Xcel Renewable Development Fund
Higher Education Research Project: Final Report

General Project Information

1. Project Name: Improving Vertical Axis Wind Turbine (VAWT) Performance with Placement Strategies
2. Name of Lead Organization: Minnesota State University, Mankato
3. Project Number: MSUM-2
4. Name and contact information for person completing this form: Patrick Tebbe, patrick.tebbe@mnsu.edu
5. Project Time Period: March 2017 to November 2020
6. Submission Date: February 3rd, 2021

EXECUTIVE SUMMARY

This project was focused on the use and placement of vertical axis wind turbines (VAWTs). Studies were focused on areas not typically addressed in previous work; small wind at very low elevations (i.e. within the boundary layer). Numerical studies were made of how VAWTs function as well as the potential wind environments they may be placed in. A simplified numerical code, based on two-dimensional potential flow functions, was developed to model flow around buildings and other structures. The code allows a rapid determination of regions where flow may experience speed-up and where turbulence may result.

Experimental facilities were designed and constructed that allowed scale model VAWTs to be tested in both a water channel and a low speed wind tunnel. Anemometer towers were also designed and constructed for measuring wind conditions at regional test sites. A large amount of experimental data was gathered from these facilities. The data covers performance measures of specific VAWT models, measured flow fields around VAWT models, measured wind flow fields at multiple test locations, and numerically predicted flow fields around structures (e.g. buildings and grain bins).

The project observed that the wake region behind a VAWT can extend as far as four diameters and will be offset toward the side of rotation. This will affect how VAWTs can be packed together into arrays. For Savonius designs, an increase in performance can be obtained by placing a second VAWT appropriate in this wake region. However, the same result was not seen for helical designs. Overall, final recommendations on placement could not be made. Recent industry research indicates that some VAWTs perform better when placed in areas of higher turbulence. This project was unable to verify those results. A better understanding of how VAWTs perform at different levels of turbulent intensity will be needed before final placement recommendations can be made.

A large number or outreach and dissemination activities were conducted to a range of audiences, including K-12, industry, the general public, as well as state and national political figures. Awareness of renewable energy and wind power in particular, was raised. Thirty-six students (undergraduate and graduate) participated actively in this project. The conducted research as well as interacted with public audiences in dissemination activities.

Several recommendations have been made for continuing or future work. With the experimental infrastructure developed through this project, some of these topics are already being pursued. Other topics related to energy research could also be undertaken in the future.

PROJECT DESCRIPTION

According to the Minnesota Department of Commerce, “wind is an increasingly significant source of energy in Minnesota” [1]. The majority of growth in this area has been accomplished with horizontal axis wind turbines (HAWTs), typically in large arrays or “wind farms” that produce utility scale amounts of power. However, small-scale systems have also seen large growth, 35% in 2012, with particular attractiveness for rural and agricultural areas [2]. Furthermore, the National Renewable Energy Laboratory (NREL) suggests that greater use of small wind turbines in the built environment can positively affect the public perception of wind energy [3].

An alternative to the HAWT design is the vertical axis wind turbine (VAWT). A VAWT spins around a vertical axis with the wind moving perpendicular to it. Blades can take different forms and are based on either lift or drag principles. VAWTs are not as prevalent as HAWTs and can suffer from lower efficiencies and height limitations but offer several advantageous aspects, particularly in terms of small-scale electricity production.

VAWTs range in style based on application and design (Figures 1 and 2). Savonius VAWTs are based on drag. They are frequently employed under low cost, consistent running applications. Generally, they have low efficiencies and low yields. Darrieus VAWTs are based on lift. They typically have higher yields but produce higher noise (above ambient) due to a tip speed ratio greater than 1. These turbines generally scale up well and are used from very small to very large applications. There are several variations for each of these types. A common form in recent years is the helical Darrieus.

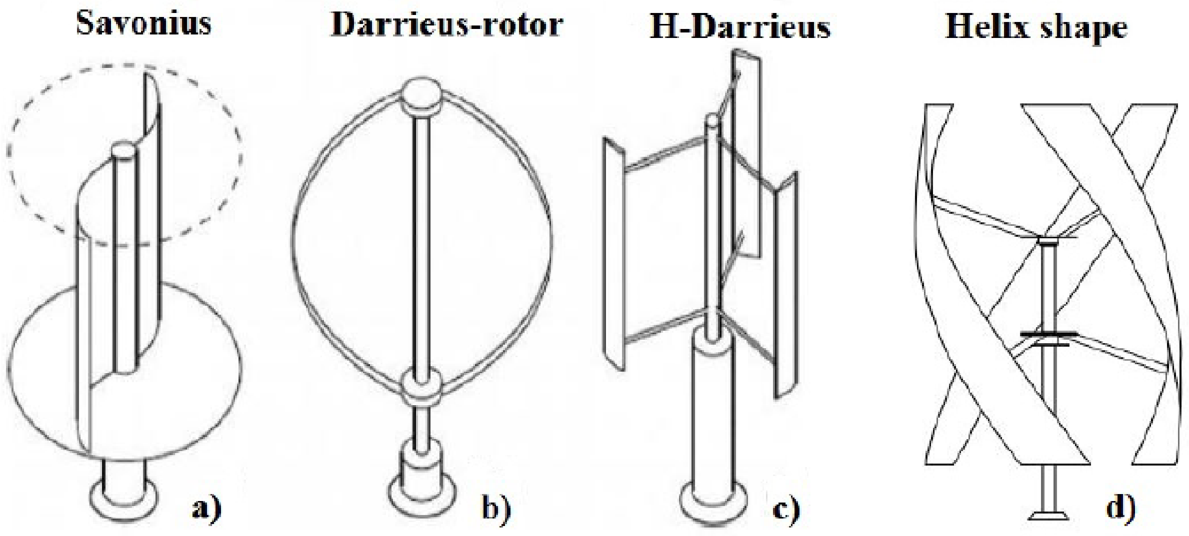

Figure 1: Different types of vertical axis wind turbines (Source: [4]).

Due to the dominance of HAWTs relatively little research has been conducted into improving VAWT performance. However, they have unique applicability to small scale production. An improved understanding of the aerodynamic flow fields around VAWTs and the resulting impact of them on performance is therefore needed. This is especially needed by consumers and small businesses that may build or install VAWTs. Two key limitations exist in this regard. First, most numerical methods for studying placement and flow fields involve the use of complicated and costly computational fluid dynamics (CFD) software. Second, wind resource maps typically represent values at 30 m or higher. Small scale VAWT installations are at a much lower level where the influence of ground effects can dominate. A greater understanding of VAWTs and wind resources in these low-level regions will help remove barriers to small-scale wind installations.

There were three goals for this project:

1. Create a simplified numerical model of VAWT related flow fields.
2. Produce strategies for the placement of VAWTs that improve performance and efficiency.
3. Determine areas of high potential for the application of VAWTs in Minnesota.

Figure 2: Test VAWTs installed on the Minnesota State University, Mankato campus (Darrieus on the left and Savonius on the right).

PROJECT ACTIVITIES AND OBJECTIVES

Objective 1: Create numerical models to study VAWT site potential

Development of a potential flow numerical model

The Leaky Rankine Body (LRB) approach represents VAWTs "with a two-dimensional potential flow model consisting of a uniform flow, a potential source, and a potential sink". Each VAWT is specified in the approach by the source strength, the sink strength, and the downstream spacing [5]. While the method is a first approximation and tends to over predict losses it has been shown to closely represent the performance of individual and arrays of VAWTs. However, as a two-dimensional model it is much simpler to solve numerically. By using the principle of superposition simple solutions can also be combined into more complex scenarios with a minimum of effort. The proposal intention was to determine if this would allow arrays of VAWTs and surrounding structures to be modeled with reduced difficulty and computational time.

A potential flow code was developed that solves for a two-dimensional velocity field. Initial software calibrations were made by simulating different shaped objects in the water channel. Data was collected and compared for:

- Two cylinders in parallel flow
- Two cylinders in tandem flow
- A cylinder and rectangular prism in parallel flow
- A cylinder and rectangular prism in tandem flow (Figure 6)
- Single cylinder
- Rectangular prism (two orientations)
- A small square parallel and rotated 45 degrees

Code results were then verified by comparison with modeled data from the Fluent CFD package, against experimental data in the water channel, and against results in the literature. The code is capable of including various shapes in different orientations. Results for flow past several basic geometries (square, circle, square and circle in tandem) were compared to numerical results from Fluent and experimental results from the water channel. These shapes represent the two-dimensional cross section for three-dimensional objects (e.g. a rectangle represents a building). It was determined that the simplified potential flow cannot accurately predict vortex fields or wakes behind objects (as was expected). Unfortunately, when multiple objects are combined, their wakes interact, and the model is unable to accurately predict general flow in several areas.

The potential flow code was validated against an existing case in the literature [6] and with experimental data collected on the Minnesota State University, Mankato campus (Figure 3 and 4). It was determined that the potential flow code could:

1. Simulate flow around streamlined bodies at high Re where the boundary layer is thin, and negligible flow separation occurs.
2. Predict the occurrence of flow separation (adverse pressure gradient along a streamline).

3. Predict stagnation if the flow direction is previously known and the axis system is chosen to align with this flow direction.
4. Simulate blocks of time-averaged predictable fluid (such as a steady vortex) as a virtual body, but overpredict the flow inside the body.
5. Predict flow around multiple objects by superposition unless their isolated boundary layers would intersect.
6. Predict flow with reasonable accuracy using panel methods, but at the expense of computation intensity.

Ultimately, accurate determination of the wake flow is not needed. Due to the high turbulence present these regions would not be preferred locations for VAWT placement. Therefore, it is much more useful to simply know where the region is. Several options for "panel methods" were explored (and continue to be explored as part of a Masters thesis due for completion in May 2021). These allow the use of pressure calculations along streamlines to determine a virtual body that encloses the recirculation (i.e. wake) region. These methods show some promise but do increase the computational complexity.

The potential flow code was subsequently used to predict high VAWT performance areas and was used to determine suitable anemometer tower locations for experimental site testing.

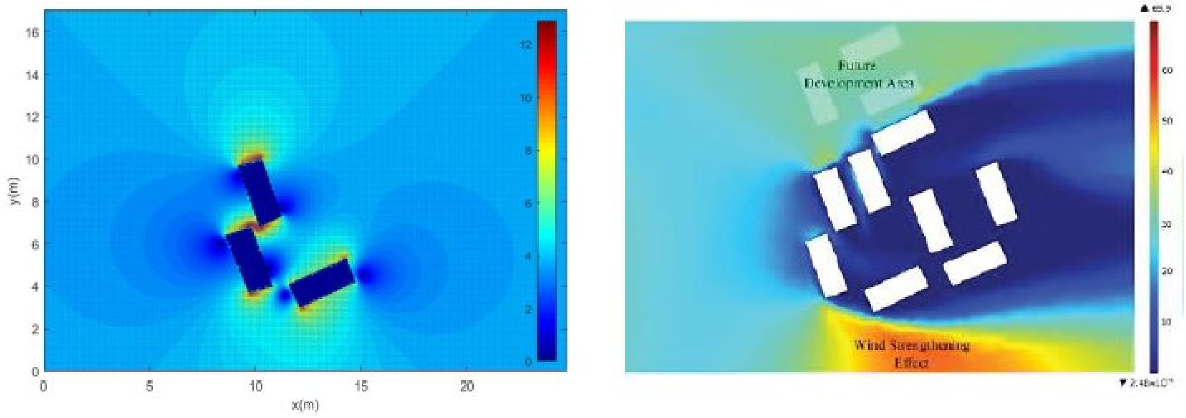

Figure 3: Simulated three building test case for velocity magnitude (Left), and Padjadjaran University study results for localized wind energy taken from [6].

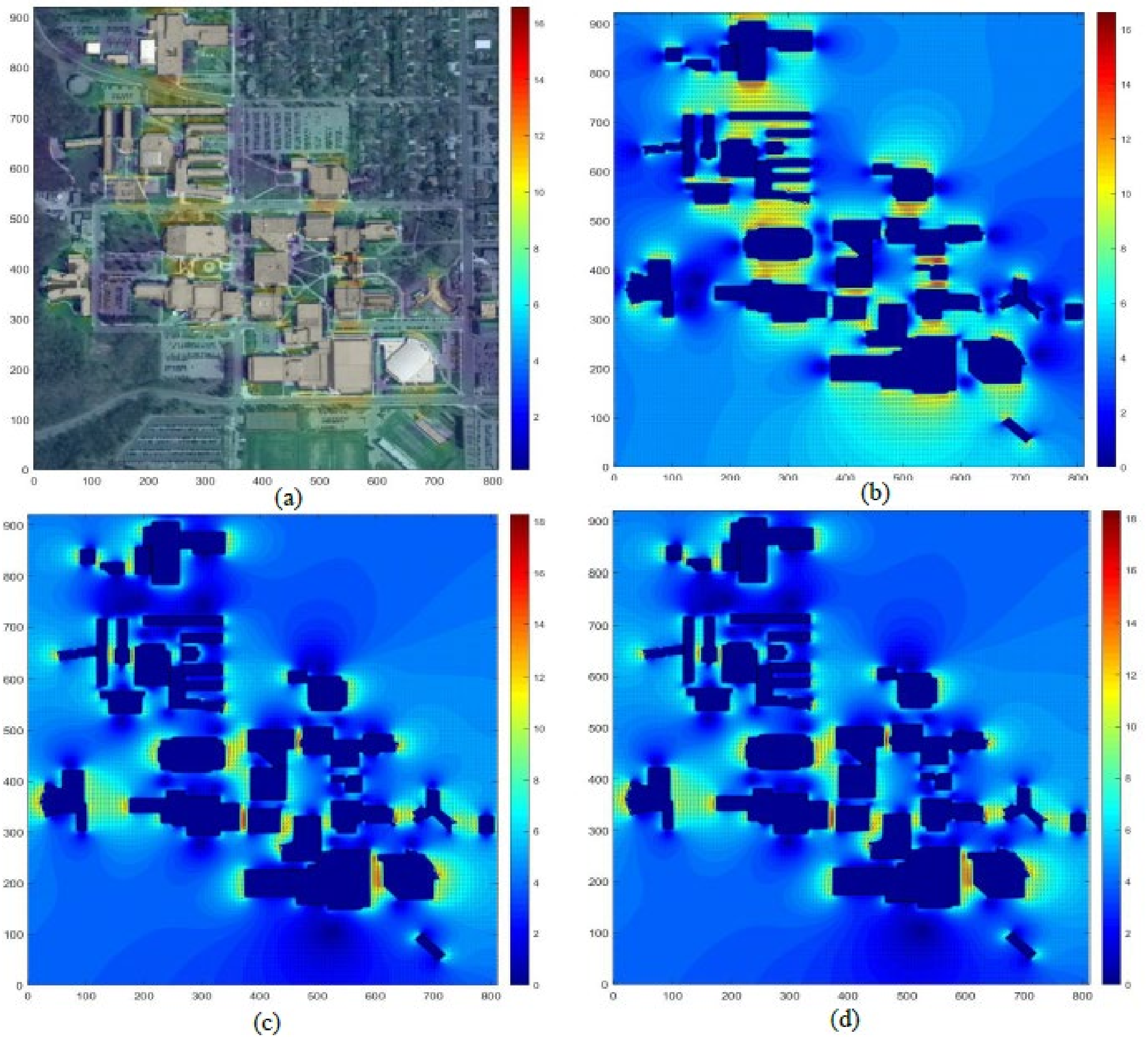

Figure 4: Campus velocity magnitude simulation for input 4m/s wind: East to West with (a) building overlay, (b) simulated objects, (c) South to North wind, (d) North to South wind.

