

Computational Fluid Dynamics of a Wind Turbine

A Major Qualifying Project

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Abstract

Currently it is difficult to determine wind speed or power output for a proposed wind turbine without on-site wind speed data and computational fluid dynamics (CFD) analysis software. Our Major Qualifying Project is to compare the results from SolidWorks's Flow Simulation package with data that was collected from an actual wind turbine test rig that was custom designed and manufactured. To do this, air was rotated through modeled wind turbine blades in the CFD simulations. On-site, an anemometer collected the local wind speeds while a free spinning wind turbine test rig measured the RPM. The local wind speed and RPM data was then compared to the predicted results from the CFD simulations.

1.0 Introduction

Renewable energy is being sought out as nonrenewable energy sources continue to become scarce and hazardous to the Earth. Two common forms of renewable energy include solar energy and wind energy. Solar power exists in both the industrial scale and residential scale. However, wind energy is almost exclusively available only in the industrial scale. In order to bring wind energy on the same level as solar power, it is necessary to calculate its potential power output. With solar power, it is easy to predict power output given the angle of the solar panels and location of installation without any on-site testing. With wind power, it is much more complicated given the nature of wind. Furthermore, two nearby locations could have vastly different wind characteristics but would have almost identical solar properties. Our Major Qualifying Project (MQP) is to provide software and data collection means for predictions of residential wind turbine power outputs.

2.0 Background

2.1 Wind Power

Power, in general, is the transfer of energy over time. In a rotational setting, power is denoted as:

$$P = T\omega \quad (1)$$

Where P is power, T is torque, and ω is angular speed. For a wind turbine, the power in the wind can be further shown as:

$$P_w = \frac{1}{2}\rho Av^3 \quad (2)$$

Where P_w is the power in the wind, ρ is the density of air, A is the reference cross-sectional area that the wind turbine blades sweep through, and v is the wind speed. At a temperature of 15 °C

and a pressure of 1 atm, the density of air is $1.225 \frac{kg}{m^3}$. The power of the wind is proportional both to the square of the diameter of the wind turbine blades and the cube of the wind speed. Because of this, we will need to use some method other than finding the average wind speed to determine the total power in the wind. A better approach is to find the average cube of wind speed (as opposed to the cube of average wind speed). For example, given a temperature of 15 °C, a pressure of 1 atm, and 1 m² of cross-sectional area, the energy contained in 100 hours of 6 m/s winds is 13,230 Watt-hours whereas the sum of the energy contained in 50 hours of 3 m/s winds and 50 hours of 9 m/s winds is 23,153 Watt-hours. Even though the number of hours and average wind speed were the same, the two scenarios produced vastly different energy outputs [1].

Wind speeds can vary in a given location. So, it is necessary to account for the probability that a certain wind speed will occur. This is generally done by recording wind data for a certain amount of time and dividing the amount of time a wind speed occurs by the total time recorded, as seen below.

$$Probability (v = v_i) = \frac{Number\ of\ hours\ v_i\ occurred}{Total\ number\ of\ hours} \quad (3)$$

And so, the true, weighted average of wind speed is as follows:

$$v_{avg} = \sum_i [v_i * Probability (v = v_i)] \quad (4)$$

Therefore, the average cube of wind speed is simply:

$$(v^3)_{avg} = \sum_i [v_i^3 * Probability(v = v_i)] \quad (5)$$

And so, the average cube of the wind speed is much different than simply cubing the average wind speed. The wind speed is measured with anemometers, which spin at a rate proportional to the wind speed [1].

There is a maximum efficiency, known as the Betz limit, associated with the power that can be extracted from a wind turbine. This efficiency exists because in order for the wind turbine to extract all of the upwind kinetic energy that goes into it, there would have to be absolutely no kinetic energy exiting the wind turbine. This would suggest that there is no downwind wind speed, and given that there is always wind blowing past the wind turbine (at a velocity that is smaller than the upwind speed), there must be some energy lost. The Betz limit occurs when the downwind velocity slows down to one-third of the upwind velocity, in which the wind turbine can extract $\frac{16}{27}$ (59.26%) of the theoretical power in the wind. By the Laws of Physics, no wind turbine is capable of extracting any energy that exceeds the Betz limit. The best modern wind turbines can obtain 80% of this efficiency, in which the turbine blades spin neither too slow nor too fast and have optimized geometry [1].

Other factors that can affect wind turbine power are altitude and temperature. These are related to air density by the ideal gas law, which is proportional to power of the wind. Because wind turbine power is proportional to the cube of wind speed, creating higher towers for a wind turbine can increase generated power. Wind speeds closer to the ground are affected by friction incurred from contact with the Earth's surface as well as trees and buildings [1].

2.2 Wind Turbines

There are two classifications of wind turbines: the horizontal axis wind turbine (HAWT) and the vertical axis wind turbine (VAWT). Most large-scale wind turbines are HAWTs, in which the blades are rotating about a horizontal axis. However, there are some smaller sized wind turbines that have blades rotating about a vertical axis (VAWTs). HAWTs can be further classified into upwind and downwind. The wind blows into the front of the blades of Upwind HAWTs and the wind blows into the back side of the blades of downwind HAWTs. Despite being able to naturally orient itself in the direction of the wind, downwind turbines are plagued by the issue that when the blades are behind the tower, there is reduced wind, leading to potential blade failure and decreased power output. Upwind HAWTs, on the other hand, require more complex control systems to make the blades face the wind. This results in increased power output and reduces the chances of blade failure [1].

VAWTs are primarily disadvantaged because their blades operate closer to the ground, so they experience lower wind speeds and thus have lower power outputs, even though their generators and gearboxes can be easily serviced because they are on the ground. They also do not need a control system because they do not need to orient with the wind direction [1].

An increase in the number of blades decreases the efficiency of blades themselves, so it is better to have fewer blades. Three blades are preferred to two blades because they have smoother operation, even if two blades can generate more power (because they spin at a faster rate) [1].

Regardless of classification, there are various characteristics that are important to all wind turbines. First and foremost, power output of a wind turbine is oftentimes the main motivation for both its production and its purchase. Wind turbines that are sold usually come with a graph that relates wind speed to power. There are some important wind speeds that

determine this power output. Namely, the cut in wind speed is the minimum wind speed needed to overcome friction and generate power. In addition, the rated wind speed is the maximum wind speed that the wind turbine is designed to handle so that the generator is not damaged. There is also the cut out wind speed which is the wind speed in which the wind turbine must be shut down to prevent excessive damage to the generator. These wind speeds are crucial to know when testing and designing a wind turbine [1].

