Performance Evaluation of a 700 Watt Vertical Axis Wind Turbine

TECHNICAL BRIEF

Renewable Energy Series

Vertical axis wind turbines (VAWTs) have blades that rotate using either aerodynamic lift or drag force. Lift-based VAWTs are capable of the high speed rotation necessary for electricity generation; however, this style of turbine is not self-starting. Conversely, drag-based turbines are high-torque, self-starting devices, but they are not practical for electricity generation due to their lower rotational speed. The 700 W VAWT presented in this study combines both lift- and drag-based blades/rotors with a design objective of using the advantages of both blade types to mitigate the flaws associated with each on their own.

Canada's current wind turbine installed capacity is over 10,000 MW, which is enough to meet the energy requirements of over 2 million homes. The 3,500 MW of generated wind energy in Ontario supply over 3.5 % of the province's electricity demand and contributed to the elimination of coal as a source of electricity (CanWEA, 2015).

This study assesses the performance of a small-scale grid-tied wind turbine, at Toronto and Region Conservation Authority's Living City Campus wind field test site in Vaughan, Ontario. The selected wind turbine for the study is a 700 W vertical axis turbine installed at a height of 18.3 m. Due to time constraints, the study took place between May and July, 2015, which typically experience the lowest average wind speeds of the year at this study location. Three turbine power curves were generated for each monitored month to help assess the turbine's performance over differing wind speed regimes. At the end of this testing period, it was determined that this particular turbine-grid-tie system resulted in overall net energy consumption, primarily due to the power draw of the grid-tie control cabinet. It should be noted that net energy consumption is a feature of this particular system and not representative of wind turbines in general. Further monitoring through the winter months of the year is required to fully assess the performance of this grid-tied 700 W vertical axis wind turbine in a Southern Ontario climate.

INTRODUCTION

Over the last decade Canadian wind energy production has seen continuous growth. In June of 2015, Canada's total installed wind turbine capacity reached 10,204 MW, meeting 4% of the nation's energy needs (CanWEA, 2015). Ontario is currently the leading province in wind energy production, being home to four of the top five largest wind farm facilities in the country (NRCan, 2014). The Canadian Wind Energy Association (CanWEA) has set a goal to continue to promote this growth and meet 20% of Canada's energy needs through wind power generation by the year 2025. Increasing the number of wind farms supplying to the grid improves the reliability of wind power, as drastic spikes or plummets in energy production are mitigated by the aggregation of more and more generation sources (IEEE, 2009).

Individual wind turbines can vary widely in their production capacity, generating anywhere from a few hundred watts to megawatts, with large-scale wind farms producing power on the scale of hundreds of megawatts. At the other end of the capacity spectrum lies small-scale wind, which is the subject of increasing interest for distributed generation. CanWEA offers guidelines defining small-scale wind, and generally recommends the use of turbines smaller than 10 kW for residential grid-tied applications. They also advise the use of those less than 5 kW as better suited for battery charging and off-grid generation.

The current wind market is dominated by horizontal axis wind turbines (HAWT). Although their design is widely accepted, alternative designs exist that may offer some advantages. The alternative design is the vertical axis wind turbine (VAWT). These turbines are capable of harnessing the wind from any direction without the need for a yaw mechanism, which is necessary for HAWT designs. This study evaluates the performance of a 700 W VAWT over the course of three spring/summer months. The objective was to assess the suitability of this specific turbine in an urban or semi-urban environment.