Use of Fluent computational fluid dynamics (CFD) package

To study both wind flow around obstacles and VAWT performance, the Fluent CFD program (ANSYS) was utilized. Initial work looked at modeling VAWTs in three dimensions (Fig. 5 and 6). Use of the Minnesota Supercomputing Institute as well as a higher end desktop computer were employed to handle the large computational load. However, it was determined that obtaining results would still be difficult. Therefore, a simpler two-dimensional model was explored. Parallelization was employed with a maximum computational efficiency reached with 24 computer cores. Simulating 10 seconds of VAWT motion still required nearly a week of computational time. However, it was possible to simulate the start-up motion of the VAWT. An example of the resulting data can be seen in Figure 7.

Fluent was also used to model flow fields from real-world test sites as well as experimental setups in the laboratory. These results will be presented under later objectives. Comparisons with experimental data were conducted to determine which turbulence model was the most effective when modeling both the basic water channel and with a scale model inserted. For the water channel simulation, the shear-stress transport (SST) model produced the best results. The Reynolds stress-baseline (RS-BSL) model resulted in the second-best accuracy; however, it also resulted in a longer computation time. In contrast, for the full simulation (with model inserted) the RS-BSL method produced the best results.

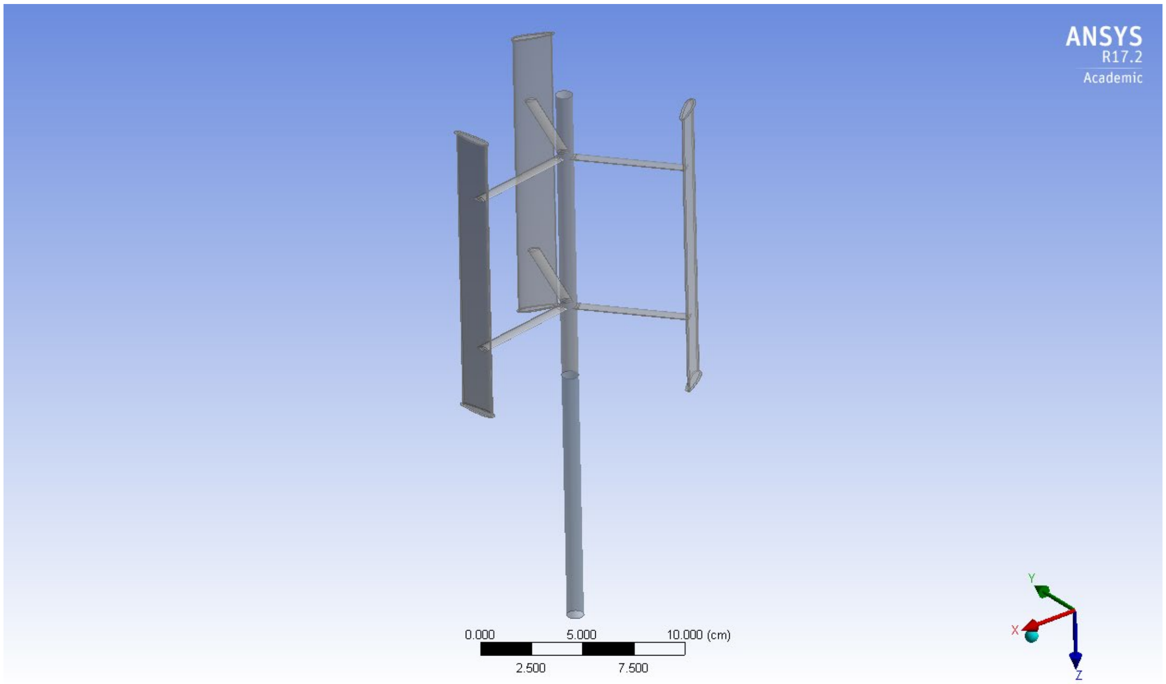

Figure 5: Airfoil VAWT based on original design by Adrian Bej (grabcad.com).

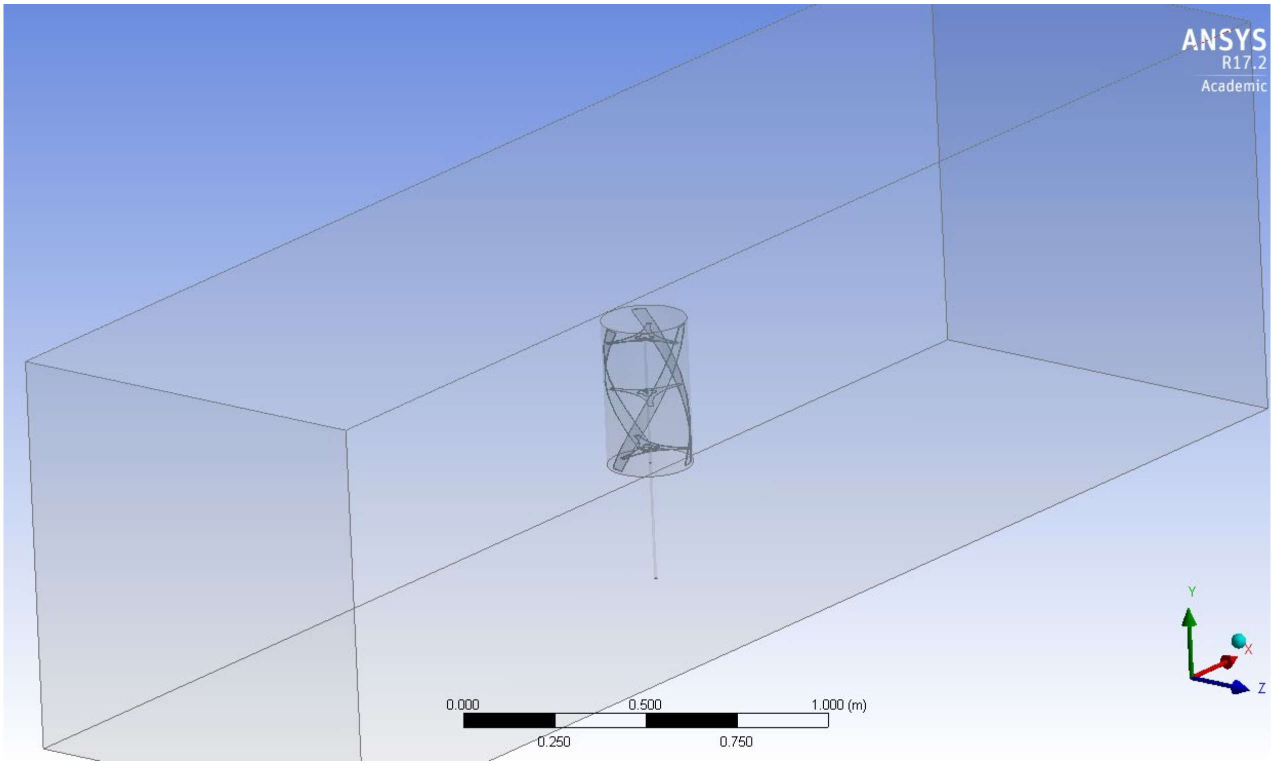

Figure 6: VAWT with rotating domain and freestream fluid enclosure. VAWT based on original design by Tanvir Sajib (grabcad.com).

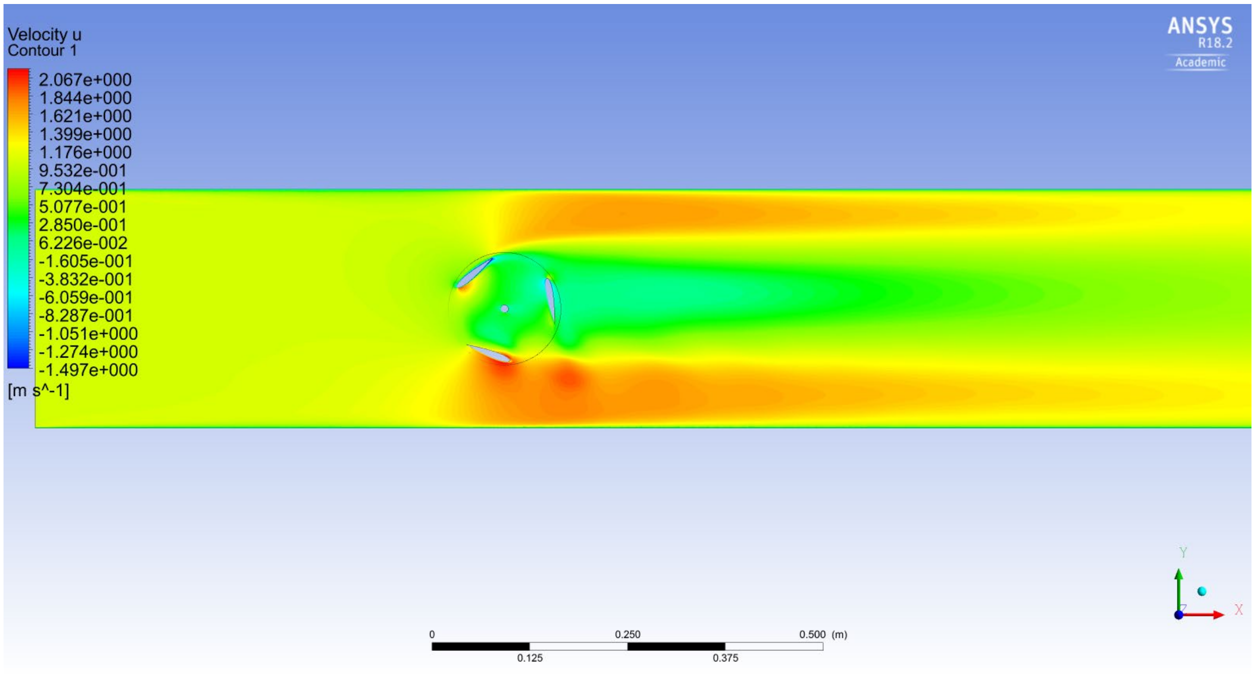

Figure 7: Example X-velocity contours around a VAWT at 1 m/s wind velocity.

Objective 2: Gather experimental data for possible installation sites in Minnesota

Several methods for measuring wind conditions at test sites were explored. A combination of these methods was used for final data collection.

Visual indicators for wind velocity

Two major types of visual indicators were tested. The first was 1 in. flagging tape. This tape is a thin light weight ribbon with a highly visible color. The tape was cut into lengths of 24 in., 16 in., and 12 in. The 24 in. lengths were attached in two different configurations. The first was directly tying the tape to the cross line, leaving a tail length of 1 in. from the knot. The second variation was to attach the tape to the cross line with a knot, but the tails were of equal length. The 16 in. and 12 in. lengths of tape were also directly tied to the cross lines with a tail length of 1 in.. The lengths of tape hung from the cross line were very responsive to the changes in wind direction and indicating the velocity of slower winds. The disadvantages observed by this indicator type was the flowing ripple effect on the tape due to turbulent winds. This ripple effects made measurement of the angle of the tapes difficult and very inaccurate.

The second type of indicator tested was a ping-pong ball hung from a length of 4 lb. test strength fishing line. The line was attached to the ping-pong ball by puncturing a small hole in the ball surface and passing the fishing line into the hole at a length of ½ inch and held in place with super glue. The ping-pong balls were hung at various heights below the cross lines to test their responsiveness to the wind. During tests it was observed that the deflection off the ping-pong ball was not measurable.

The third test was a hybrid of the first two designs. This was comprised of a 6 in. length of tape tied to the end of the light weight 4 lb. test strength fishing line (Figure 8). This device showed interesting characteristics when compared to the other two indicators. It was much more responsive than the ping-pong ball at slower wind speeds. This model also did not show the ripple effects from turbulence like the long tape strip did, but it did respond slightly slower to the wind changes. An observed downside with this indicator was that it is very difficult to reference the small tape to any known point, along with reading an angle of deflection from the string.