3.0 Preliminary Work

3.1 Computer Aided Design Models

In order to find simulated power output of the wind turbine test rig, a Computer-Aided Design (CAD) model of the wind turbine test rig blades is needed. As such, the blades were modeled in SolidWorks, a CAD software, as seen in Figure 1:



Full Defi

Figure 1 - Computer Aided Design Model of Wind Turbine Test Rig Blades

The blades were modeled by first modeling a tube and creating a plane tangent to the surface area of the tube to perform a sketch. The material that was not needed was cut away (similar to how a sculpture is conceived), and the remaining material was a singular turbine test rig blade that wrapped around the tube's surface area. Various aspects of the fan blade were

measured and inputted into SolidWorks so that the model could match the real thing. After that, the fillets were inserted and holes were made for the bolts to fit in.

The central area of the fan blades was modeled such that at first only a third was modeled (because there are three blades). Within this third, all of the linear lengths were measured so that the curved length could be determined by constraints. Afterwards, the fillets and holes were added. This third was then rotated and copied twice to create the entire central part and the turbine test rig blades were assembled by putting together three blades and the central part.

3.2 Slip Ring Consideration

For the wind turbine test rig, we will need slip rings or a 90-degree gear since the nacelle must rotate but the pole underneath it will not rotate with it. Slip rings are needed because in the case of this MQP sensors will be added to the wind turbine test rig. In a real-world case slip rings will also be needed since either electrical power will be generated or sensors will be needed to calculate speed. There are two types of slip rings, pancake and drum. The pancake slip ring is a horizontal slip ring, as seen in Figure 2: [These figures will be redrawn in the Final Report]:

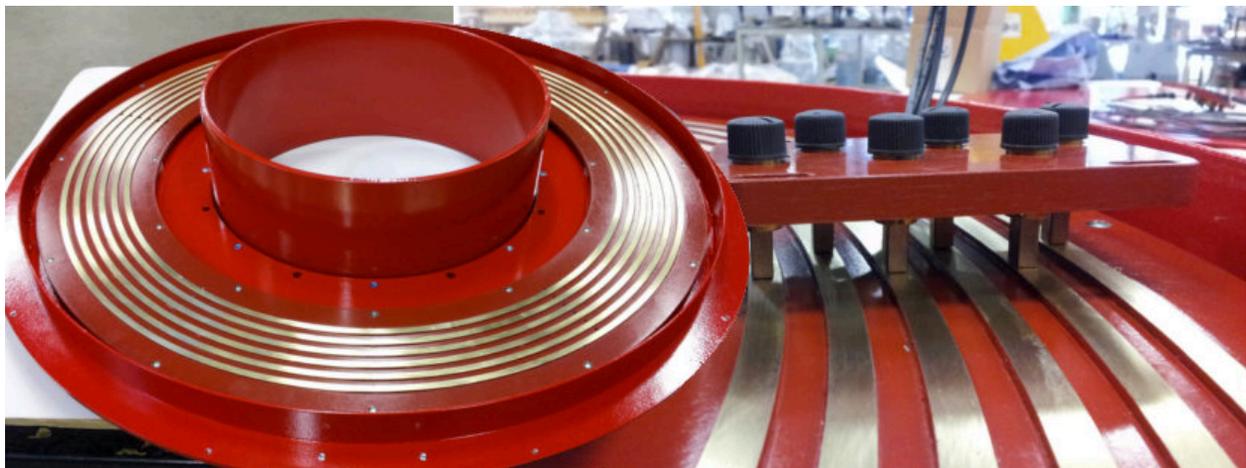


Figure 2 - Pancake Slip Ring

A drum slip ring is a vertical slip ring, as seen in Figure 3:

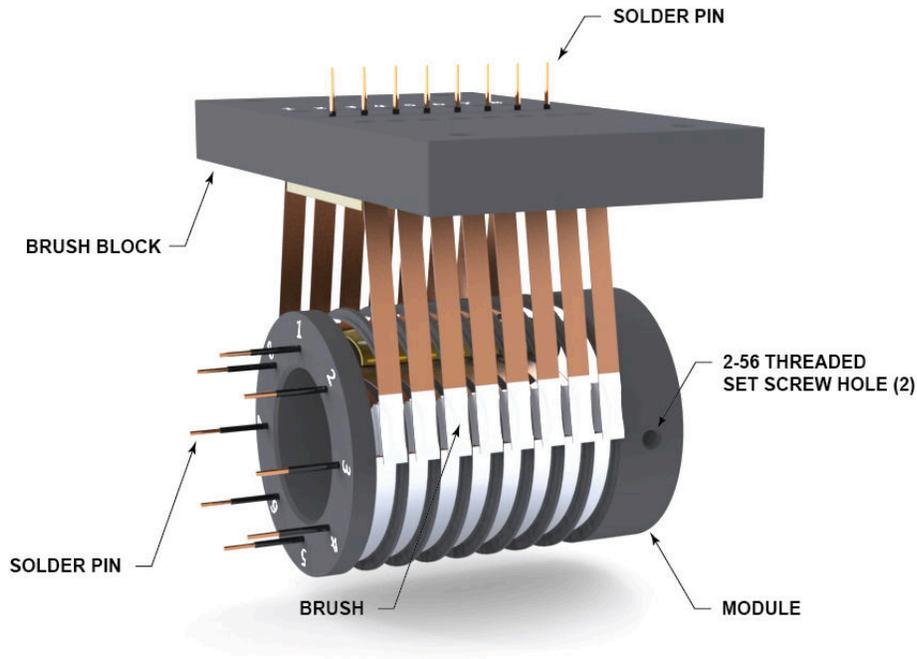


Figure 3 - Drum Slip Ring

Purchasing a retractable cord reel would give us access to a pancake slip ring. There is also the option of directly buying a slip ring or constructing our own. We wish to pursue the slip ring option over the 90-degree gear because they are relatively inexpensive and with the 90-degree gear the turbine test rig blades will be difficult to properly configure due to how the 90-degree gear would inadvertently rotate the entire assembly.

3.3 Preparations for Installation

Given the time that we are working on our MQP, it is important to be aware that the ground will possibly freeze over depending on time of year. As such, we have begun to make the

necessary preparations to install the wind turbine test rig into the ground. First and foremost, a sleeve was inserted two feet into the ground for the pole. In addition, three stakes have been hammered three feet into the ground for the guy wires. Finally, all of the lengths of the guy wires have been measured for future purposes. Figure 4 and Figure 5 show the sleeve in the ground.



