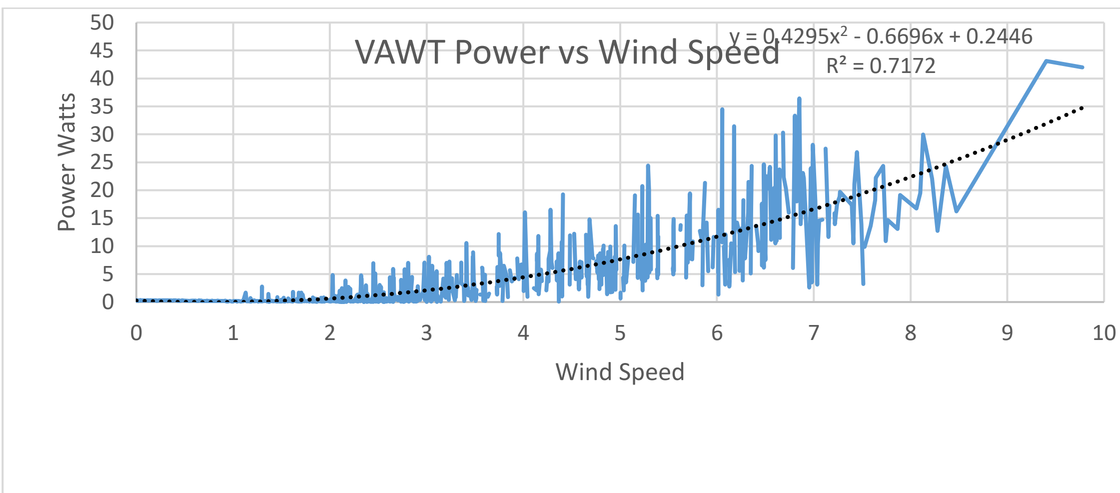

Figure 3: Power curve for the vertical axis wind turbine. The R^2 value is 0.7172.

Figure 1 depicts power generation for the two turbines over the course of a day on February 9th, 2017. Both turbines closely follow the changes in wind speed. The HAWT generated more energy than the VAWT at nearly every wind speed. This can also be seen in the power curves for the two turbines, where power production is measured at varying wind speeds (Figure 2 and 3). The R^2 value for the HAWT is 0.52. The VAWT's R^2 value is 0.72. Figure 4 and Figure 5 represent the amount of available energy available in the wind at certain speeds and the amount of energy produced by the turbines.

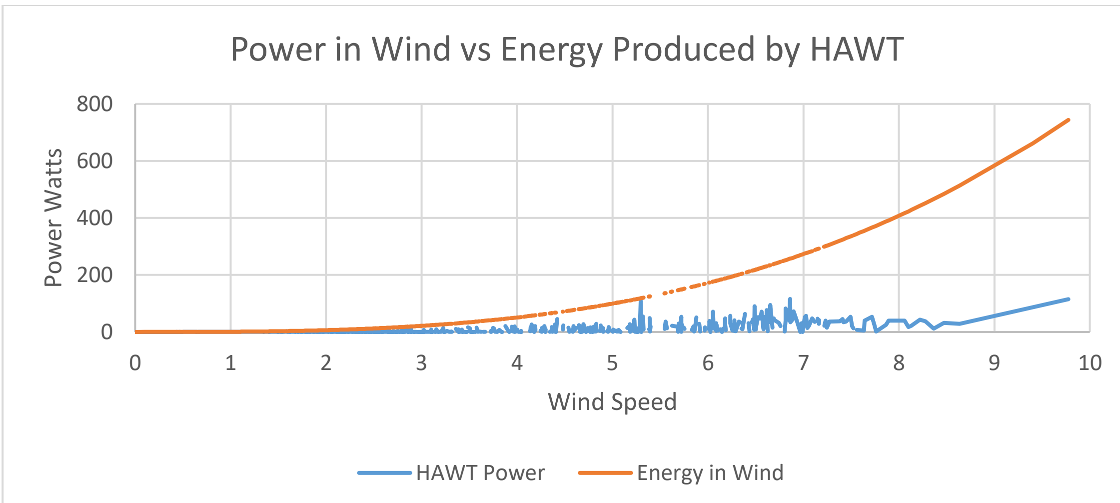

Figure 4: Available power in the wind and actual power output. The orange line represents the power available in the wind and the blue line represents the power the horizontal axis turbine was producing at that speed