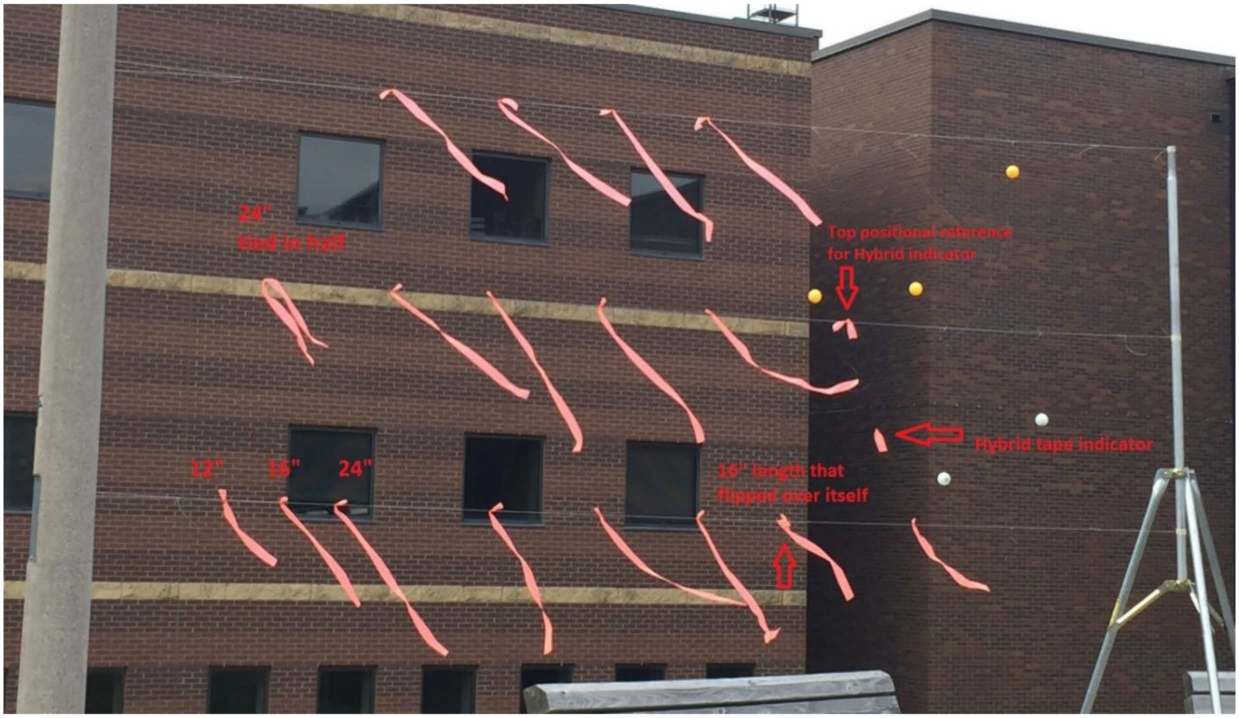

Figure 8: Tape and ping pong ball indication of wind.

Design and construction of the anemometer towers

An initial tower was constructed from existing Hobo Weather Stations. This allowed exploration of data collection at different heights as well as a tripod structure that would be needed for support. Data was taken at several locations on the Minnesota State University, Mankato campus.

Based on these preliminary tests, a new anemometer tower was designed from scratch. Four completed towers were constructed. Each tower was comprised of four main parts: a base mount, mast, booms, and sensors. The main mast sections were comprised of 8 ft. sections of rigid metal conduit with an outer diameter of 1.9 inches. Total tower height, and the placement of the sensor booms, were adjustable to various heights (Figures 9 and 10).

The tower incorporates two sensor types for a total of three sensors per tower. The highest mounted sensor is a Davis Instruments 6410 anemometer. This sensor comes as a kit and can measure both wind speed and direction. The second sensor type is an 8-pulse anemometer from Inspeed. The tower design calls for two sensors of this type. All sensors on the tower were connected to a National Instruments myRIO-1900 device. The myRIO device runs a LabVIEW application and all data is recorded to a connected USB drive. Each myRIO is powered by an eight-cell battery pack. To calibrate the sensors and data acquisition system, the anemometers were mounted in the low speed wind tunnel (Figure 11). The system was calibrated for wind speeds up to 40 mph.

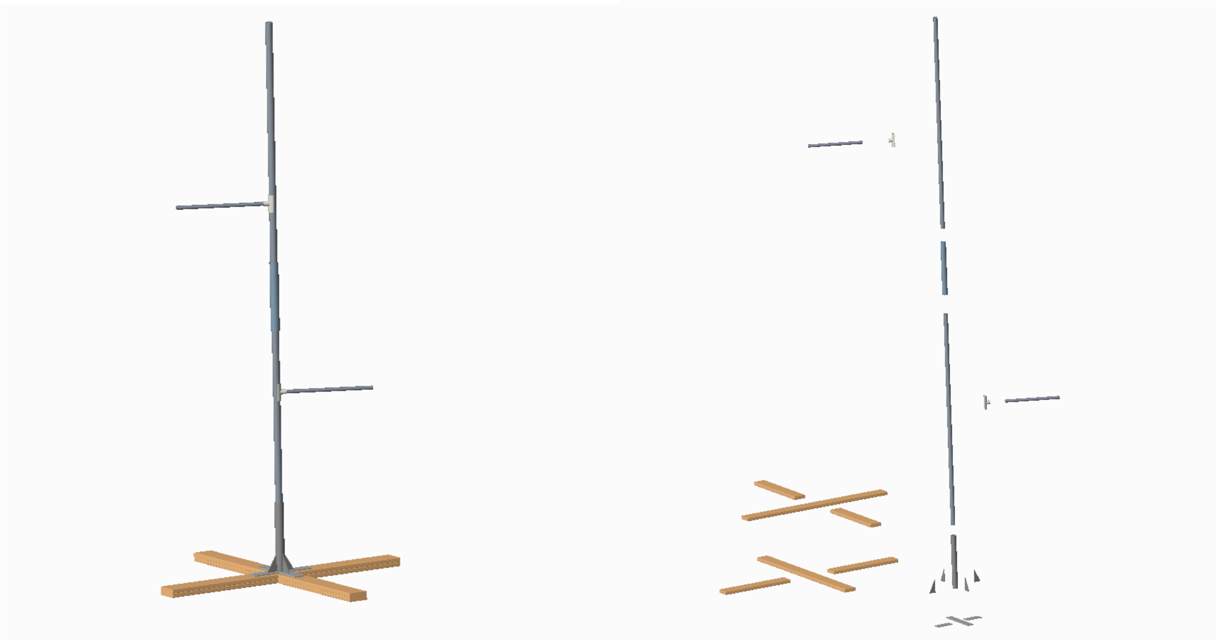

Figure 9: Assembled and exploded views of the tower and base.

Figure 10: Anemometer tower assembled with three mounted sensors.

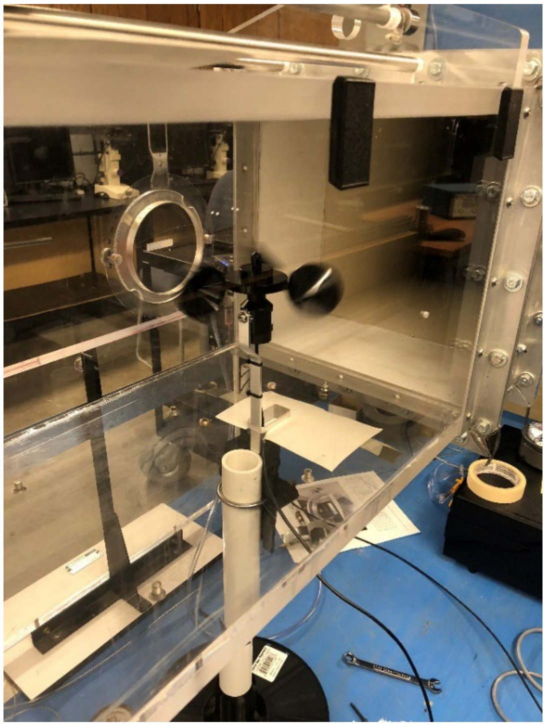

Figure 11: Inspeed sensor being calibrated in low speed wind tunnel.

Data collection for HyVee VAWT installations

Due to the visible nature of the VAWTs installed at the HyVee sites in Minnesota, the project paid special attention to them. The HyVee corporation was contacted and basic information the installations was provided. While access to the recorded monitoring data was promised, it was not provided, at least not before Covid-19 forced a shift in processes. An alternative method of data collection was devised using GoPro cameras to record the spinning VAWTs. The rotational speed of the VAWT was then determined visually and correlated to wind speed readings taken at the same time around the parking lot.

Objective 3: Design and construction of experimental facilities

Design Analysis of Possible BLWT

MSU possesses a low speed wind tunnel and a water channel. However, these are not large enough to allow more than one or two (stacked) VAWTs to be studied. A larger apparatus was desired to examine VAWT arrays and VAWT interactions with surrounding structures. The project initially explored the option of designing and building our own boundary layer wind tunnel (BLWT) that was 1) portable so it can be used for multiple projects or courses, 2) storable when not in use, and 3) relatively inexpensive. Working dimensions were desired with a 1 m x 1 m test section and a length of at least 10-15 m.

A mechanical engineering senior design team worked on this design and determined that a fully portable BLWT was not feasible. The required fan/motor combination would weigh too much for easy and safe movement or assembly. Therefore, the team switch to designing a permanent BLWT that would fit inside one of the MSU mechanical engineering laboratories (see full student report in Appendix). The design involved the analysis of the contraction and expansion shapes, rapid generation of the boundary layer using boundary layer elements, and the effect of roughness from simple construction materials like plywood.

The final design was a BLWT that was 10.21 m long with a test section that was 0.6 m square (see Figure 12). The final material cost was found to be approximately $25,000. A design quote was obtained from Engineering Laboratory Design Inc. for comparison. While the design parameters were very similar the quoted price from ELD was $110,000.

Following the design analysis for a new BLWT, a cost comparison was made between what could be measured with the new wind tunnel versus what could be measured if funds were spent to upgrade the capabilities of the existing water channel and low speed wind tunnel. When taking into consideration laboratory space limitations and the availability of the St. Anthony Falls Laboratory, the decision was made to upgrade the existing equipment.

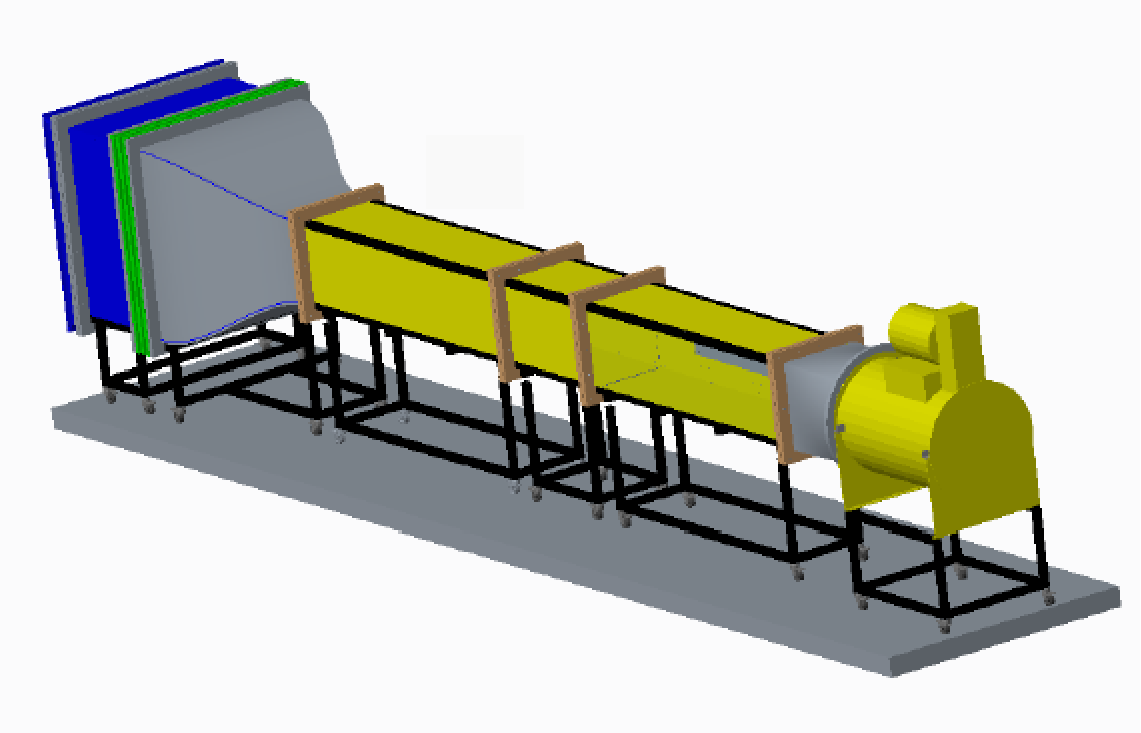

Figure 12: Creo model of final BLWT design.

Creation of VAWT scale models

The use of 3D printing was determined to be a cost-effective method of producing scale models for testing. The first model produced was based on a NACA18 airfoil. A bearing and mounting system were designed so that the model could be secured within the water channel or the wind tunnel (Figure 13).

The design and manufacture of 3D printed scale models has continued with several different VAWT designs. In particular, research was done on the helical VAWTs installed at the HyVee stores in Minnesota. A geometry was obtained for this design and a sample model was eventually constructed. The thinness of the blades caused some manufacturing difficulties initially. However, several successful versions have been produced (Figure 14).