Figure 4 - Sleeve in the ground (1)



Figure 5 - Sleeve in the ground (2)

Other considerations for the installation include the fact that the wind turbine test rig will be established with a 17-foot pole. This pole will consist of two poles joined together. Due to this, we do not wish it to take axial loading. This could be caused by wind if there are guy wires attached to it in certain areas. Therefore, we have determined that it would be best to attach the guy wires as far up the pole as possible. This may not be a simple task to connect it to the top though, as we might need to screw bolts into the pole or make eye bolt mounts in the housing to attach the cables.

4.0 Flow Simulation

The goal of this wind turbine test rig is to compare rotational flow simulations in SolidWorks and on site wind data with actual results from the test rig. We hope that in the future this will allow companies and organizations to predict maximum potential wind turbine power output at specific residences. It is important to note that a wind turbine would not achieve its full potential if its maximum power output is not found. In addition, preliminary background research pointed out the fact that the maximum power output is not only dependent on the machine but also the probability of wind speed. As a result, it is necessary to optimize the wind turbine such that it will produce the most amount of power that takes both the wind turbine blades' rotational speed and the fastest wind speed of high probability (while also factoring in the Betz limit).

Though ANSYS is a popular option for computational fluid dynamics and related applications, familiarity with SolidWorks ultimately led to it being the favored choice. SolidWorks, a computer-aided design software typically used for building models of machine designs, has a Flow Simulation package that can be used to determine the torque value that we desire.

4.1 Flow Simulation Setup

After some initial research and failed attempts to set up the flow simulation ourselves, we were put in contact with Joe Galliera who is the Senior Technical Sales Specialist for SolidWorks Simulation for D'Assault Systèmes. He walked us through how to properly set up the flow simulation and gave us good insight on how to set up the mesh.

To begin a flow simulation, the Wizard button was clicked in the 2017-2018 SP 4.0 Academic SolidWorks Flow Simulation software to set up the Flow Simulation. From the pop-up

window, units for velocity and pressure were changed to MPH and $\frac{lb_f}{in^2}$ respectively [2]. The Flow Simulation was configured in SolidWorks Simulation such that it would be an internal flow. This is because of the volume control and how it creates a boundary separating the flow from the rest of the environment, which is why it is not an external flow [3]. In addition, the physical features were designated to be Rotation, with a Local (averaging) region type because the wind was only expected to travel in a single direction. Reference axis was set to Z given the orientation of the CAD model. Default fluid was set to air. For the initial conditions, velocity in the Z direction can be set to the linear wind speed required for each test. On the left sidebar under Rotating Region, Insert Rotating Region was clicked. Rotating region in the Computer-aided Design (CAD) model was selected, as seen in Figure 6:

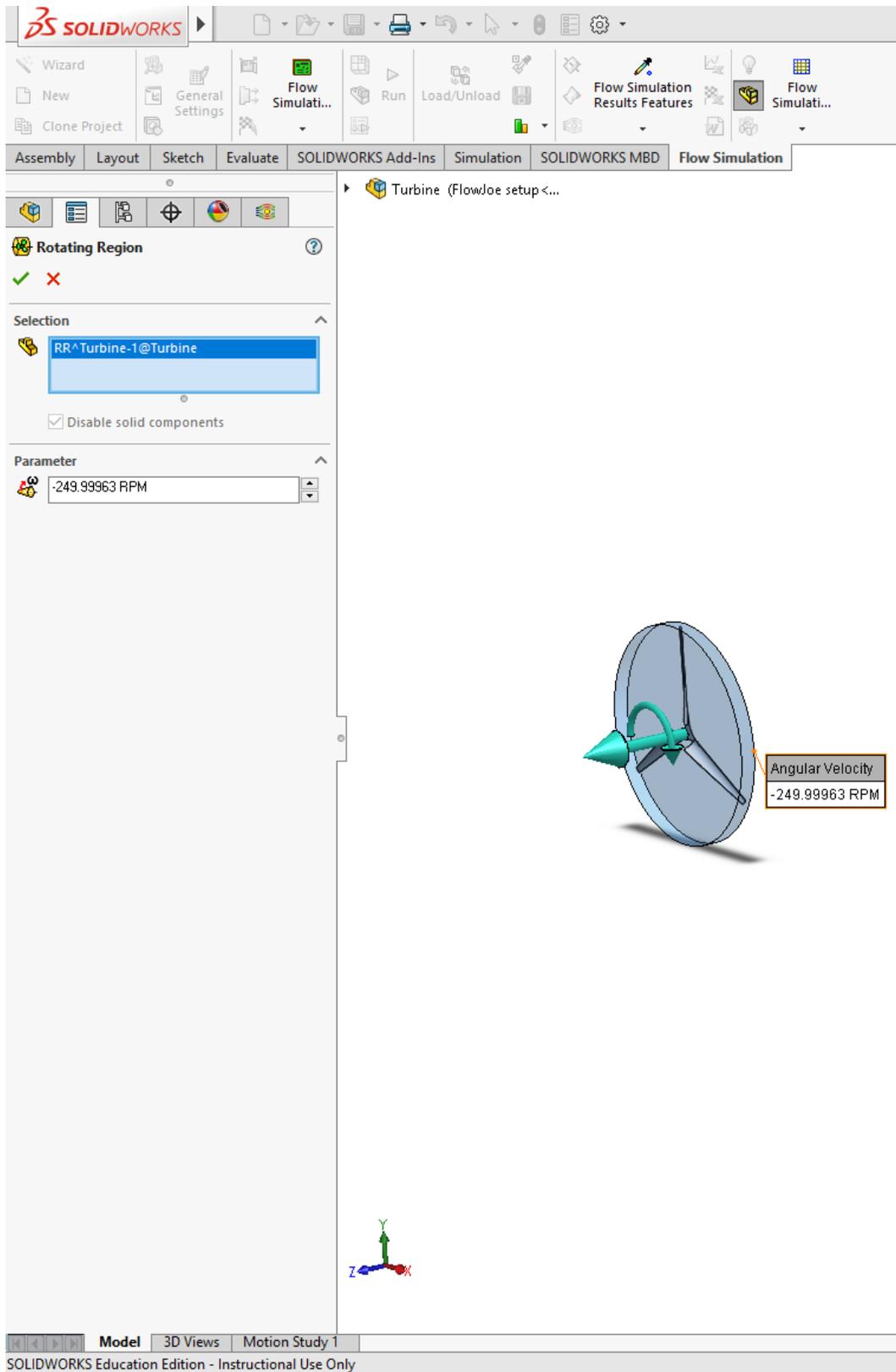


Figure 6 - Rotating Region

The negative of the angular speed was inputted for each individual test. This is because the wind turbine test rig blades cannot be rotated in the simulation; therefore, it was necessary to rotate the air in the opposite direction [2].