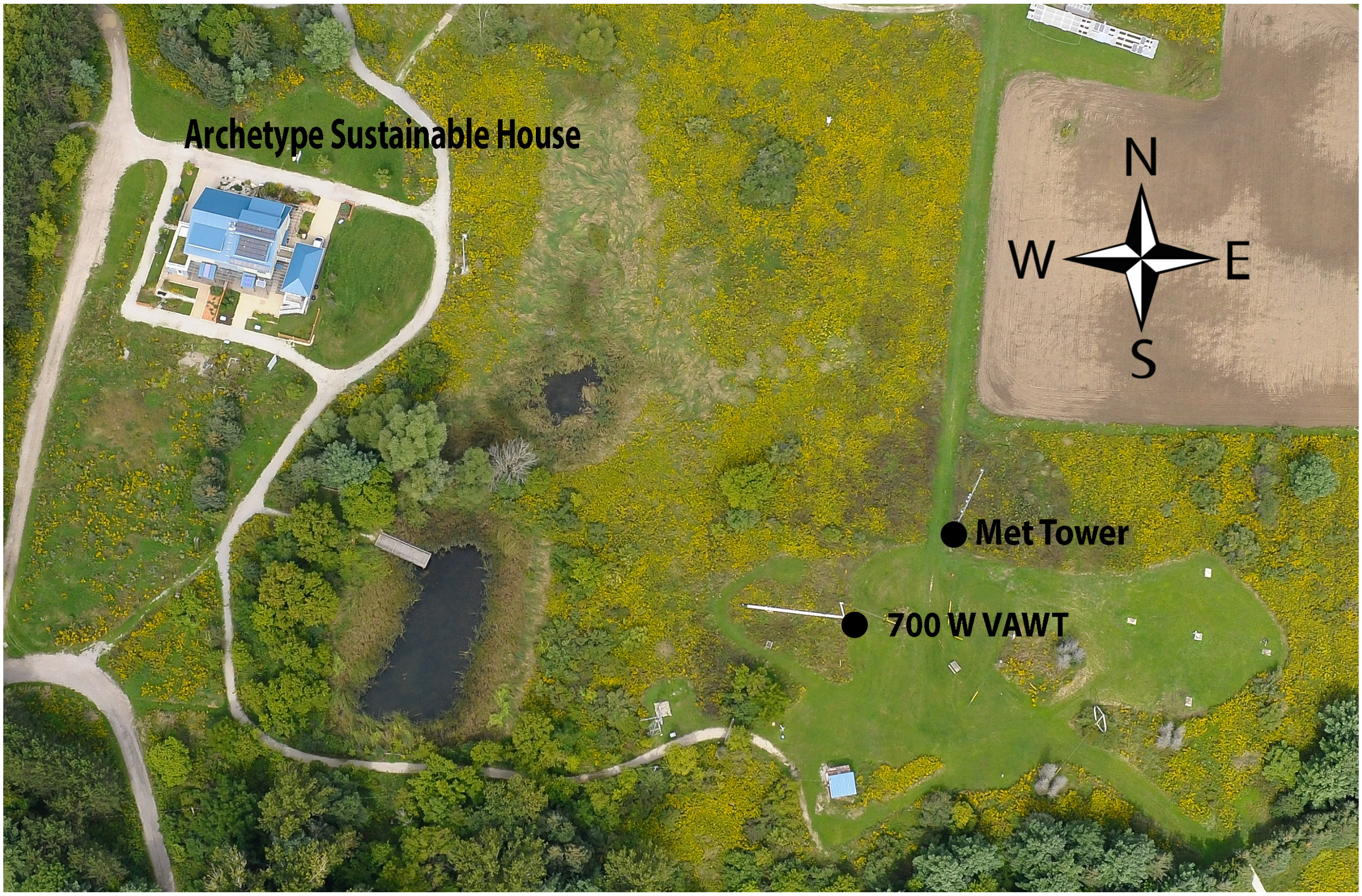

Figure 1. Turbine and meteorological (met) tower positioning at the Kortright Centre for Conservation, Vaughan, ON.

STUDY SITE

The study was conducted at the Toronto and Region Conservation Authority's small-scale wind turbine and photovoltaic test site at The Living City Campus at Kortright in Vaughan, Ontario. The test site is located approximately 30 km north of Lake Ontario, within a 4 hectare grassy field surrounded by mature trees, and 188 m above sea level. The test field is situated 325 meters southeast of the semi-detached Archetype Sustainable House. As nearby objects obstruct wind regimes, this test site provides insight into the operation of wind turbines in non-idealized environments such as residential and urban settings. This testing facility experiences wind regimes dominated by southeast and northwesterly winds. Vaughan experiences average spring and summer temperatures between 15 to 25°C, with average winter temperatures just below freezing. Figure 1 shows the location of the turbine and its proximity to the nearby meteorological tower and Archetype Sustainable House.