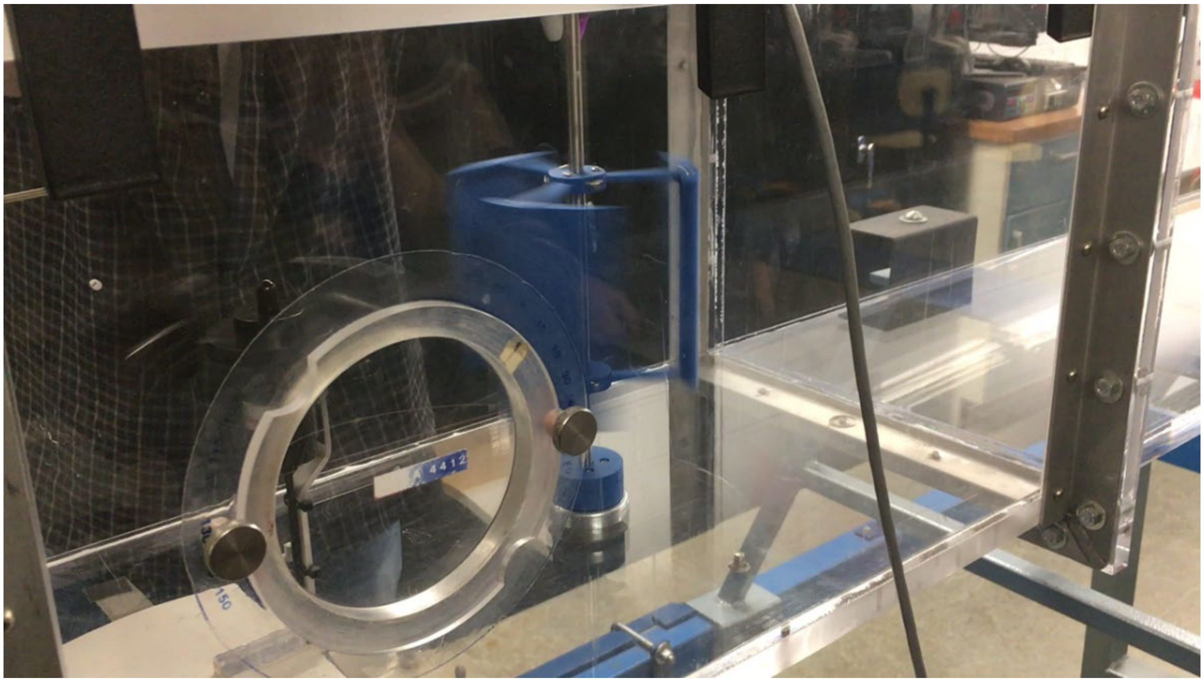

Figure 13: Scale model of an airfoil design VAWT being tested in the wind tunnel.

Figure 14: An electric vehicle charging station at HyVee (left). A scale model of the same VAWT that was 3D printed (right).

It was determined that the 3D printed models absorbed water during their use in the water channel. Since this would change their mass and inertia, experiments were performed to determine how much water was absorbed. Two identical helical Darrieus turbine models with heights of 134.4 mm, diameter of 101 mm and dry weight of 66.8 g were studied. They were made from polylactic acid (PLA). While PLA is known to absorb water, the majority of added water was filling the hollow gaps within the 3D printed structure. The weight of the test specimens increased by 13 g at 108 minutes. The specimens were then dried in open air. Most of the drying occurred in the first 40-50 hours; however, complete drying was estimated to take over a month.

The roughness of the model's surface and slight variations in its shape can affect how fluid flows over it. Since several different 3D printed models were being used interchangeably, it was necessary to determine how geometrically similar they were. A coordinate measuring machine (CMM) was used to compare different copies of the same VAWT design (Figure 15). Values for four copies were compared to the specifications in the original CAD file. Most differences were between 3% and 5%, but they could be as high as 8%. Demonstrating that care must be given to matching printer settings. PLA is also known to shrink by up to 2% given different temperature and humidity settings.

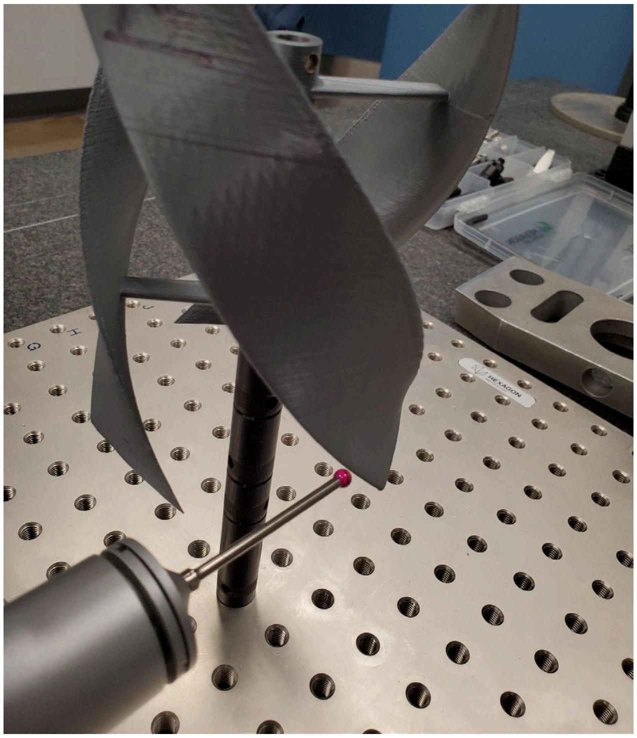

Figure 15: CMM probe following the blade curvature using individually picked point.

Torque and Velocity Measurements

An acoustic velocimeter (Nortek Vectrino) that can measure liquid velocities in three dimensions was selected. A mount and interface hardware were created for the Vectrino velocity sensor (Figures 16 and 17). The mount has a traversing system that can be fully adjusted to any location in the water channel for readings with 1/10” accuracy. Calibration studies were performed to verify the Vectrino’s operation. Comparison values were taken with a Prandtl-Pitot tube. The initial results indicated there was a discrepancy. After consulting with the manufacturer, the power level was reduced, a better velocity range was selected, and limits for probe distance from the wall were adjusted. One potential issue with this probe is possible reflections from the channel surfaces if it is too close. Some surfaces were covered with sound absorbing materials to help eliminate this.

A Futek torque sensor was also selected and mounted for use in the water channel (Figure 18). Interfacing issues arose with the electronics but were resolved by creating a custom LabVIEW interfacing program. Calibration was done using small weights to generate known torques. A belted brake was constructed to apply a counter force for the torque measurement. Later, this device was adapted for mounting on the low speed wind tunnel.

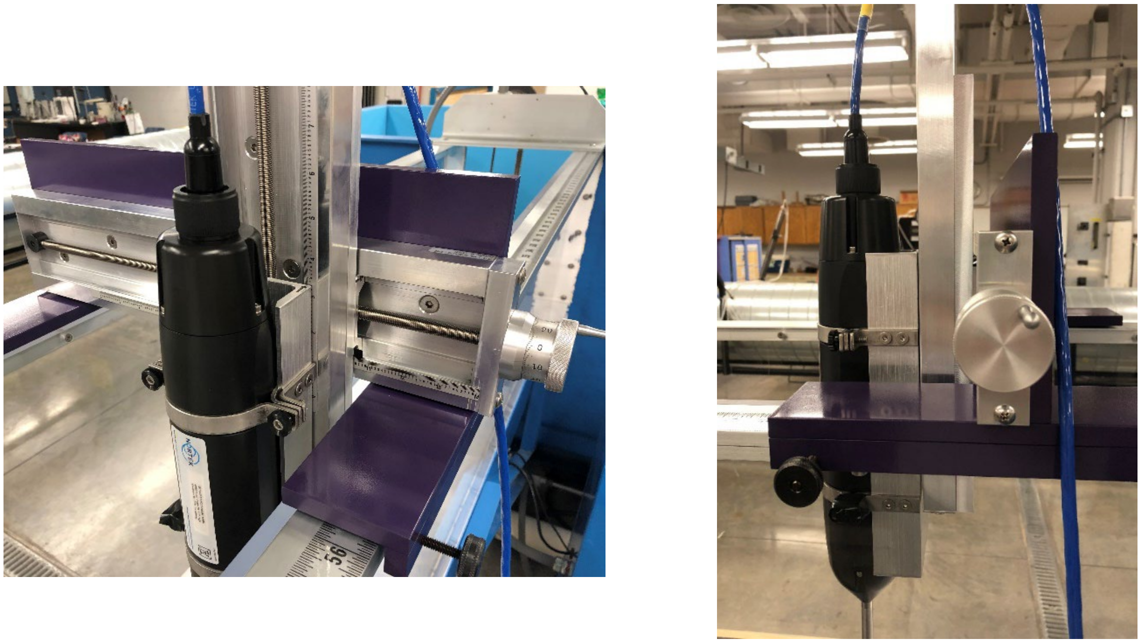

Figure 16: The Nortek Vectrino mounted to the traversing mechanism on the water channel.

Figure 17: Vectrino shown measuring flow field around a model VAWT in the water channel.

Figure 18: The Futek torque sensor and its 3D printed mount for the water channel.

Objective 4: Identify VAWT placement schemes for maximum performance.

Using a combination of the water channel and the wind tunnel, several placement aspects were investigated:

- The individual performances of the 3D printed VAWT models,
- The flow field around individual 3D printed VAWT models,
- The performances of two 3D printed VAWT models placed in the flow field together.

Experiments were conducted for several different types of VAWTs as well. Fully details on these experiments are provided in the Appendix. As an example, Figure 19 shows the flow field around a single helical VAWT, rotating clockwise. The resulting flow field shows an asymmetric shift in the direction of rotation.

Several conclusions can be made from the resulting data. Power curves of 3D printed VAWT models were obtained for both CW and CCW direction rotation. While RPM and respective power had similar results in both rotation directions, there was a notable difference between the two configurations in the minimum flow velocity for self-sustained rotation. This was higher for CCW compared to CW.

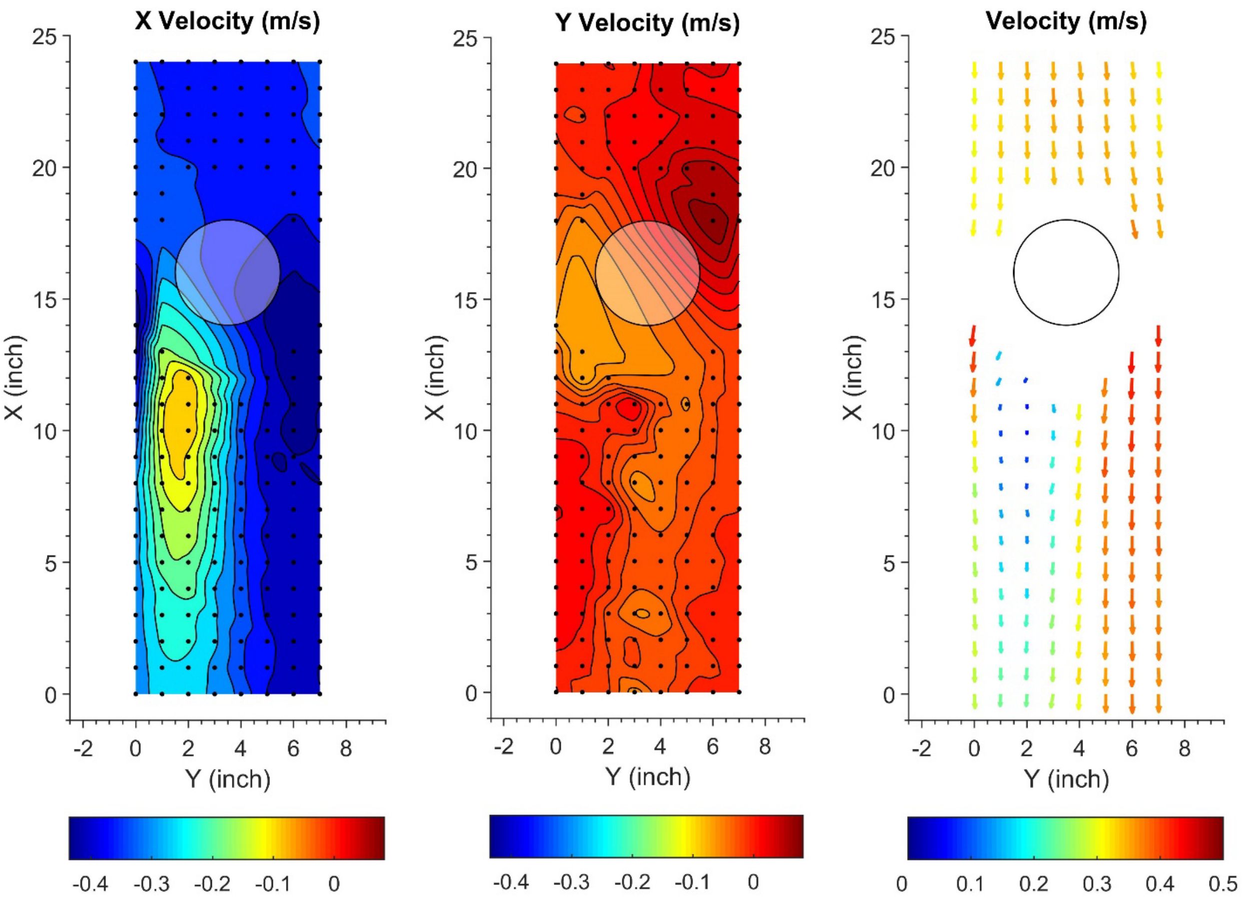

Figure 19. Velocity field around Helical Model (clockwise rotating).

For all models (Helical and Savonius rotating CW and CCW) a notable wake region was formed that could expand to 4 diameters downstream. The wake region was not symmetrical and was on the left side of CW rotating models and on the right side of CCW rotating models.

Based on the RPM data for two VAWT experiments, we concluded that the back model had a negligible effect on the performance of front model. We positioned the back model to different offsets in x (flow) and y (perpendicular to flow) directions. The front model was affected by the back model if this offset was less than one diameter.

For our experimental conditions, we concluded that the Savonius models were more efficient (higher RPM values for both CW and CCW) than the Helical models. However, the Helical model data was more consistent overall.

Based on the RPM data for two VAWT experiments, we noticed a remarkable decrease in back model performance when the model was in the wake field of the front model (as expected). In the literature, it is suggested that the performance of the back VAWT model may increase if it is placed in the accelerated flow field behind the front model. However, we only observed that behavior for the Savonius model. We assume that this behavior is not observed for Helical models because the width of the accelerated flow field was small compared to the turbine diameter.