We then set the Boundary Conditions from the Insert Boundary Condition button, as seen in Figure 7:

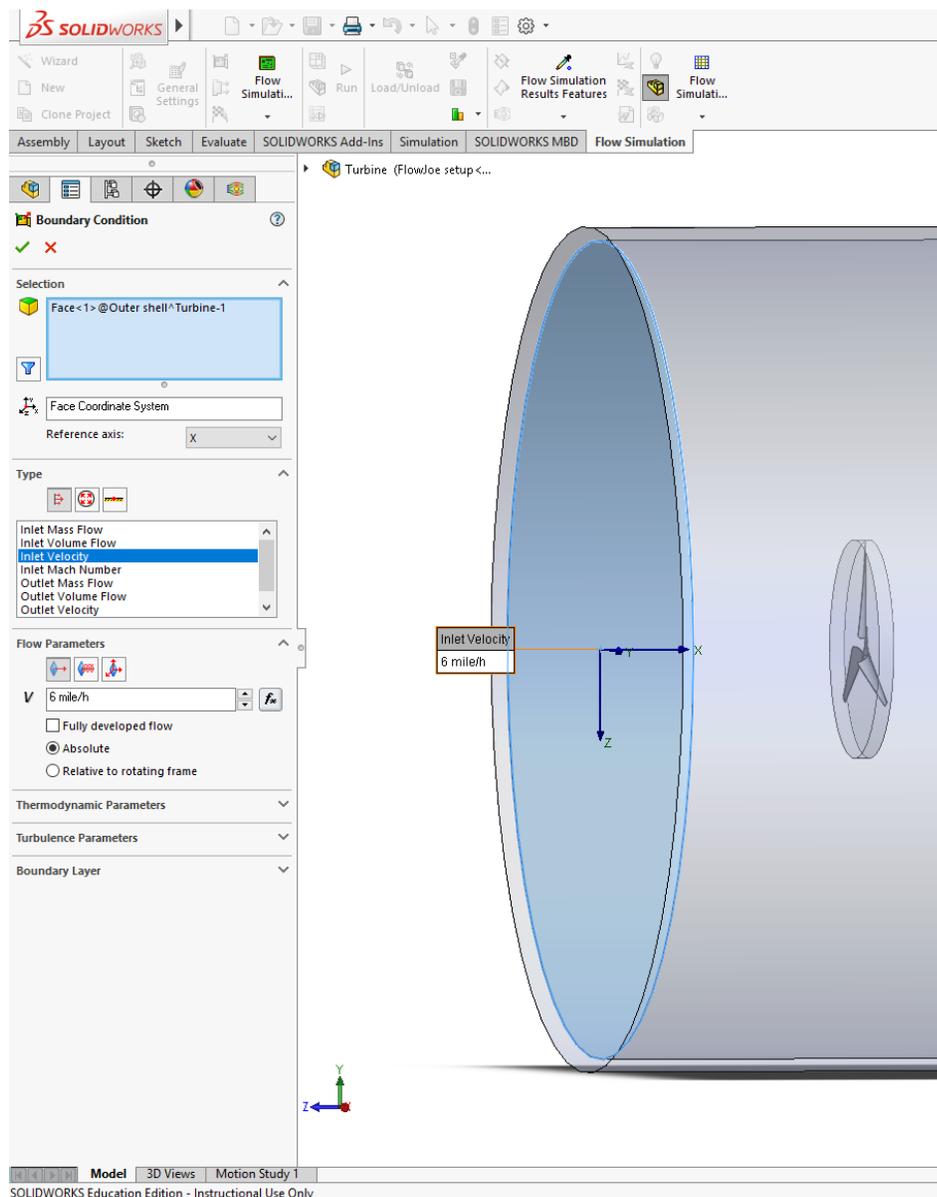


Figure 7 - Inlet Velocity Boundary Condition

Type was identified as Inlet Velocity and Flow Parameters was set as normal to the face at the linear wind speed. The inside front face of the volume control (separated by the thin extrude, a three-dimensional object created by extending a two-dimensional shape perpendicular to its plane) was selected because the fluid is flowing on the inside. In addition, an Environmental Pressure Boundary Condition was set for the back inside face of the volume control in order to allow the air in the simulation to flow out of the volume control (instead of recirculating), as seen in Figure 8:

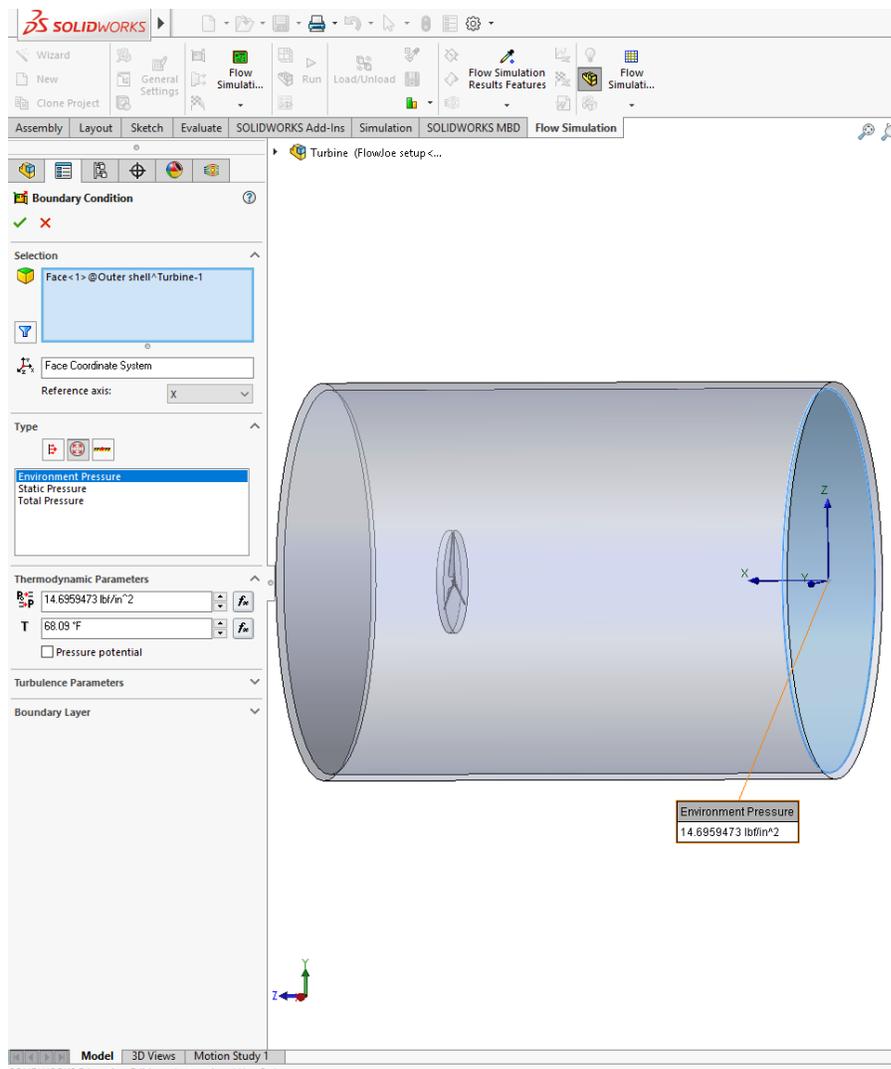


Figure 8 - Environment Pressure Boundary Condition

Type was identified as Pressure Openings and Environment Pressure. Finally, an Ideal Wall Boundary Condition was set by selecting the entire inside lateral area, as seen in Figure 9:

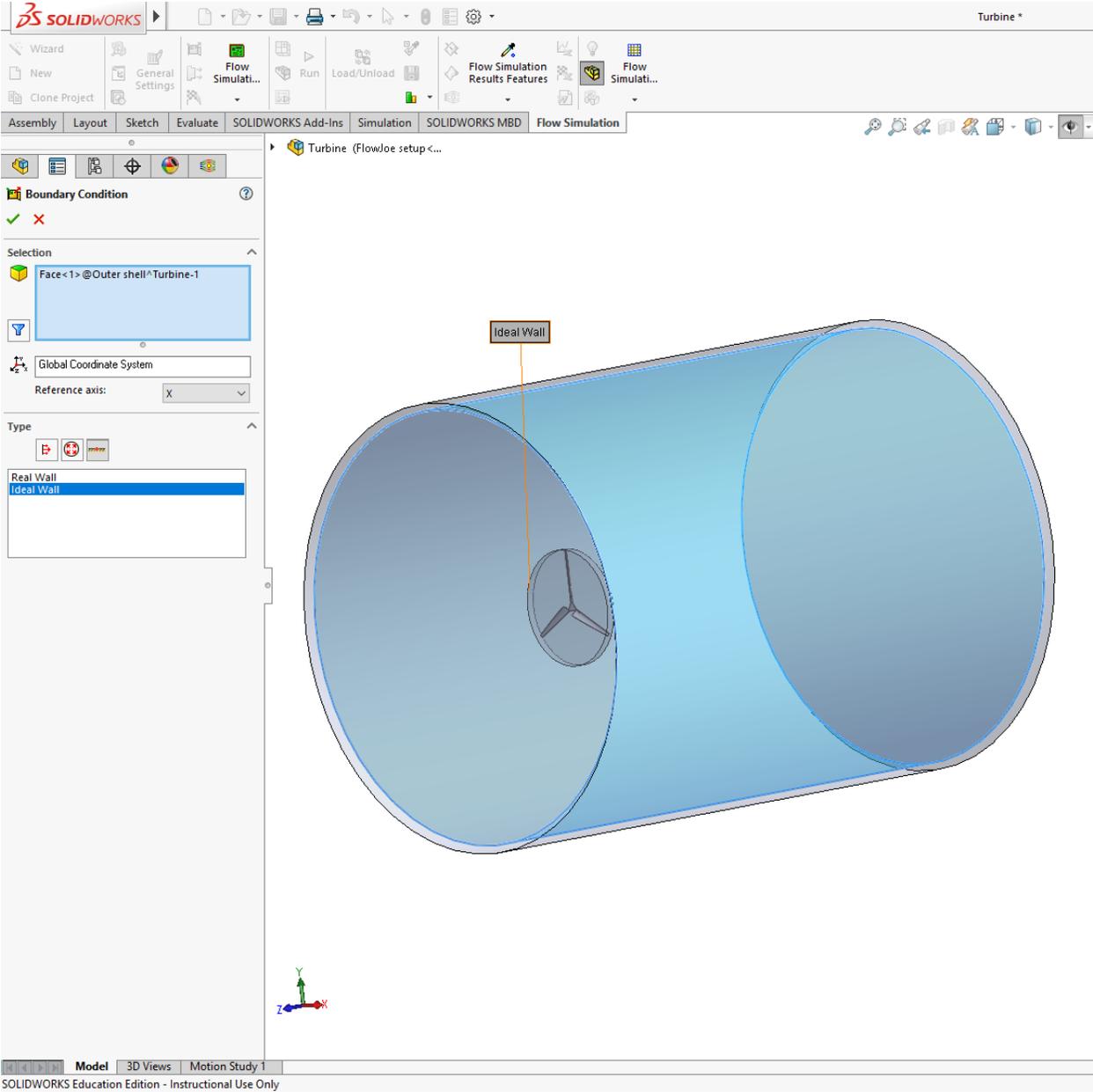


Figure 9 - Ideal Wall Boundary Condition

The type was identified as Wall, specifically Ideal Wall. The Ideal Wall simulates outdoor conditions by making the conditions of the inner face of the volume control to be the same as the conditions of the outer face of the volume control (separated by the extrude) [2].