APPROACH

Turbine Specifications

In a conventional HAWT design, the axis of rotation is parallel to the ground and the rotors are driven by lift forces. These turbines must orient themselves into the wind for maximum performance using a yaw mechanism. This increases complexity but it has the advantage that the rotor blades can be turned out of the wind for overspeed control.

The rotational axis of VAWTs is perpendicular to the ground and this means that they can harness the wind from any direction without the need of a yaw mechanism. However, VAWTs still require overspeed control and, since the rotor cannot be turned out of the wind, other methods must be used.

VAWTs come in various designs but generally fall into two categories - units with an airfoil or lift rotor similar to those used on HAWTs. The most common example of this is the Darrieus design, with blades that resemble an egg beater. The other style of a VAWT incorporates a drag scoop like a cup anemometer. An improved variant of a drag design is the Savonius S-type rotor which has slightly higher capture efficiency.

Turbines incorporating a lift style rotor design have a theoretical maximum coefficient of performance of 0.59 (Betz limit of 59%) and perform well for electrical generation as they can achieve the higher rotational speeds that are required.

VAWTs that incorporate a drag or Savonius S-type rotor produce higher torque useful for mechanical applications like pumping water but lack the speed suitable for electrical generation. Their conversion efficiency is on the scale of 15%.

Table 1. 700 W VAWT technical specifications.

General Dimension	
Rotor Diameter	1930 m
Height	1547 m
Weight	52 kg
Blades	
External Darrieus	3 Blades
Internal Savonius	2 Layers
Blade Material	Anodized Aluminum
Operation Mode	
Cut-In Wind Speed	< 3 m/s
Cut-Out Wind Speed	15 m/s
Survival Wind Speed	60 m/s
Safety Mechanism	
Overspeed Braking	Yes. (Setup by Power Controller)
Generator	
Type	AC, Direct Drive, Weather Sealed, 3-Phase Synchronism PMG.
Rated Output	700 W at 12 m/s

Turbine Configuration

The 700 W VAWT used in this study consists of three airfoil Darrieus blades surrounding an S-type Savonius rotor. Table 1 summarizes the turbine's technical specifications. Turbines by this manufacturer are not commonly deployed in Canada, and the VAWT design is also not typical to Canadian installations. The turbine was mounted at a height of 18.3 m (60 ft) from the ground, and was located 26 m southwest of the 30 m tall meteorological tower. The meteorological tower was equipped with eight anemometers and two wind vanes at different heights along the tower, with one anemometer mounted at a height of 18.3 m to correspond to the height of the turbine.