The torque data was obtained to calculate the power output of models was not consistent. Therefore, we tried calculating the power output using a predictive equation. The power output calculated was unrealistically high. Our data gave high performance coefficients (close to or at limiting 59.3%) that we did not rely on. Nevertheless, we suggest the RPM as a good indicator for the performance output.

We plan to further investigate the multiple VAWT model behavior around 3D models of buildings and other obstacles (grain silos, trees, and the like) in the future.

Objective 5: Evaluate VAWT potential of sites in Minnesota.

Characterization of VAWTs

Using Department of Energy information and based on a search of available VAWTs on the market, this project used the following category ranges to classify VAWT models. This project was focused primarily on the Small range.

> **Small (≤ 0.4 kW):** The small designation is for off-grid, remote power systems usually dedicated to a single system or application. Making a system of this size grid-tied would do little to support the energy needs of a small home.
>
> **Medium (0.4 kW to 20 kW):** Systems of this designation may significantly contribute to, or fully sustain, the energy requirements of a normal household. These systems may be setup as stand-alone units or closely packed in small wind farms.
>
> **Large (≥ 20 kW):** VAWTs in this category may be used for community power, business and industrial applications, or true wind farms. Many models in this category would provide excess power for a single household and are specifically designed for use in larger installations.

One hundred different VAWT designs were identified as being available during the time period 2011-2017. The distribution of these into the three categories can be seen in Figure 20. The resulting trends for other factors such as cut-in speed and mounting height can be seen in Table 1.

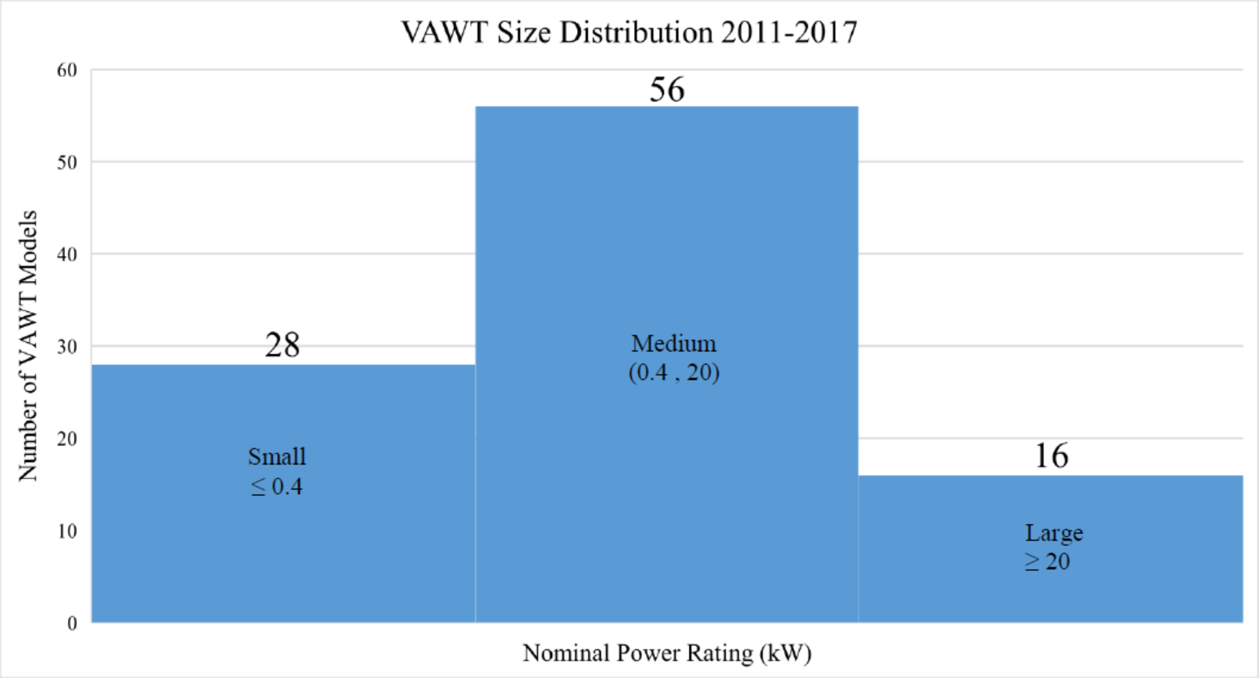

Figure 20: Distribution of available VAWTs by power category.

Table 1: VAWT characteristics (2011-2017).

	Power (kW)		Cut-in Speed m/s (mph)		Roof Mount Height m (ft)		Ground Mount Height m (ft)		
Data Types	Ave.	Range	Average	Range	Average	Range	Average	Range	General Description
Small (28)	0.2	0.01 to 0.4	2.9 (6.5)	1 to 5 (2.2 to 11.2)	2.1 (6.9)	0.4 to 4 (1.5 to 13.1)	6.8 (22)	0.48-14.8 (1.6-48.6)	Dedicated Off-Grid Systems
Medium (56)	3.7	0.4 to 20	2.8 (6.3)	1 to 4 (2.2 to 8.9)	4.0 (13)	2 to 8 (6.6 to 26.2)	9.0 (29.5)	2.1-24 (7.0-78.7)	Urban and Small Business
Large (16)	39.1	20 to 70	3.2 (7.2)	2 to 4.5 (4.5 to 10.1)	8.0 (26)	-	23 (75)	10-46 (32.8-151)	Community and Wind Farm Use

Use of Wind Analysis Software

A typical energy analysis package, RETScreen, was considered for VAWT analysis. Although many horizontal axis wind turbines have been accurately analyzed by the program, the software has not yet been validated for vertical axis wind turbines. The textbook states: "The main limitations of the model are that the stand-alone wind energy projects requiring energy storage currently cannot be evaluated, and that the model has not yet been validated for vertical axis wind energy systems" [7].

To try and determine if RETScreen could accurately model VAWTs, a test case was run from the following publication: Performance Evaluation of a 700-Watt Vertical Axis Wind Turbine Renewable Energy Series [8]. The RETScreen predicted values were significantly higher than the actual output. However, it could not be determined if this was due to inaccurate wind speed inputs or some inability to model VAWTs in general.

Nevertheless, we attempted to use RETScreen to predict the power output of the VAWTs installed in several HyVee parking lots. Input values were taken from local weather station data and the VAWT manufacturer's performance curve (Table 2). Note that the program predicted no output for Eagan because the input wind profile was not high enough to provide output.

Table 2: RETScreen predicted electricity output for HyVee installations.

Location	**kWh**
Lakeville	232
New Hope	136
Austin	144
Eagan	0
Oakdale	136
Savage	153

Placement of VAWTs near Grain Bins

Grain bins are typically one of the larger structures in an agricultural setting. The Fluent CFD model was used to study the flow around grain bins and validated against scale model results in the water channel. Sample images can be seen in Figures 21 through 23; however, full details are provided in the thesis at the following link: https://cornerstone.lib.mnsu.edu/etds/951/

Due to possible variability in wind direction and grain bin placement, results can only be considered generally valid. With multiple grain bins, the speed-up region between them can become unstable. The ideal placement location behind a grain bin was found to be on a 5-degree offset and approximately 10 feet behind the bin. However, a higher mounting height would still be required to stay out of the turbulent wake. If the bins are closer than 5 ft they should be considered as a single blocking object. It was estimated that a speed-up of 1.09 could be experienced in these conditions.

Larger grain bins were found to have longer wake regions, with a large bin having a wake that extends 18 diameters past it. However, for some cases the amount of disruption (and resulting turbulence) had already reduced by half within 4 diameters. These recommendations were made under the assumption that the highly turbulent regions have an adverse effect on performance. If the opposite is true, as some researchers now suggest for VAWTs, then placement within these areas may increase VAWT output.

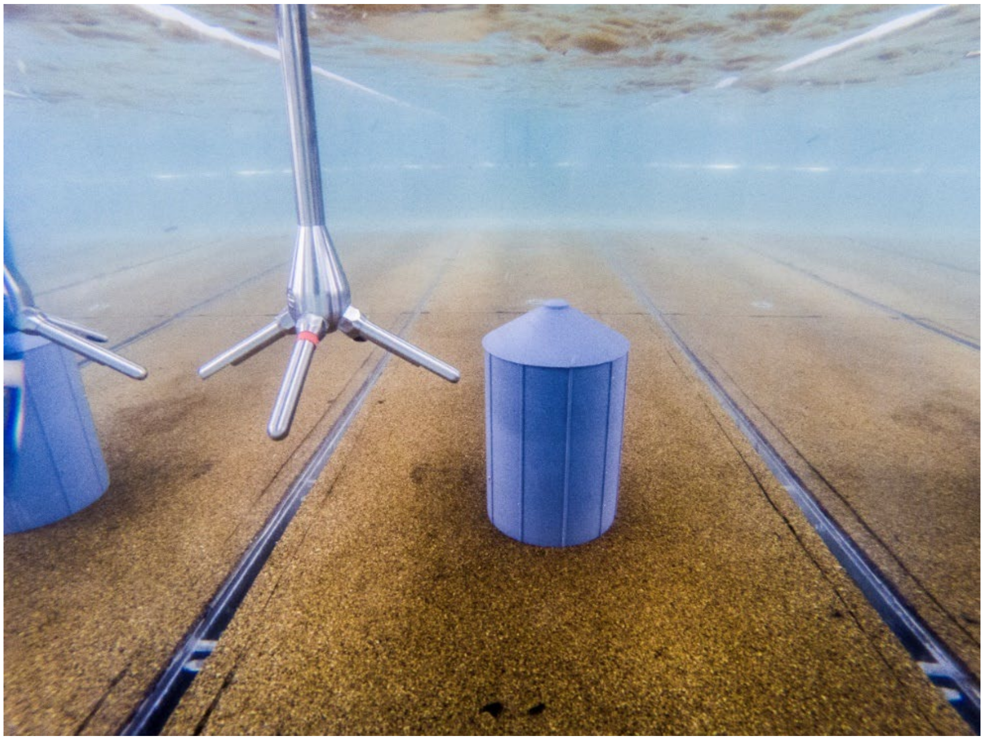

Figure 21: A single scale model grain bin being studied in the water channel.

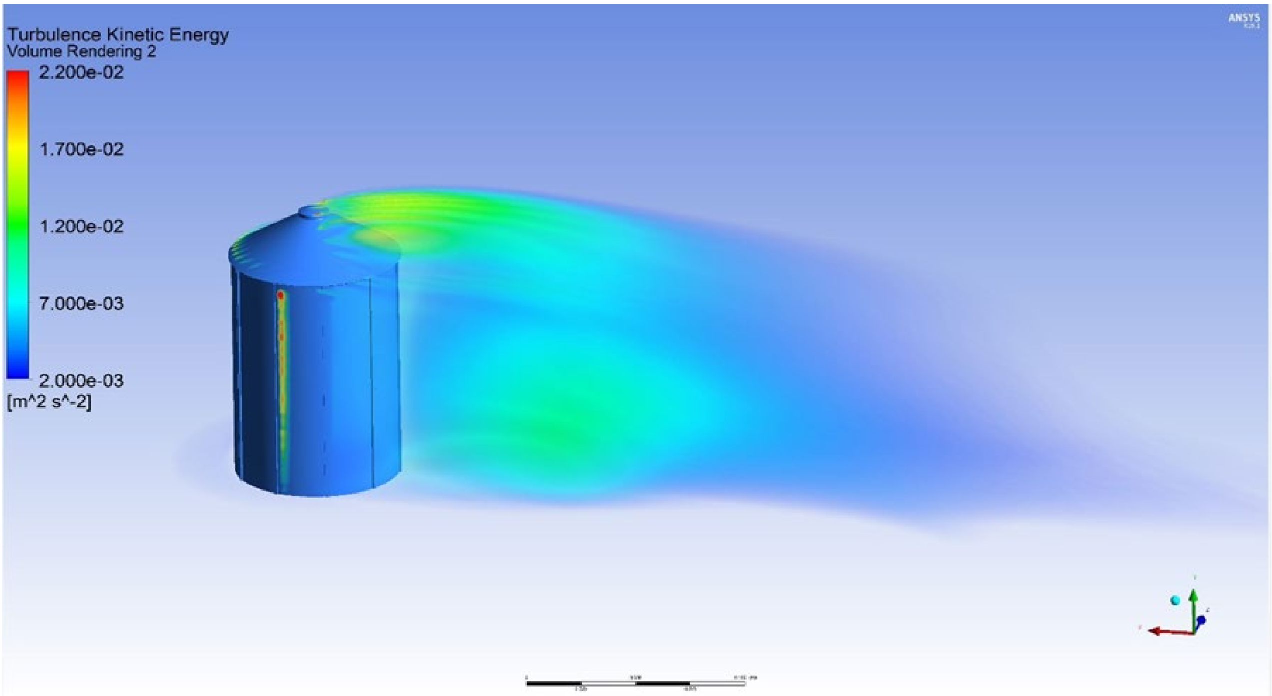

Figure 22: Contour plot of turbulent kinetic energy behind a single grain bin.