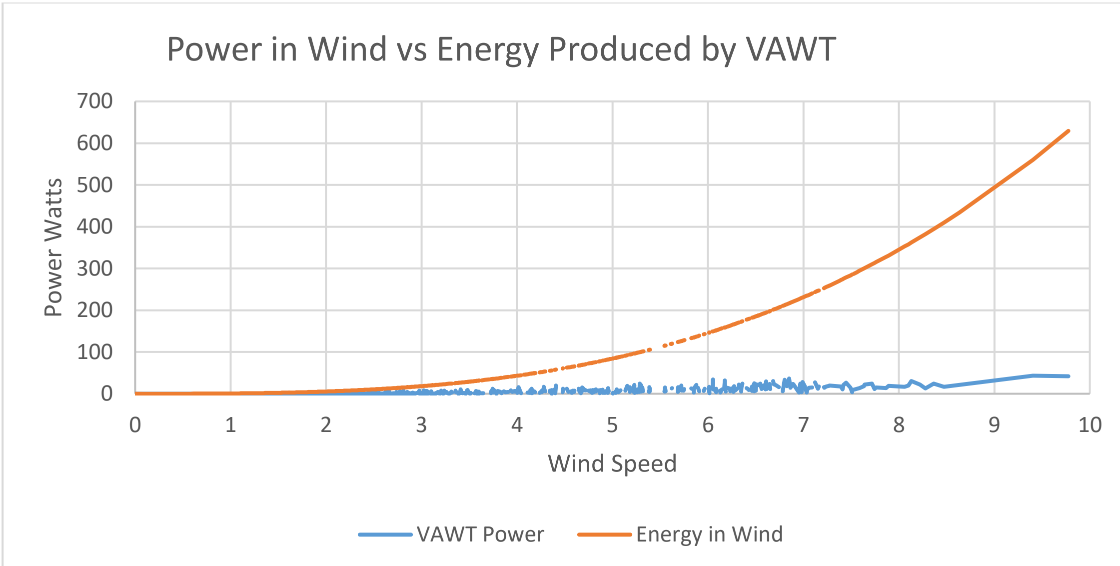

Figure 5: Available power in the wind and actual power output. The orange line represents the power available in the wind and the blue line represents the power the vertical axis turbine was producing at that speed

Dividing the energy in the wind at a given speed, as shown in equation 1, by the energy produced by a turbine, results in the machines' efficiencies. Table 2 shows the C_p values for each turbine at wind speeds from 1 m/s to 15 m/s. The average C_p value for the HAWT was 0.07 and the value for the VAWT was 0.06. The HAWT's maximum C_p was 0.14 at 4 m/s. The VAWTs maximum C_p was 0.11 at 3 m/s.

A histogram was created of the wind data to show the frequency with which the local environment received winds at different speeds (Figure 6). The histogram shows that most of the wind seen by the turbines has a velocity between 2 and 3 m/s, with an average speed of 2.9 m/s. Winds between 5 and 6 m/s account for 20% of the wind on the roof.

Wind Speed	HAWT C_p	VAWT C_p
1	-0.38	0.01
2	0.05	0.11
3	0.13	0.11
4	0.14	0.10
5	0.13	0.09
6	0.13	0.08
7	0.12	0.07
8	0.11	0.06
9	0.10	0.06
10	0.09	0.05
11	0.09	0.05
12	0.08	0.05
13	0.08	0.04
14	0.07	0.04
15	0.07	0.04
Average	0.07	0.06