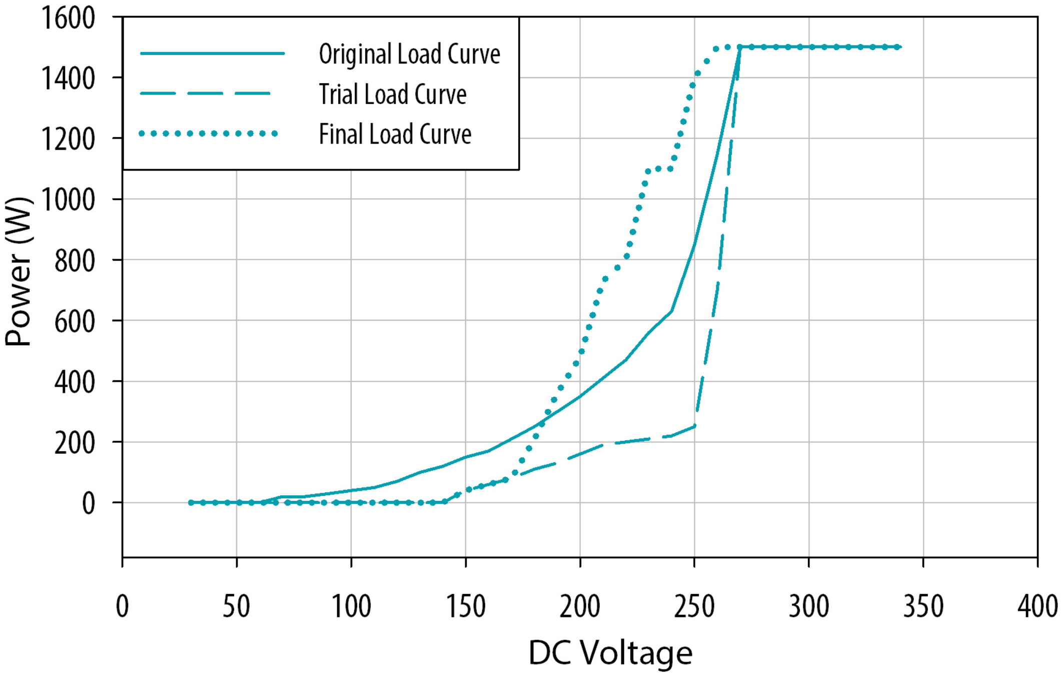

Figure 2. GCI-3K 2-in-1 inverter load curves.

The wind speed was measured using NRG Systems 40C anemometers, with accuracy of ±0.5 m/s. For the purposes of this study the effect of wind direction on the performance of the VAWT was not analyzed, as wind direction is not expected to significantly influence a turbine of this type.

The 700 W VAWT was connected to a manufacturer provided grid-tied system that consisted of a GCI-3K 2-in-1 Inverter, and a control cabinet. While the inverter was pre-programmed with the manufacturer's load curve, it was found in the field that this load curve resulted in suboptimal turbine operation. When attempting to operate the turbine with this load curve, no usable energy was produced. Troubleshooting was therefore required, which delayed data acquisition until May, 2015.

In operation with the factory supplied load curve, the turbine was unloaded until the cut-in voltage of 70 volts was reached and the controller applied a 20 watt load. It was determined that at this voltage the turbine had insufficient torque to meet the applied load and would slow the rotational speed below the cut-in voltage. This caused and on / off cycling with no power being produced even in extreme wind conditions. To correct this issue, various load curves were applied to the turbine. Figure 2 displays the original, a trial, and the final modified load curves programmed into the inverter.

Based on the fact that the turbine required sufficient torque to handle the load, curves were established that refrained from applying the load until adequate torque was achieved. Both the trial and final load curves did not apply any load until the turbine reached 150 VDC.

Throughout the load curve development it was also determined that braking for overspeed protection was also a problem. The inverter's response time was too slow to apply the load so as to ensure that the turbine remained within its operational range. At 420 RPM the turbine controller transferred the turbine output from the inverter to an electric dump load which stalled the rotor for ten minutes. The final load curve reduced the frequency of unnecessary overspeed protection but it was far from optimal.

Both the control cabinet and inverter required power to function. The control cabinet drew a constant amount of power throughout its entire operation. The inverter also drew power, although the amount was negligible if it was not applying a load.

The control cabinet was outfitted with instrumentation to measure the DC voltage and current generated by the turbine. The DC voltage from the turbine was measured utilizing a combination of a Caddock Electronics USF370-1.00M-0.01%-5ppm metal film resistor and a Vishay S102JT Foil Resistor. The Caddock and Vishay voltage dividers had resistance tolerances of ± 0.01% and ± 0.005% respectively. The current was measured using an LA-5-100 shunt from Canadian Shunt Industries, which had an accuracy of 0.25%.

All voltage, current, and wind measurements were taken by National Instruments (NI) software and equipment. Both the voltage and current were measured on two channels on an NI-cFP-AI-118, an eight channel analog voltage input module. The wind speeds were measured by an NI-cFP-AI-112, a 16 channel analog voltage input module. Both modules were connected to an NI cFP-2220 Controller. A data acquisition program was written using LabVIEW, which measured voltage and current at a sampling rate of 500 Hz, and took wind speed measurements at a rate of 1 Hz. All recorded values were averaged over 5 seconds and recorded to a database.