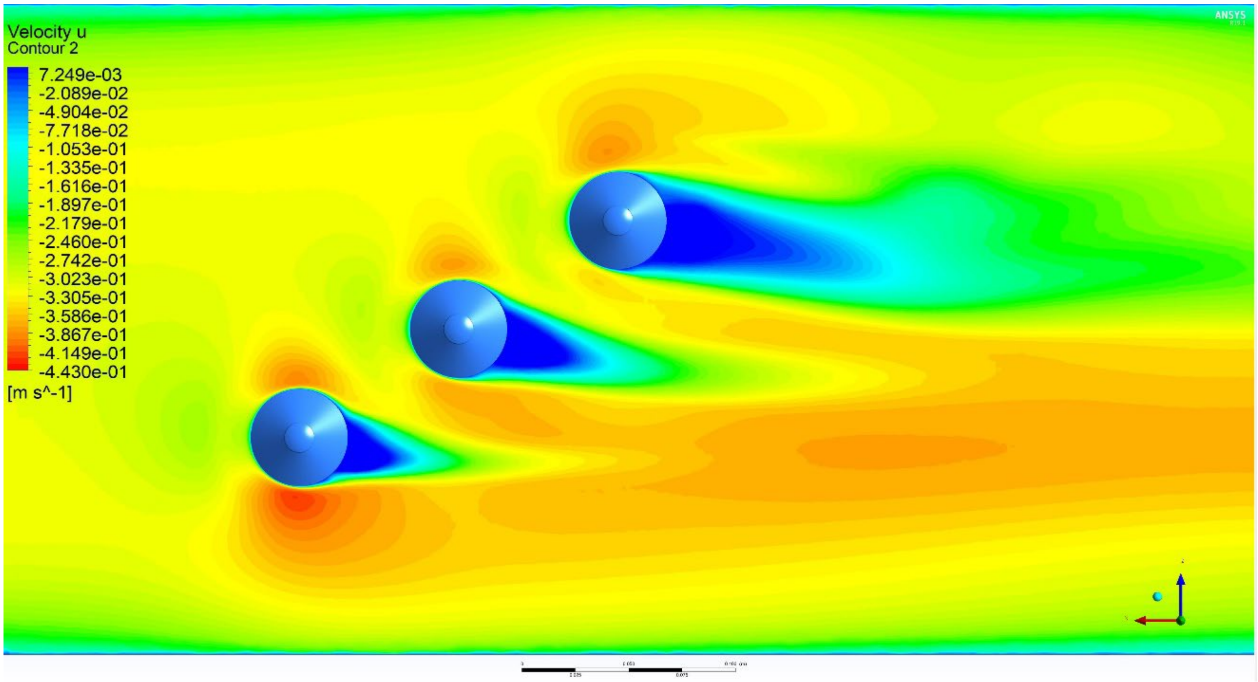

Figure 23: Velocity contours behind multiple grain bins.

Conclusions from HyVee Parking Lot Study

Three regional HyVee sites were selected for study; Shakopee, Savage and Eagan. Data was recorded for wind speed and VAWT RPM (determined visually from GoPro data). The resulting RPM values are shown in Figures 24 through 26. For Shakopee, the left camera for the left VAWT stopped recording due to overheating, resulting in zeros. For Savage, the battery on the camera for the right VAWT ran out of charge, resulting in a short period of zero. In contrast, for Eagan the values of zero RPM are due to a lack of wind.

As seen in the results, for some locations (e.g. Shakopee) the behavior of the two VAWTs can be starkly different, while for others (e.g. Savage) the two follow each other closely. This is reinforced by the collected wind data (Tables 3-5) that demonstrates wind speeds can vary greatly across the Savage parking lot. Also note, the previous RETScreen results indicated no output from Eagan due to low wind speeds. This data clearly indicates the locally available weather station data does not represent the “on the ground” situation there.

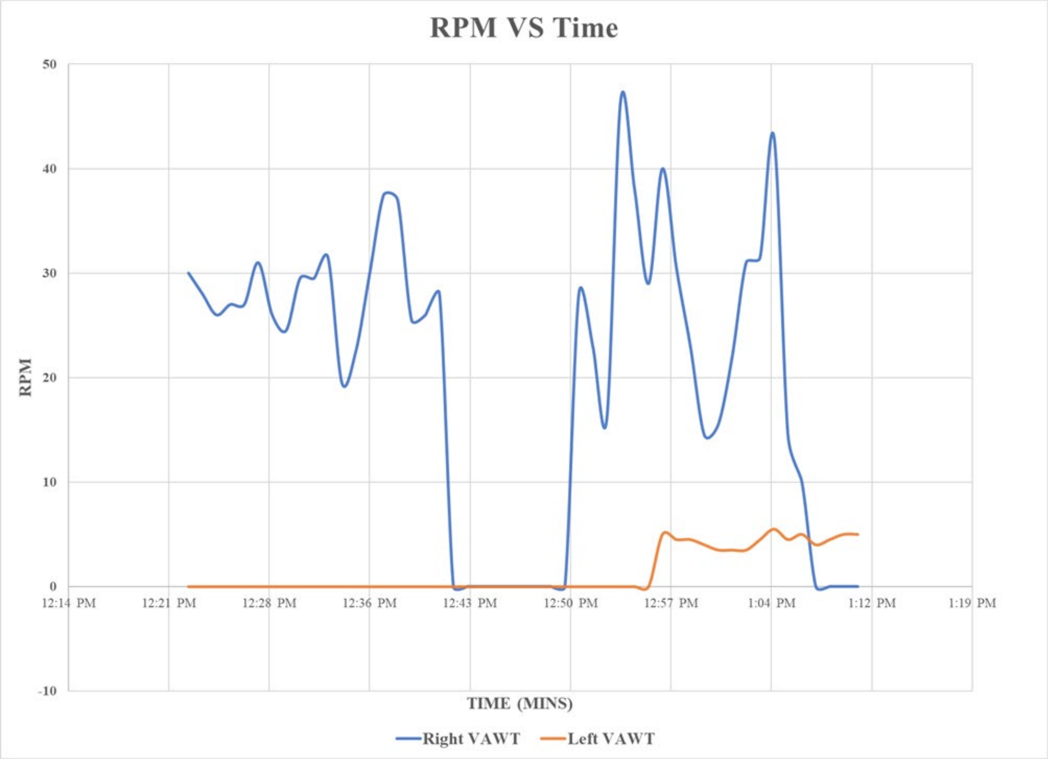

Figure 24: Calculated RPM values for the Shakopee HyVee VAWT.

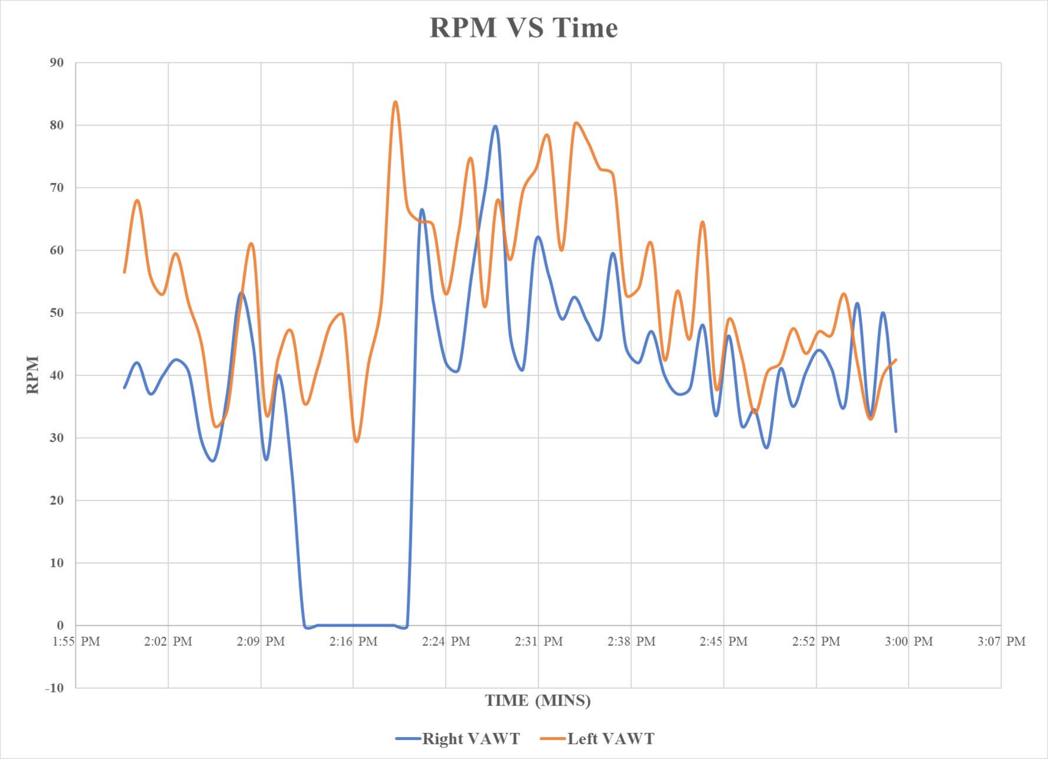

Figure 25: Calculated RPM values for the Savage HyVee VAWT.

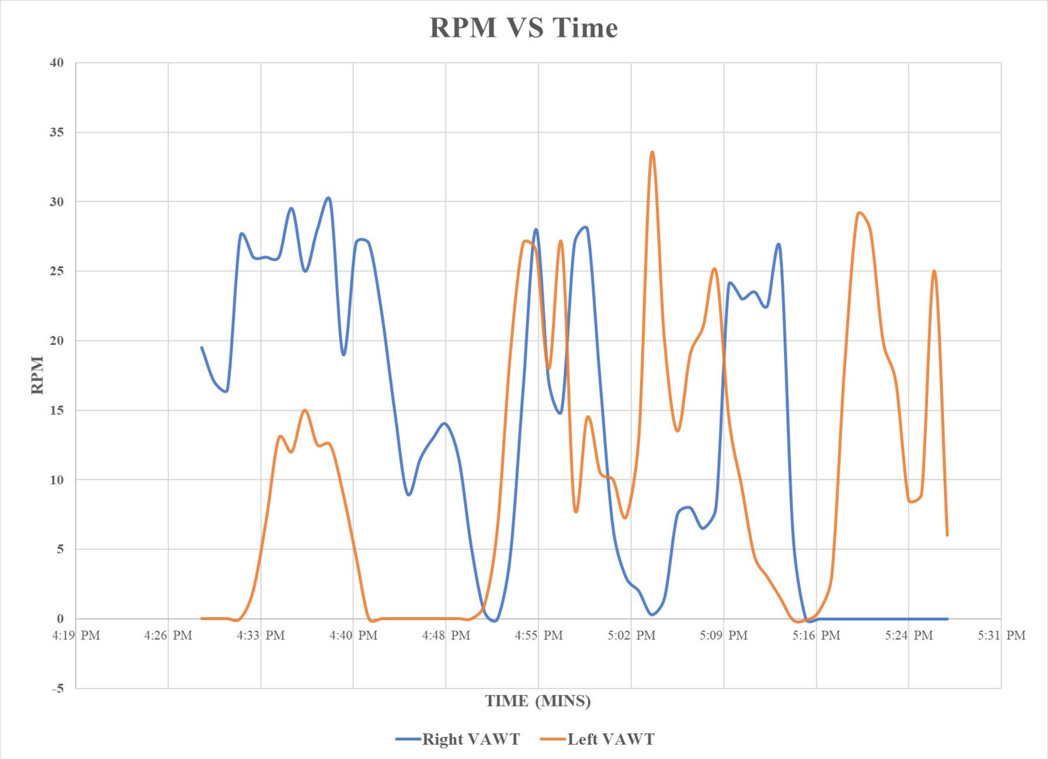

Figure 26: Calculated RPM values for the Eagan HyVee VAWT.

Table 3: Shakopee Wind Speed Data

Location	**Wind Speed (mph)**					
	Run 1			**Run 2**		
	Min	**Max**	**Mean**	**Min**	**Max**	**Mean**
Base	1.1	3.8	2.3	0	5	2.4
1	1.1	3	2.5	1.2	3.4	2.7
2	0.9	3	2.5	2.1	3.4	2.7
3	1.8	3.9	2.7	0.8	3.6	1.8
4	1.2	2.3	1.6	2.1	4.7	3.5
5	1.9	4.1	3	0	3.2	1.1
6	0	1.3	0.5	1.3	4.8	2.6
7	3	5.1	4.1	0	2.3	0.8
8	0	1.5	1	1.5	2.3	2
9	2.4	3.2	3	2.6	3	2.8
10	1	2.2	1.7	2.2	5.6	4
11	1.2	3.7	2.5	1.1	3.2	2.3

Table 4: Savage Wind Speed Data

Location	**Wind Speed (mph)**											
	Run 1			**Run 2**			**Run 3**			**Run 4**		
	Min	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
Base	2.4	5.4	3.5	0.8	7.1	4.6	1.9	5.6	3.1	4	8	6.3
1	3.9	5.7	4.9	4.4	6.4	5.3	3.6	5.5	4.4	1.7	4.8	3
2	3.1	4.6	4.1	5.1	9.4	7.1	1.7	6.3	4.1	1.6	8.9	4.1
3	1.1	3	2	4.5	7.3	5.8	2.1	7.4	4.4	1.7	5.9	3
4	0.8	3.9	2.3	3.6	8.1	5.3	0	3.8	2.4	2.8	7.3	4.7
5	5	6.1	5.6	1.6	3.7	2.1	2.5	5.2	4	3.7	8.3	6.3
6	2.7	7.4	5.3	0.8	9.1	5.6	6.8	11.4	8.2	7	9.4	8.1
7	2.7	5.7	4.3	1.6	3.4	2.2	2	5.8	4.2	1.1	7.1	3.8
8	3.7	6.1	4.7	0	9.4	5.4	3	6.1	4.9	5.4	8.1	6.7
9	4.1	6.1	5.1	1	7.8	4.3	1.7	6.6	3.8	2.7	5	4

Table 5: Eagan Wind Speed Data

Location	**Wind Speed (mph)**											
	Run 1			**Run 2**			**Run 3**			**Run 4**		
	Min	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
Base	0	3.7	2.3	1.3	3	2.4	1.1	2.6	1.7	1.1	2.9	2
1	1.1	2.6	1.8	0	1	0.9	1	3.5	1.6	1.8	3.8	2.7
2	2	4.5	3.4	0	2.1	1.2	0	1.6	1.2	2.6	4.5	3.2
3	0.9	2.3	1.3	1.2	2.5	1.8	1.3	2.3	1.6	0	3	2.1
4	1	3.2	2	0	1.7	1.2	0	2.1	1.5	0	3.7	1.4
5	0.7	3.8	2.2	0	2	1.3	1.5	3	2.3	0	2.3	0.9
6	1.1	3.7	2.1	0	1.9	1.4	1	2.4	1.8	0	1.5	0.5
7	2.5	5.9	3.4	1.1	2	1.7	1.2	2.3	1.6	1	4.3	2.3
8	1.8	4	2.9	1.5	2.8	2	1.3	2	1.6	2.4	4.7	3.8

Experimental measurements from regional test sites

Likely locations for small scale VAWTs were determined to be light industrial, agricultural, and residential. Urban was briefly considered but a full analysis was not possible by the end of the grant period. Characteristics of typical Minnesota farms was determined and a test site near Hartland, MN was used. The possible impacts of trees and shelter breaks was of particular interest here. Three light industrial sites around Mankato, MN were also selected. They were Nidec Engineering, NextGen RF, and MTU Onsite. The project looked at typical characteristics of residential sites but Covid-19 and weather prevented any on-site data collection for these cases.