Table 2: Maximum power coefficients at each wind speed from 1-15 m/s

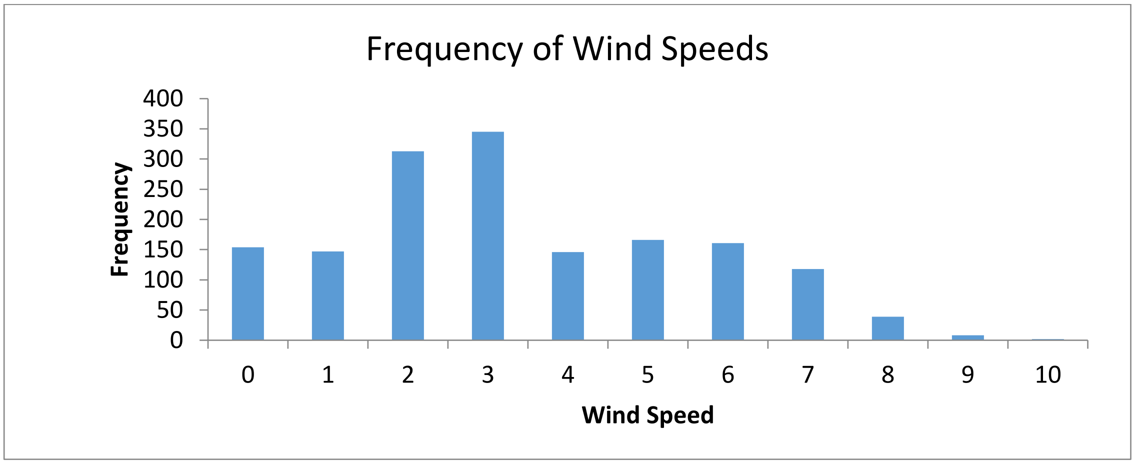

Figure 6: Chart showing the minutes that the wind was traveling at each speed.

5 Discussion

This research uses a case study at Clark University, Worcester, Massachusetts to examine the capabilities of a horizontal axis wind turbine and a vertical axis wind turbine to generate power. It also compares their functionality in the urban environment. Most of the roofs on Clark University's campus, and the roof that houses the study turbines, are flat. CDF studies show that curved roofs and buildings above 20 feet are beneficial for wind generation [25]. While all roof shapes have been shown to create wind acceleration effects, curved roofs are optimal because they demonstrate the greatest acceleration effect and the least amount of turbulence generation [8]. The height ensures that the turbines reach more reliable wind, which becomes more consistent with elevation. Even though a flat roof creates wind acceleration, it also generates the greatest amount of turbulence [8]. Therefore, the turbines used in the microgrid project are at a disadvantage in this respect, which may have skewed the data.

The study location had a roof height of 36 ft. The HAWT and VAWT study subjects were installed at a height of 23 ft. and 16 ft. above the roof respectively, which greater than 30% of the building's height. The 7 ft. difference in height between the two turbines could explain some of the differences seen in power output. To mitigate the effect of turbulence, turbines should be placed at a position that is 30% of the building's height above the roof, where the acceleration effect is the strongest and the turbulence effect diminishes [8]. Clark University's Sackler Science Center is a 3-story building that falls within Hsien et al.'s height criteria for a beneficial location. Unfortunately, Clark's two tallest buildings block the study area and reduce the amount of wind it receives. Even though the parameters outlined by the literature were followed as closely as possible the wind resource is not ideal. However, the goal of this study was to examine the two kinds of turbines and determine their efficiency. From this, their effectiveness at greater heights can be extrapolated.

The VAWT was installed in 2015 as the culmination of a past student's project. The HAWT was installed on December 2, 2016. Data collection began on January 27, 2017. On the evening of February 13, the HAWT malfunctioned and had to be lowered for maintenance. The data analyzed in this research was from January 27 to February 13 when the HAWT malfunctioned. Wind data was extracted for the day of February 9, when both of the turbines had a moderate output. The small size of these data sets is not ideal for analysis. However, correlations could be made between wind speed and power output which could then be applied to wind data taken in the future at different locations.

The results of the analysis on energy generation in Table 1 were expected. The HAWT outperformed the VAWT for 77% of the study days and generated 55% more energy. This was expected because HAWT's are not affected by backtracking and are therefore more efficient. On top of this, the HAWT is rated at 300W and the VAWT rated at 120W. The HAWT is simply a stronger machine so its raw output is expected to be greater.

Interestingly, the VAWT did outperform the HAWT on four days, not excluding days after February 13th. This could be explained by the VAWT's cut-in speed, which is a specification that represents the slowest wind speed at which a turbine can generate electricity. Literature shows that VAWTs typically have a lower cut-in speeds than HAWTs. This means that a VAWT can operate when the wind is too slow for a HAWT. The four days where the VAWT outperformed the HAWT are days when the combined energy generation was less than 12 Wh, indicating low wind speeds. This is not conclusive, because the data suffered from zero-calibration errors which made the values at slow wind speeds unreliable.

The two study turbines are difficult to compare because the HAWT has a maximum rated output that is 2.5 times greater than the VAWT, so it will outperform the VAWT at nearly every wind speed. The literature often reports that an advantage of a VAWT is that it is more efficient at operating in turbulent and omnidirectional winds [6][15]. Statistical analysis of turbines' power curves show that the VAWT did better at tracking variations in the wind. The power curves in Figures 2 and 3 show the power each turbine generated at different wind speeds. A theoretical power curve for a turbine is a smooth exponential line. The experimental power curves demonstrate a significant amount of variability. This variability may be the result of sporadic gusts of wind, imperfect timing of measurements between wind speed and power, or directional changes in the wind.