Data Treatment

Wind speeds recorded at the turbine hub height (18.3 m) were grouped by month and sorted into bins 0.5 m/s in width. This was used to analyze the wind speed frequency, and determine the amount of available wind for each month. The recorded wind speeds were compared to those observed in a previous study at the same test site (TRCA, 2015).

The DC voltage and current readings were used to obtain the power generated by the 700 W VAWT. The power measurements were then grouped into each predetermined wind speed bin. The mean power generated in each wind speed bin could then be determined, creating an experimentally determined power curve. Three power curves, one for each month of data, were generated in this fashion.

Testing in the field involves highly variable and turbulent winds, when compared to those generated in a wind tunnel. Due to the fluctuations in wind speed in the field, a power curve generated simply by grouping all power values in their respective wind speed bins would not truly be representative of the turbine's steady state performance at a given wind speed. To attempt to alleviate some of the error associated with testing under such variable wind speeds, power readings that occurred only during timescales in which the wind remained within its associated wind speed bin for at least ten seconds were used to generate steady-state power curves. Furthermore, those times in which it was determined that the turbine had initiated its overspeed braking procedure were identified and removed from the dataset for this analysis.

Based on the entire set of power measurements, the energy generated over the course of each month was determined. It could then be determined at which wind speeds the most energy was generated. In addition, the power draw of both the inverter and control cabinet were measured to determine the net energy produced or consumed by the entire grid-tied system each month.

FINDINGS

Wind speeds observed over the course of this testing period were relatively low, limiting the potential for a thorough analysis of power generation at varying wind speeds. The wind speed distributions and cumulative percent frequency curves for each month are shown in Figure 3. Due to project deadlines, a complete year's worth of data was not achieved. Additionally, due to networking and infrastructure maintenance, data logging did not occur over the entirety of each monitored month. Data are missing for approximately four, eight, and two days for the months of May, June, and July, respectively. Table 2 shows the average monthly wind speeds over the course of the 2015 test period, and from a previous study conducted at the same site in 2013 (TRCA, 2015).

The wind speeds observed during these months are among the lowest observed on an annual basis. Very few wind speeds of interest, including those at the rated wind speed of the turbine, were observed over the course of this testing period. It was found that 76% of the time the wind speeds were below the rated cut-in speed (3 m/s) of the turbine, and were therefore not useful for power generation. This location experiences its highest wind speeds through the winter months, and it is recommended that data monitoring continue to capture those conditions.