For each site, local weather was determined and input to the potential flow code. Solutions were obtained over a range of wind directions, based on the local wind rose. The results were then used to suitable references locations (with good freestream wind) and points of interest (i.e. areas with predicted speed-up or high turbulence). Figures 27 and 28 demonstrate these for two of the industry sites. Figure 29 shows a close-up view of predicted speed-up regions at MTU Onsite.

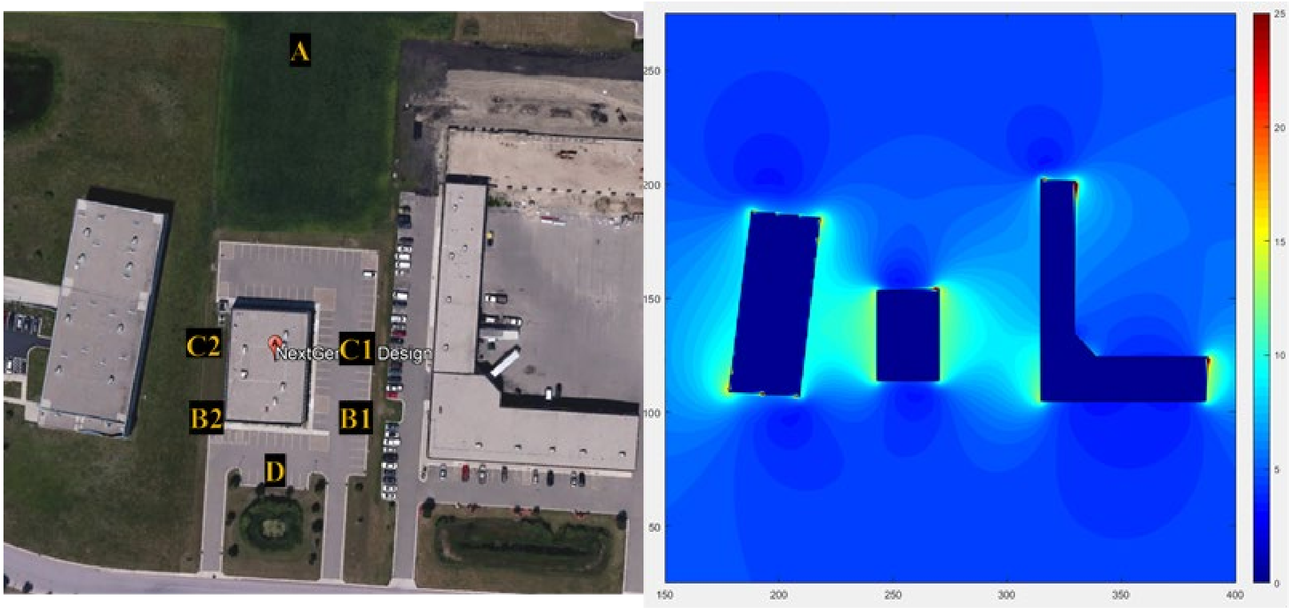

Figure 27: Aerial view and potential code simulation results for NextGen.

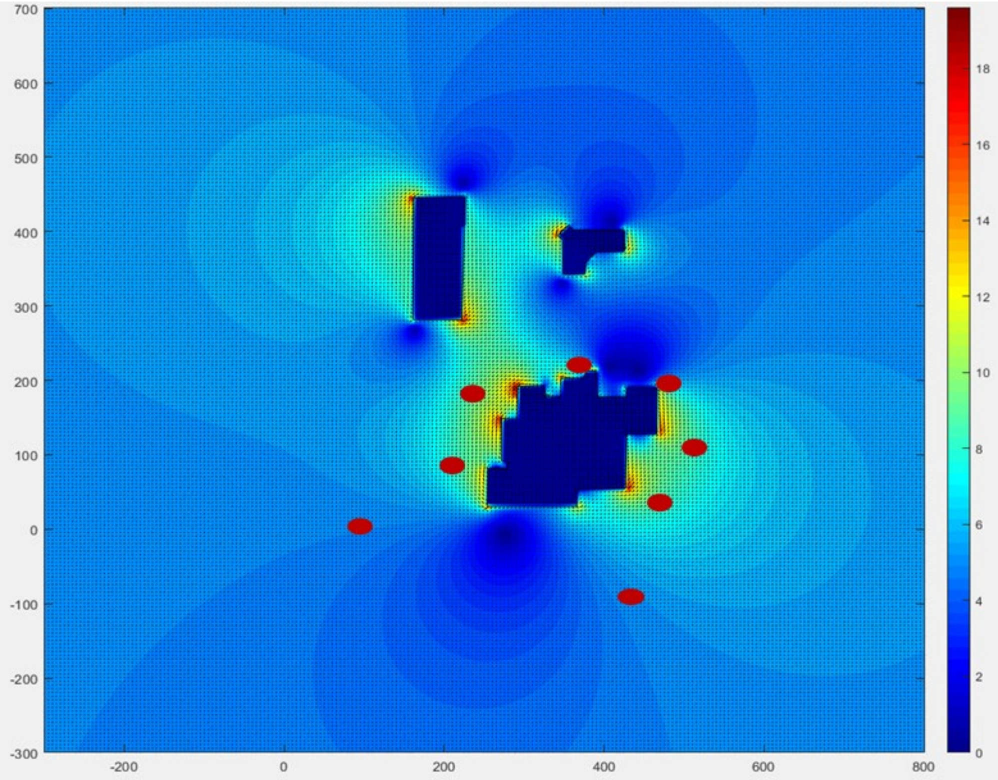

Figure 28: Simulation results and points of interest for NIDEC.

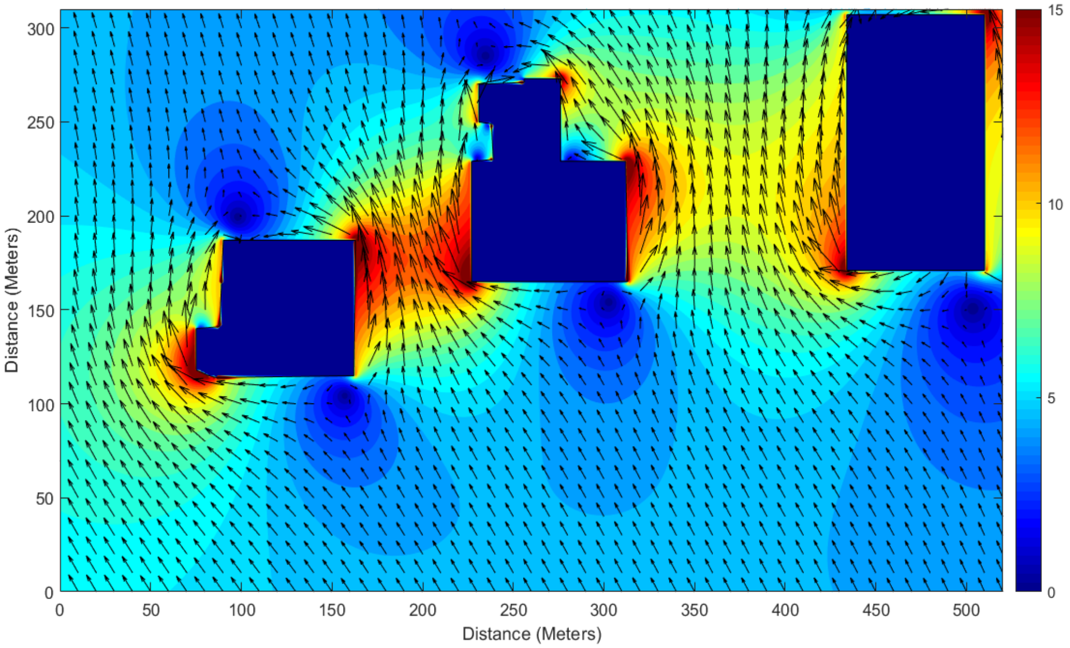

Figure 29: Predicted regions of speed-up around MTU Onsite.

Objective 6: Create public awareness of the research and disseminate results.

Rather than create a dedicated project website, several different social media outlets were used for the project. An Instagram site (https://www.instagram.com/mnsumankatovawt/) was established for basic updates on the project. Later in the project, a Facebook page was been added (https://www.facebook.com/mnsumankatovawt/). The team intended to identify as many VAWT installations (of any size and type) in Minnesota as possible. We were to use a crowd sourced approach to this with the "Great MN VAWT Hunt". However, Covid-19 shut campus down soon after that and this plan never got off the ground.

A series of short videos were made about the project. These were shown during exhibit times at the 2020 Energy Expo and are available online through the CSET Minnesota State University, Mankato YouTube channel as part of the Department of Mechanical and Civil Engineering playlist (https://www.youtube.com/playlist?list=PLw1ptCz6omhyZvh255WFdrQzch4Iu097m). The related videos currently posted are:

- What is a VAWT? Explained by the Minnesota State Mankato VAWT Project
- Description of small wind from the MN State Mankato VAWT Project
- How we use CFD for the MN State Mankato VAWT Project
- Experimenting on wind for the Minnesota State Mankato VAWT Project

During the course of the grant the team has participated in a number or presentation and outreach activities:

- Bruce Peterson, Matt Julius, and Patrick Tebbe presented on "Minnesota State Energy Center Renewable Electric Energy Research Program" at the 2017 Worthington Bioscience Conference.

- Dr. Tebbe participated in a panel presentation at the Minnesota Renewable Energy Roundtable (hosted by AURI) on August 23rd, 2017.

- Senator Al Franken visited campus to discuss the agriculture bill and renewable energy (October 2017). The VAWT research team was one of the groups selected to present to him (Figure 30).

- Tebbe, P., Wodzinski, N., and Lee, N. "Improving Vertical Axis Wind Turbine (VAWT) Performance", 2018 Best Paper Award for Energy Conservation and Conversion Division, Proceedings of the 2018 ASEE Annual Conference & Exposition and 2019 Focus on Exhibits Poster Session, American Society for Engineering Education, 2018 and 2019.

- A panel discussion was held on the MSU campus in December, 2018 dealing with renewable energy. State Senators Frentz, Senjem, and Rosen were in attendance. The VAWT team showcased several of their VAWT models, distributed briefs on the project, and discussed the project with attendees.

- A poster display was made at the Recharge Mankato event (10/6/18). Student workers and Principle Investigators were present. This was a public event to showcase sustainable and renewable energy technologies. In September 2019, the VAWT team again hosted a table at the ReCharge Mankato event. This year we made a special effort at displaying more models, including one which was spinning from a small fan. Figures 31 and 32.

- In April 2019, the MN Department of Commerce Commissioner Steve Kelley, and other elected officials, visited campus to discuss clean energy initiatives. Part of this visit was a tour of the lab and the VAWT experiments being conducted in the water channel (Figure 33).

- Two undergraduate student teams had posters accepted to the 2019 National Conference on Undergraduate Research (NCUR) based on their work with the VAWT project (Figures 34 and 35).

- In October, 2019 the team participated in the 7th Grade Career Readiness Day. Students from the Mankato school district visited campus and toured the labs. Students from the VAWT project talked to them about the wind tunnel, water channel, and 3D printers. They demonstrated using one of the VAWT models in the water channel. The team repeated this event in February, 2020.

- The research team conducted outreach as an exhibitor at the Duluth Energy Expo, Feb. 23-24, 2020. The display included videos of our experimental and numerical work, as well as multiple samples of our 3D printed models (Figure 36). We discussed the project with a range of people.

- Two undergraduate teams from the project have posters accepted to the 2021 National Conference on Undergraduate Education (NCUR). The first is titled “The Effects of Bisymmetrical and Bilateral Symmetrical Vertical Axis Wind Turbine Designs” and the second is “Characterization of Wind Flow Around Buildings in the Context of Small-Scale Urban Wind Power”.

Figure 30: Members of the VAWT team, and other MSU researchers, meeting with Senator Al Franken (October 2017).

Figure 31: VAWT project display at the Recharge Mankato event 2018.

Figure 32: VAWT group at the ReCharge Mankato event (Sept. 21, 2019).