The directionality of the wind plays a large part in the efficiencies of the turbines. While the HAWT produces more power than the VAWT, a polynomial regression shows that the VAWT has an R^2 value of 0.72 which is 0.2 higher than the HAWT's. This indicates that the VAWT more closely responds to changes in the wind. This is likely because of the VAWT's omnidirectional capabilities and demonstrates that the turbine is more efficient in environments that are more turbulent. A visual analysis of the power curves also demonstrates the performance in highly variable winds. The HAWT's power consistently drops to 0, even at wind speeds that should sustain it, whereas the VAWT rarely stops. The difference in power generation occurs, not because the HAWT is more efficient, but because it has a higher rated maximum output. These results show that, theoretically, a VAWT with a comparable rated output would produce more power in the urban environment than a HAWT due to its omni-directional capabilities and slower cut-in speeds.

This case study also demonstrates advantages of the VAWT aside from energy efficiency. Observational analysis also revealed that the VAWT was less noisy. The HAWT's noise of operation was detectable when standing on the ground outside of Sackler Science center, whereas the VAWT was inaudible. Noise is an important factor when considering urban wind power because it can be distracting to the public. Noise is not as much of a consideration for large commercial turbines because they are often located far away from observers and do not cause any disruptions.

Maintenance is another important factor when considering the overall cost of a wind system. The VAWT has been installed on the roof for three years at the time of this study and has never had any problems. The HAWT has been installed for almost three months since December, 2016 and has malfunctioned twice. The first incident involved storm-like conditions which overwhelmed the turbine and knocked the hub and blades off, requiring the purchase of a new set of blades. The second incident was internal - a magnet slipped out of its holding within the turbine and caused it to jam. Fortunately, Clark had the capacity to open the device and fix the problem, but most consumers would not have this option and would need to purchase a new machine. The VAWT has proven to be more durable.

5.1 Limitations

This research was limited in that the equipment was purchased on a budget and demonstrated inefficiencies and that only a small amount of data could be extracted given the time scale. Data analysis was challenging due to zero-calibration errors, especially when analyzing turbine performance at low wind speeds where the measurements were most likely to be inaccurate. The turbines did not have a comparable rated output so the performance of more powerful machines had to be extrapolated based on the performance seen by the study turbines. These calculations were performed on data taken over the course of 18 days. This small amount of data is not ideal for making conclusions and further analysis should be performed as more data comes in.

6 Conclusion

Wind has been utilized by humans for thousands of years. Recently, the concept of urban wind generation has received more attention due to the use of computational fluid dynamic models and innovative turbine designs. The traditional horizontal axis wind turbine, which has dominated the wind industry since it appeared during the Middle Ages, is being challenged by vertical axis wind turbines' utility in the urban environment. This study analyzed power data for both a HAWT and a VAWT installed at Clark University and compared their performance through an analysis of raw energy generation, efficiency (C_p), ability to track the wind, and observation.

In terms of raw energy generation, the HAWT proved to be best. The HAWT was capable of producing more energy because it had a rated output 2.5x greater than the VAWT. However, this is not a feasible form of analysis because the two turbines were not comparable in this regard. The VAWT outperformed the HAWT on several low-wind days which is consistent with observations that VAWTs have lower cut-in values. Unfortunately, the power produced on these days was almost negligible.

Better comparisons can be made based on efficiency because it takes into account the strength of the turbine. The average C_p values were very similar. The HAWT only had an average C_p value that was 0.01 higher than the VAWT (Table 2). The VAWTs R^2 value demonstrated its ability to track variations in the wind including changing wind direction and sudden alterations in wind speed (Figures 2 and 3). The HAWT had more difficulties responding to the turbulent and sporadic wind patterns of the urban environment. In this environment, the HAWT struggled to perform at its peak while the VAWT flourished. A VAWT with a comparable rated output would most likely outperform the HAWT because of its ability to handle turbulent and omni-directional wind.

The power curves and efficiency tables for the two study turbines can be merged with wind data from different locations to predict the performance the turbines would have. The two study turbines are currently on a roof overshadowed by Clark University's tallest buildings. Wind data is currently being gathered on top of these buildings, where the wind is more likely to be stronger and more consistent based on the elevation. There will also be no wind shadowing effect to disturb data collection. The current location of the turbines does not allow them to contribute to the microgrid system in a significant way other than for research purposes. Further analysis is required to predict the performance on the tallest buildings. This work will aid future research by providing the power curves for Clark's turbines.

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