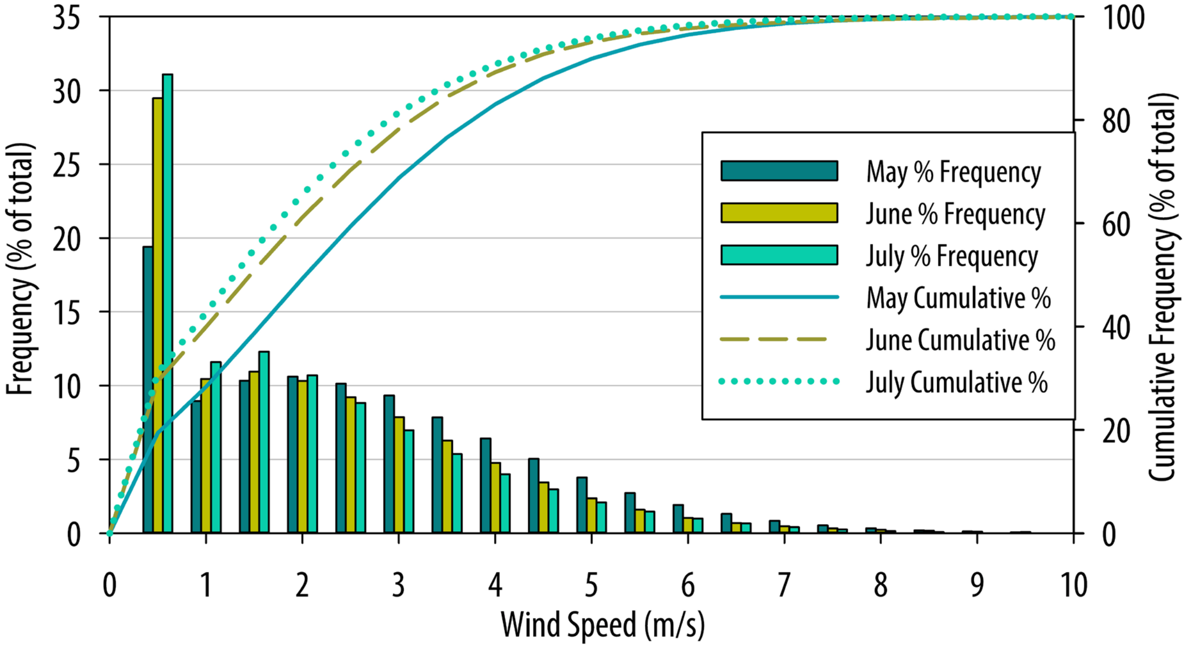

Figure 3. Hub height wind profiles and cumulative distributions.

Table 2. Comparison of mean monthly wind speeds between 2013 and 2015.

Month	2015 Average Wind Speed (m/s)	2013 Average Wind Speed (m/s)
May	2.56	2.92
June	2.09	1.99
July	1.95	1.34