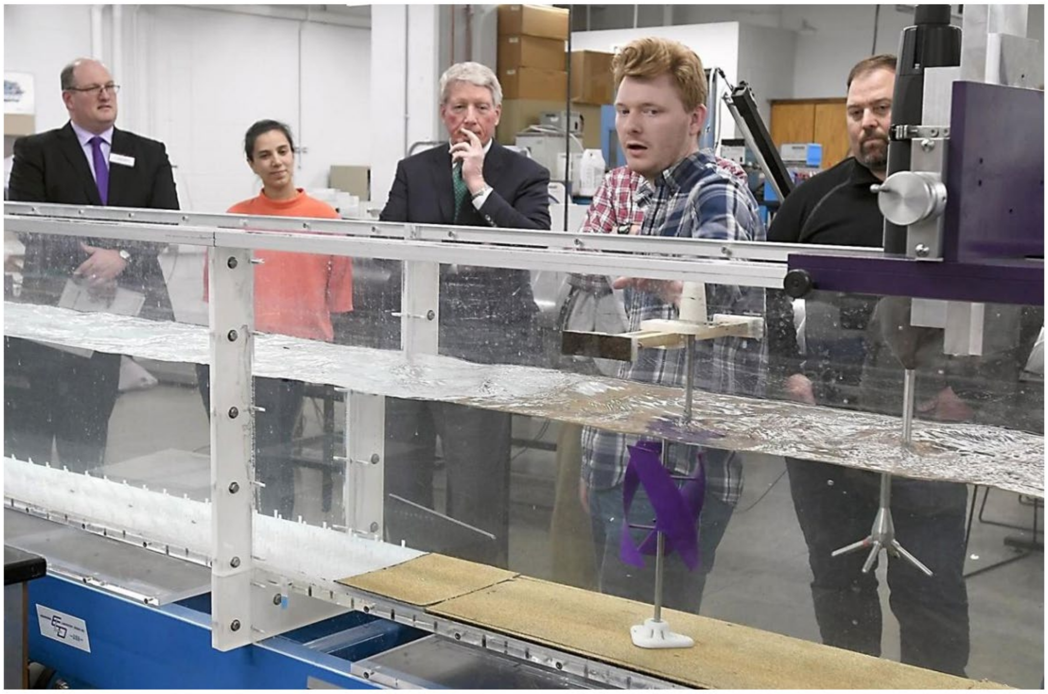

Figure 33: Photo from the April 22nd, 2019 Free Press article discussing MN Commerce Commissioner Kelley's visit to campus.

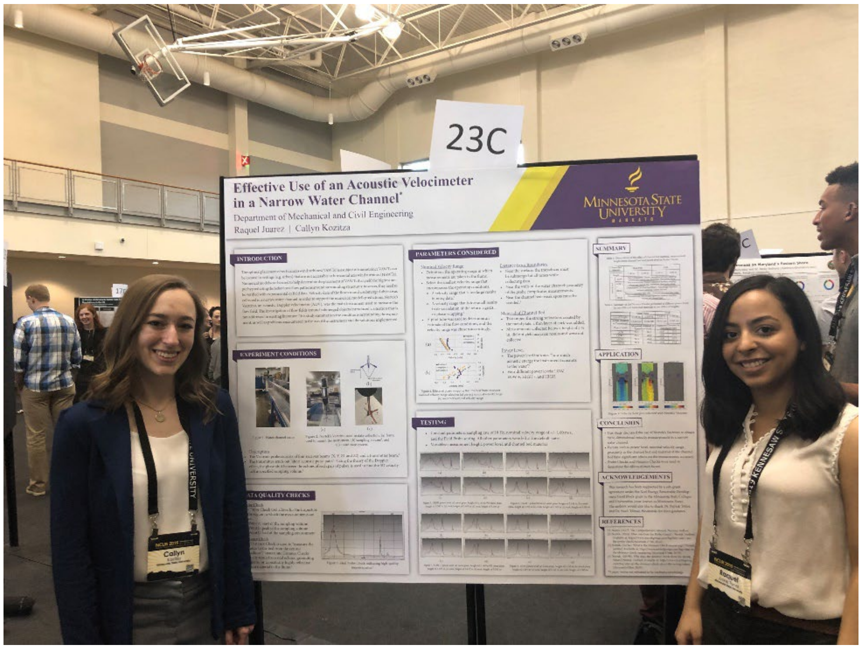

Figure 34: First student team presenting at the 2019 NCUR conference, "Effective Use of an Acoustic Velocimeter in a Narrow Water Channel".

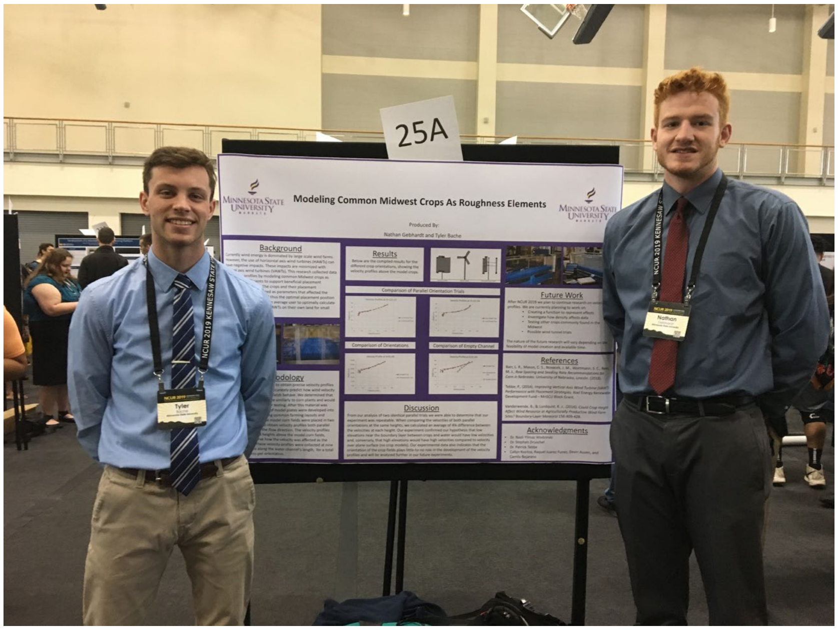

Figure 35: Second student team presenting at the 2019 NCUR conference, “Modeling Common Midwest Crops as Roughness Elements”.

Vertical axis wind turbines (VAWTs) offer advantages for small-scale electricity production, particularly in regions not ideally suited to the more common horizontal axis wind turbines (HAWTs).

Many VAWTS are located for public relations, not performance. Most installation guidelines were developed for HAWTs, not VAWTs. There is still confusion about cost and optimization.

This research has been supported by a sub-grant agreement under the Xcel Energy Renewable Development Fund Block grant to the Minnesota State Colleges and Universities (now Minnesota State).

VAWTs can accept wind from any direction without a yaw mechanism.

Figure 36: Exhibitor display table at 2020 Duluth Energy Expo.

Changes and Problems Encountered

As the research evolved multiple topics arose where the basic industry understanding of VAWTs was lacking. These ranged from issues of public acceptance to technical issues, such as how VAWTs handle turbulence. The project adapted by expanding to explore several of these topics, but this did take time away from the original objectives. Several of these topics could easily be expanded into their own long-term research study in the future (and are outlined in the next section).

One original goal was to produce a software code that would be simple for the public to use. While a simplified code was produced, it would not be considered user friendly for the general public. This would be a difficult task to achieve if VAWT performance was well understood, which is not the case yet. The technical questions referenced in the last paragraph introduce a great deal of uncertainty for any predictions, but especially for ones used by a potential non-technical audience.

There were several delays with the purchase of software required for the project. The State of Minnesota requires that software licenses purchased by Minnesota State University, Mankato must abide by state law. Most software licenses do not, typically due to a provision requiring any conflicts to be resolved under another state’s, or nation’s, laws. The process for contract review and legal negotiation to resolve issues too months.

The largest disruption to the project was Covid-19. This shut down access to most facilities needed for the research. The final laboratory data could not be recorded because campus was closed and off-site data collection was not possible. When access was returned, a new issue had arisen. The delay meant that most of our trained research students had graduated or were otherwise unavailable (e.g. under Covid health restrictions or working elsewhere). To try and complete the last few months of the project a new team of undergraduate researchers had to be brought on board. The time required to train them meant their overall productivity was low.

IMPACT OF THE PROJECT

The project resulted in several findings about VAWT performance and wind flow fields in general. A large amount of data has been gathered in the laboratory and at real world locations, that can be used to conduct further analysis and studies related to wind energy in general, and VAWTs in particular. The findings will aid in industry decisions regarding small wind and help guide future development of VAWTs by the marketplace

The experimental and testing facilities of Minnesota State University, Mankato have been strengthened by the addition of several key pieces of equipment (either purchased or constructed). These resources can be used for a range of energy related research projects, collaborations, and related education.

The project has promoted renewable energy and energy research through several dissemination avenues. These included K-12 students, the general public, industry, as well as state and national politicians.

Thirty-six students (undergraduate and graduate) participated in this project. These students received training in research and exposure to energy related topics. The availability of a paid research position helped them financially manage their education. Two of the undergraduates are now pursuing advanced degrees in STEM related fields. By May 2021, three graduate students will have completed a thesis or project based on this research.

POTENTIAL FUTURE RESEARCH

There are several research topics or outreach activities that could be continued by members of the project team. All have had some preliminary work done on them during the grant project and would be of interest to the larger energy community.

- One of the confounding issues with modeling wind potential closer to the ground, is trees. Trees not only create an obstruction for the wind, inducing changes in the flow field and increased turbulence, but they can also be considered porous (i.e. part of the wind flows through them). Preliminary work was started examining how to include trees in the project’s two dimensional potential code but was not completed due to the amount of effort it would have required. An Alternate Plan Paper (APP) titled “Employing 2-D CFD & LRB Model Around Trees to Improve VAWT Placement” did result from one of the graduate students and can be found here: https://cornerstone.lib.mnsu.edu/cgi/viewcontent.cgi?article=1947&context=etds

- The impact on wildlife from wind turbines is a key concern for the public. VAWTs have traditionally been held out as safer for birds and bats. A literature review was conducted on the topic and while the research tends to confirm the public opinion, the exact mechanisms involved are not fully understood.

- A large number of wind turbines are placed in agricultural areas. Large turbines are placed high enough that they are not affected as much by the ground roughness. However, smaller (shorter) turbines an be impacted by the objects below them. A pair of students researched how different crop types and crop heights might affect the boundary layer development, and hence the turbine output. Laboratory work was presented at NCUR 2019, but there was not time to conduct any field measurements.

- Recently several researchers have reported that not only do VAWTs perform better than HAWTs in turbulent environments, but higher levels of turbulent intensity may actually increase VAWT performance. Since this could potentially affect placement schemes, the project started to examine this aspect, hoping to make use of a hot wire anemometer system in the low speed wind tunnel. Unfortunately, with Covid-19 delays and subsequent changes in personnel this task was not completed. Since the end of the grant we have also been put in touch with Dr. Erik Möllerström, a faculty member at Halmstad University in Sweden. Minnesota State University, Mankato and Halmstad are developing possible collaborations and one of Dr. Möllerström's research areas is VAWTs. Their team is currently conducting research dealing with the turbulence intensity issue.

- Through our exhibit at the 2020 Energy Expo, we were contacted by Chris Burda (Minnesota Renewable Energy Society) about collaborating on an interactive wind energy exhibit for the Minnesota State Fair. Discussions proceeded until the State Fair was canceled due to Covid-19. In the future, this could be an avenue of continued outreach activity.

- Public opinion and acceptance of VAWTs is a poorly understood issue. There are many positive and negative misconceptions about the technology. At the end of the project, one student began researching more on public opinion. A short survey was created that measures preferences between HAWTs and VAWTs for several settings (e.g. residential, urban, agricultural). It is expected that this student will seek Institutional Review Board (IRB) approval and administer the survey during Spring 2021.

PARTICIPANTS IN THE PROJECT

Principal Investigators
Dr. Patrick Tebbe, Mechanical & Civil Engineering
Dr. Nazli Yilmaz Wodzinski, Mechanical & Civil Engineering
Dr. Namyong Lee, Mathematics and Statistics

Graduate Students
Jon Richter (graduated August 2019)
David Basey (graduated August 2019)
Subhan Khalid (graduating May 2021)
Joshua Dickinson (graduating May 2021)
Manish Verma

Undergraduate Students

Austin Hiemstra, Cameron Landherr, Diviyanath Shanmuganathan, Jordan ZumBerge (ME Senior Design team, not paid by project)

Devin Ausen
Callyn Kozitza
Josiah Geiger
Matthew Bulger
Samuel Domeier
Raquel Juarez Funez
Callyn Kozitza
Paul Kriegel
Daniel Stroberger
Sydney Blake
Tinbit Betre
Andrew Sanden
Carson vanSytzama
Jackson Smith
Peyton Wolf
Rishab Humagai
Maryam Betre
Oluwaseun Sholola
Annalisa Tostenson
Mahder Awol
Heidi Welu
Elle Emanuel
Yacouba Koita
Jeremiah Kirch
Tyler Bache
Suiabou Ceesay
Nathan Gebhardt

REFERENCES

1. Wind Energy website, Minnesota Department of Commerce, https://mn.gov/commerce/consumers/your-home/energy-info/wind/, accessed July 12, 2016.
2. "Small Scale Wind Energy on the Farm" by Cathy Svejkovsky and David Ryan, National Sustainable Information Service, www.attra.ncat.org, Nov. 2012.
3. "Built-Environment Wind Turbine Roadmap" by J. Smith, T. Forsyth, K. Sinclair, and F. Oteri, National Renewable Energy Laboratory, technical report NREL/TP-5000-50499, 2012.
4. "Experimental Vibration Analysis of a Small Scale Vertical Axis Energy System for Residential Use," F. Castellani, D. Astolfi, M. Peppoloni, F. Natili, D. Burra, and A. Hirschl," Machines, Vol. 7, 2019.
5. "Low-order modeling of wind farm aerodynamics using leaky Ranking bodies" by D. Araya, A. Craig, M. Kinzel, and J. Dabiri, Journal of Renewable and Sustainable Energy, Vol. 6, 2014.
6. "Development of the flow model to determine the placement of the vertical axis wind turbine (VAWT) in the Padjadjaran University area" AIP Conference Proceedings 1712, 030004 (2016)
7. RETScreen International, www.retscreen.net. (2005). Clean energy project analysis, RETScreen engineering & cases textbook (3rd ed.). Natural Resources Canada.
8. Toronto and Region Conservation. (2015, July). Performance Evaluation of a 700 Watt Vertical Axis Wind Turbine Renewable Energy Series, Technical Brief. https://sustainabletechnologies.ca/app/uploads/2016/08/700VAWT_TechBrief_Jan2016.pdf