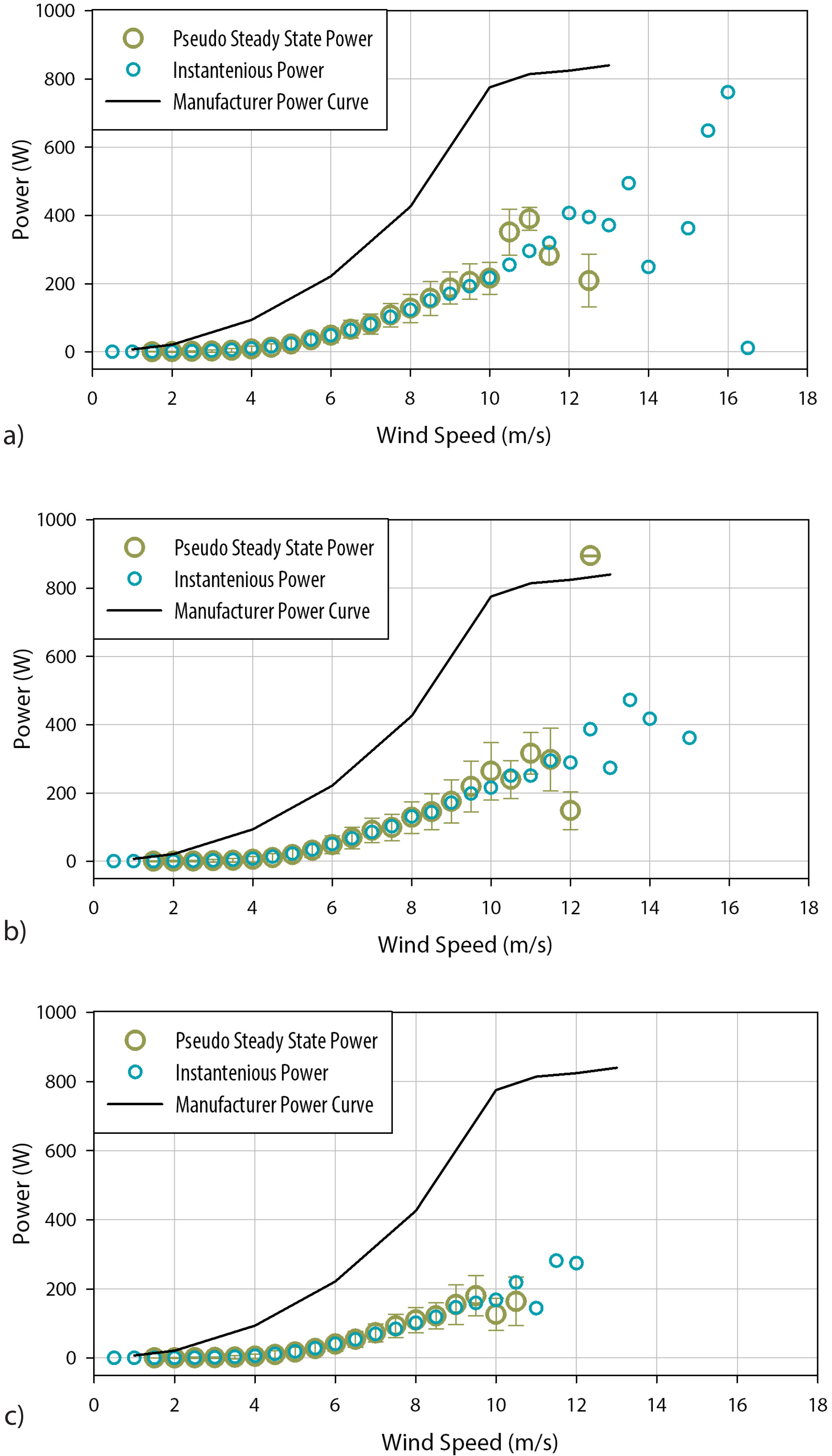

Figure 4. Manufacturer power curve, instantaneous power and pseudo steady-state power for a) May, b) June and c) July.

The 700 W VAWT underperformed its manufacturer rating. Figure 4 displays the power curves representing the performance of the turbine throughout each month. The blue points represent data generated by using all instantaneous power data. The beige points represent conditions that met the steady-state restriction described previously. The solid black lines show the manufacturer's power curve provided for this turbine. Error bars accompany the steady-state points, which represent the standard deviation associated with averaging the data points. This steady-state filter reduced the standard deviation by an average of 15%, when compared to simply averaging all power data points per wind speed bin.

It is clearly visible that calculated power values at higher wind speeds become much less certain for the entire monitoring period. This is due to a lack of high wind speeds observed throughout the testing period.

It is important to note that the power curves determined through testing used a different inverter load curve than was used to determine the manufacturer power curve. As a result, the curves cannot be directly compared, as the turbine experienced

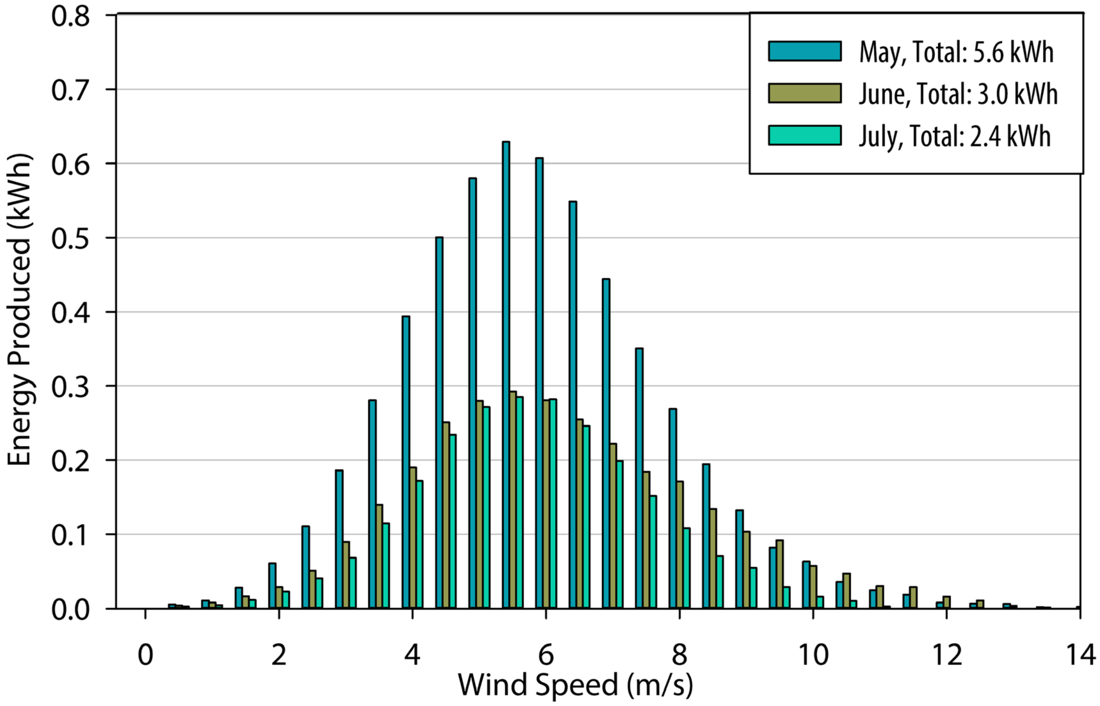

Figure 5. Monthly production of DC energy as a function of wind speed.

different loads in each case. Despite these differences, it is clear that the turbine did not perform near the level claimed by the manufacturer. A single data point exists in June that shows performance near the rated power curve. This point was however due to a single case where the wind speed was found to be within the 12.5 m/s bin for over 10 seconds. Other than this single instance, the steady-state power curve never rises above 500 W, well below the turbine's 700 W rating.

Further testing during winter months is required in order to obtain sufficient data to enable a more accurate assessment of the turbine's performance under high wind speed conditions.

The control cabinet and inverter grid-tie system consumed more energy than the turbine produced over the course of the study. Figure 5 displays monthly DC energy produced by the turbine, as measured prior to reaching the inverter. The energy is plotted against the wind speed at which it was generated. For example, in the month of May, approximately 0.5 kWh were generated at winds of 4.5 m/s. The bell-shape of the curves indicates that while mid-range wind speeds were less frequent than lower speeds (Figure 3), they enable the production of more energy.

Despite the measured power, the tare losses of the grid-tie system were found to be significantly higher than the energy generated by the turbine. Throughout the study, it was determined that the system consumed a constant 0.3 ± 0.1 A. This corresponds to losses ranging between 1.15 – 2.30 kWh/day, or around 51.8 kWh/month.

To determine whether this turbine can produce enough energy to mitigate the tare losses of the grid-tie system, its performance will have to be investigated over the winter months. CanWEA recommends that a turbine of this size is likely better suited for off-grid battery charging applications.

If this turbine was used in a battery charging application the associated tare losses of the inverter would be eliminated but the constant draw of the controller would remain. The biggest advantage of a direct battery connection for this turbine would be the elimination of most overspeed shut down events since the battery bank voltage remains relatively stable. Further study into the effectiveness of this turbine in such an application is warranted.

CONCLUSIONS

This study examined the performance of a grid-tied 700 W VAWT, a combined Darrieus-Savonius vertical axis wind turbine, over the months of May, June, and July 2015. The testing took place at The Living City Campus at Kortright in Vaughan, ON.

The initially provided inverter load curve caused the turbine to perform poorly. Troubleshooting was therefore required, as a load curve had to be developed to combat unwarranted turbine braking. This delayed the commencement of testing until May, 2015.

Wind speeds at the turbine height were recorded and grouped into bins, creating a wind profile histogram for each of the three months of testing. DC voltage and current measurements from the turbine were collected and used to determine the power produced by the turbine over the range of observed wind speeds. The study occurred during a time of year when relatively low wind speeds are typically observed, which limited the potential for wind power production. As a result, a thorough assessment of the turbine at high wind speeds could not be completed. However, these initial results clearly show that the turbine did not perform up to its manufacturer rating.

Tare losses of this particular grid-tie system were found to be greater than the amount of energy produced by the turbine over the course of this study. Although the observed wind speeds were low, these preliminary results indicate that this turbine is likely better suited for battery charging applications.

The results of this study are only relevant to this particular small-scale turbine design, and are not reflective in any way of the performance of other turbine models. Due to surrounding obstacles, wind speeds for small-scale wind generation are inherently reduced. Testing was conducted in an environment that does not experience wind speeds typical of large-scale wind power generation. Without data at higher wind speeds, comments as to how the design of the turbine itself affected performance would be premature.

Data collection will continue throughout the upcoming fall and winter months, in hopes of generating more data at higher wind speeds. Monitoring the 700 W VAWT throughout these seasons is essential in order to accurately assess the turbine's performance in a Southern Ontario climate.

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Toronto and Region Conservation for The Living City