First mesh that was established was a local mesh by right clicking on mesh and selecting local mesh, as seen in Figure 10:

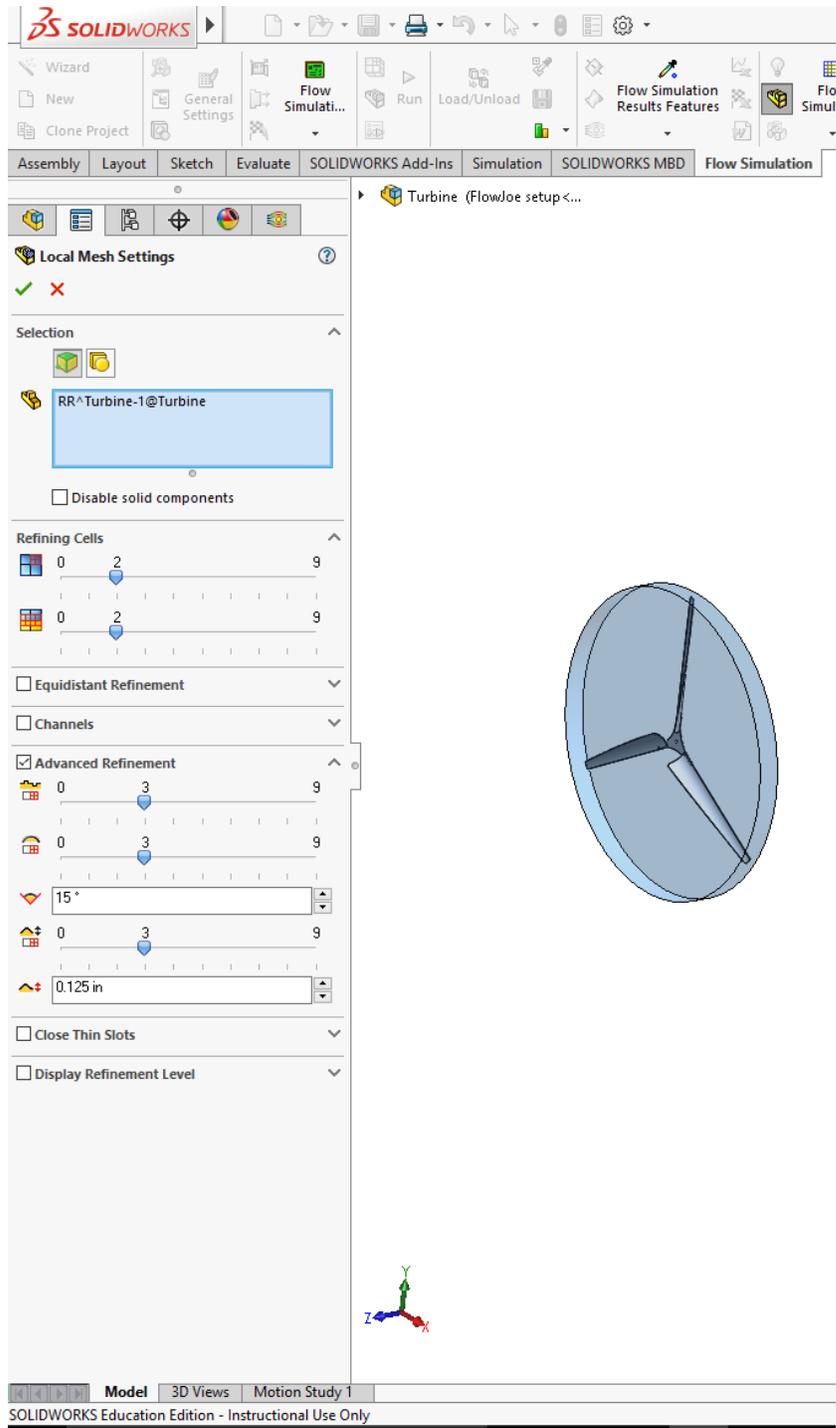


Figure 10 – Local Mesh 1

Type of selection was identified as Reference so that the mesh could be established relative to part of the CAD model. The Rotating region was selected. Refining Cells (both the Level of Refining Fluid Cells and the Level of Refining Cells at Fluid/Solid Boundary) were set to 2 because it used the smallest sized cells while allowing for an accurate mesh. A mesh is like a window pane (a rectangle cut into four smaller rectangles), and refining cells by a level cuts each individual rectangle into four smaller rectangles. Channels were unselected because they were not considered useful for our applications. Advanced Refinement allows for geometric features that further refine the mesh. For the first local mesh, the Small Solid Feature Refinement Level, the Curvature Level, and Tolerance Level were all set to 3. The Curvature Criterion was set to 15°. The Tolerance Criterion was set 0.125 inches because it was the thickness of the blades. Local mesh 2 was designated as a region selection, which utilizes a shape to define the mesh, as seen in Figure 11:

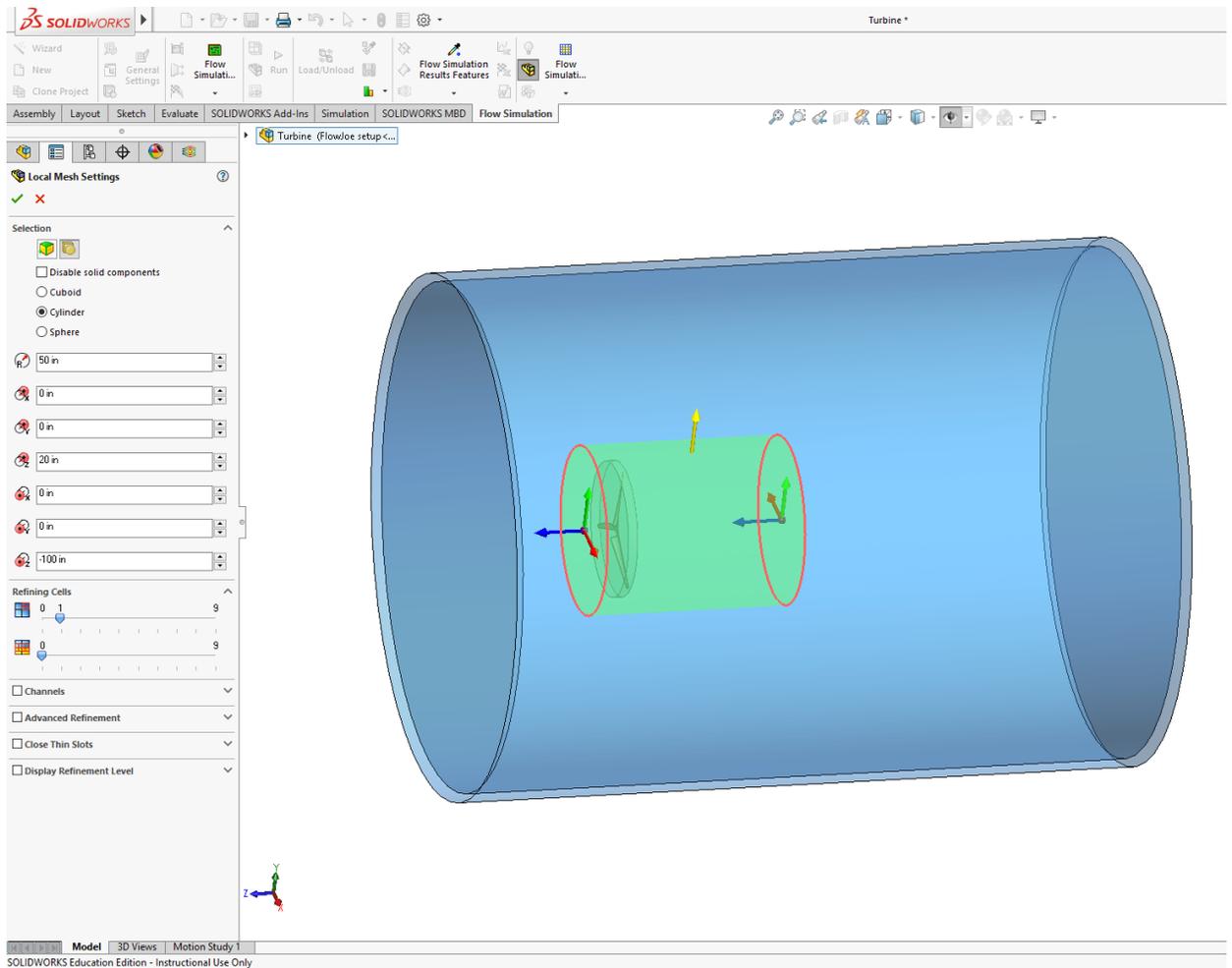


Figure 11 - Local Mesh 2

The type of region was identified as a cylinder, with a radius of 50 inches and a height of 120 inches. This local mesh is meant to take the global region and refine the mesh as it approaches the wind turbine test rig blades. Therefore, the Level of Refining Fluid Cells was set to 1 and the Level of Refining Cells at Fluid/Solid Boundary to 0. Channels and advanced refinement were not used for this local mesh. Local mesh 3, seen in Figure 12, the local mesh associated with the wind turbine test rig blades, was a Reference selection, similar to local mesh 1.

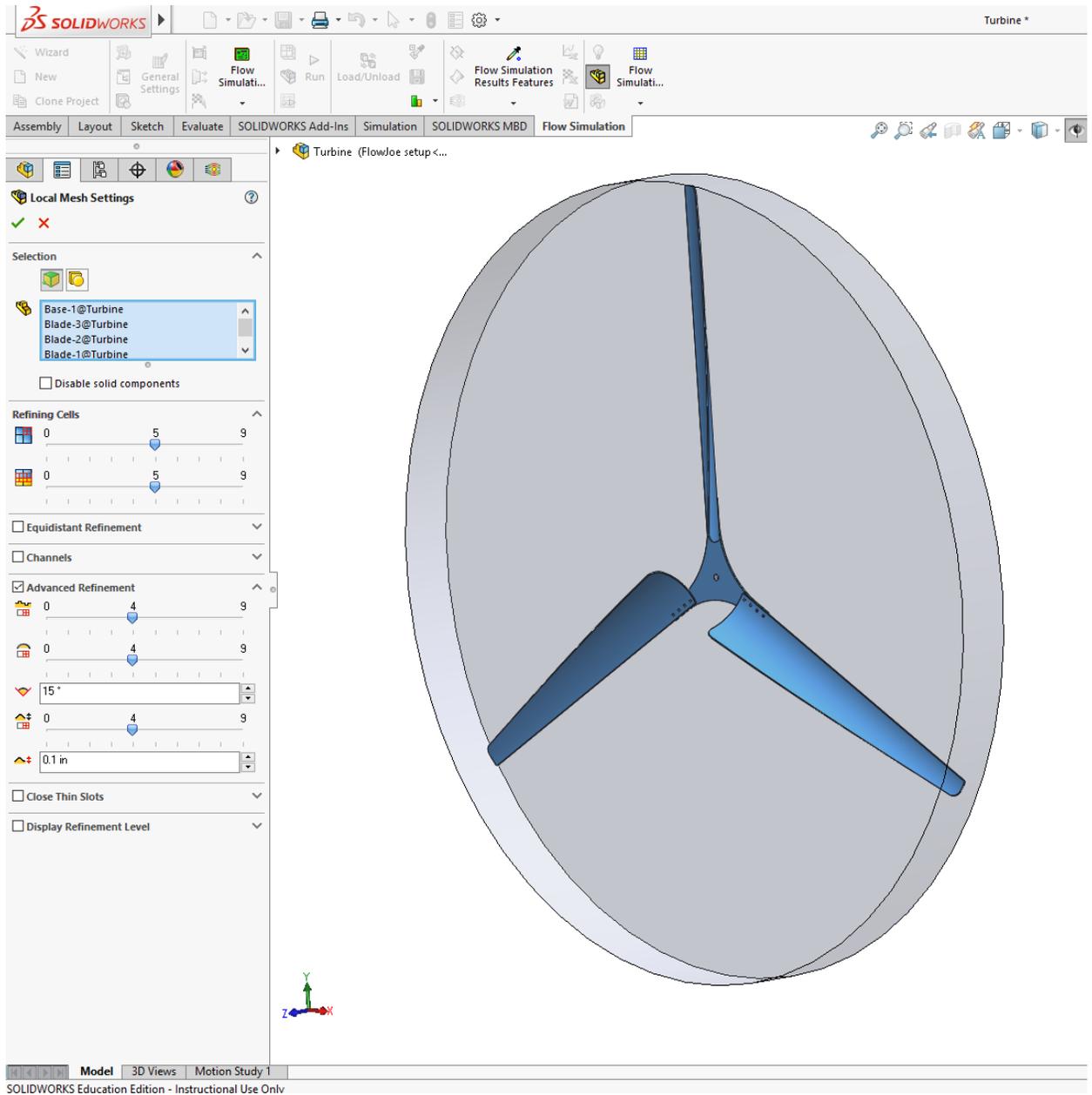


Figure 12 - Local Mesh 3

The wind turbine test rig blades and the base plate (the piece that connects the blades) were selected. The Level of Refining Fluid Cells and the Level of Refining Cells at Fluid/Solid Boundary were both set to 5. For the Advanced Refinement, the Small Solid Feature Refinement Level, the Curvature Level, and Tolerance Level were all set to 4. The Curvature Criterion was

set to 15°. The Tolerance Criterion was set 0.125 inches. Local mesh 4 was also a Reference selection, selecting the faces and lateral area of the rotating region, as seen in Figure 13:

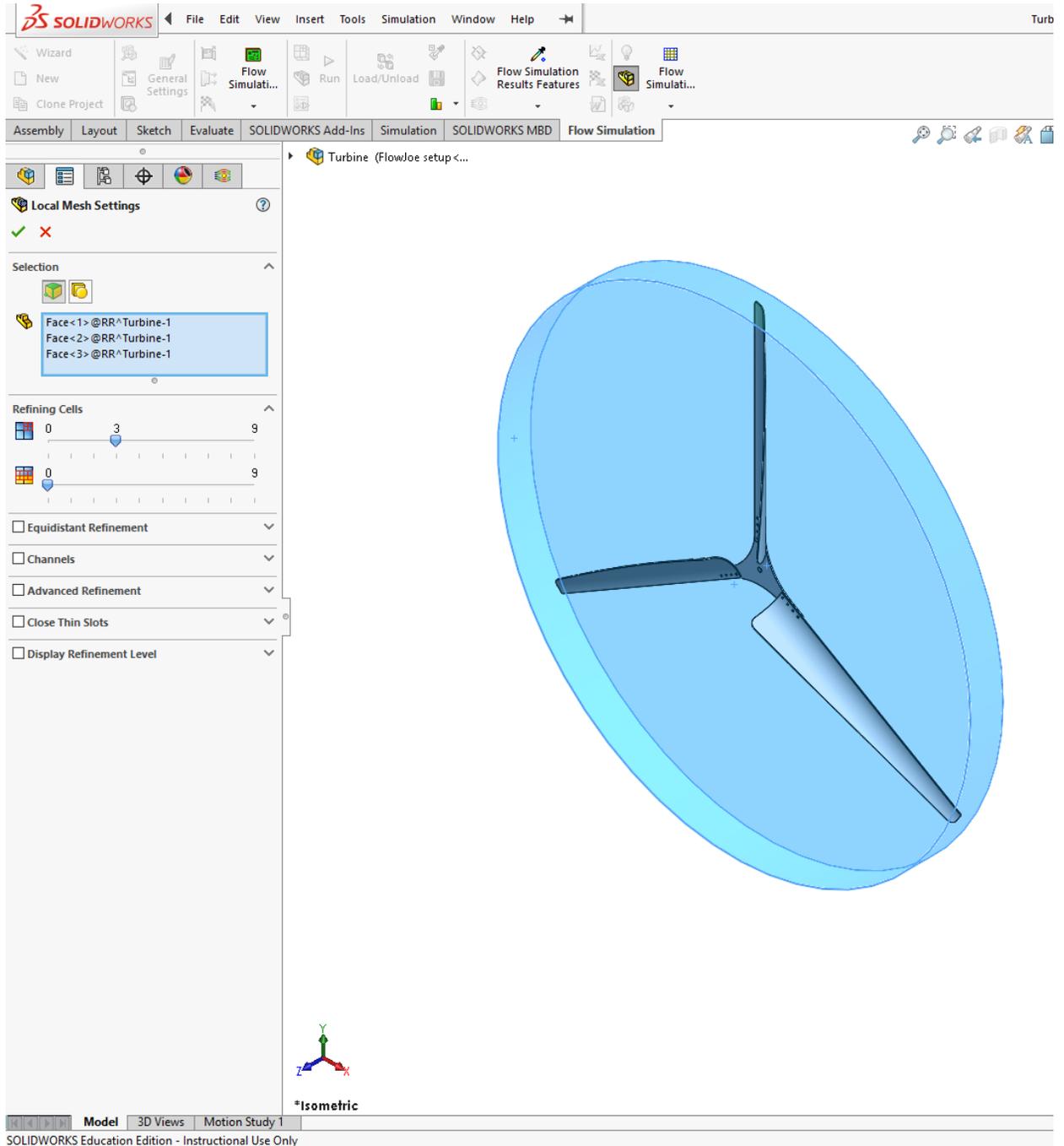


Figure 13 - Local Mesh 4

The purpose of local mesh 4 was to establish another boundary between local mesh 1 and the global mesh, which creates another layer of refinement. The Global mesh was set to the automatic type for ease of use and settings were set to the 7th level because it was the smallest cell size in the automatic type [2].

After completing all the necessary meshes, goals were established for converging towards a solution and cutting down on computational time. The four goals for our wind turbine test rig were the torque value, the static pressure, the minimum wind velocity, and the fan volumetric flow rate. The torque value, the main objective of the flow simulation, was set as a surface goal, as we were attempting to ascertain the amount of torque applied to the surface of our blades. In order to properly simulate a free-flowing wind turbine test rig, for a given wind speed we hoped that our estimate of the RPM would result in a torque value of 0. If this does not happen, we would go back and input a different RPM estimate until we achieved our objective. The static pressure was set as a global goal to find the average static pressure. This value was simply found for convergence and was not critical. The minimum wind velocity was set as a global goal. The minimum was found because all inputted wind velocities were negative due to the orientation of the wind turbine test rig blades (and so finding the minimum was essentially finding the absolute maximum). The purpose of this goal was simple to have a way to gauge accuracy of results. Finally, the Fan Volumetric Flow Rate was established at the request of Joe Galliera [2].

In order to proceed with the flow simulation, we set up a “What If” analysis parametric study (not goal optimization). We chose a parametric study instead of a regular run (the other option) because the regular run was giving us inconsistent results due to a bad mesh. Furthermore, a parametric study is easier to set up and run [4]. A “What If” analysis shows what would happen given that we change a certain variable. For the purposes of our wind turbine test

rig, we chose to change the angular velocity to see what would happen with the torque on the wind turbine test rig blades. To begin, initial conditions of velocity in the Z direction were established due to the orientation of the CAD model by going to General settings and clicking on Initial conditions. Then, by going to the Rotating region section, the angular velocity was selected. To establish Boundary conditions for the parametric study, the environment pressure was set and the inlet velocity was made to be normal to the face. The Level of Refining Fluid Cells and the Level of Refining Cells at Fluid/Solid Boundary of Local Mesh 1 were considered for the parametric study. For velocity, the linear wind speeds were inputted. Initial conditions should be opposite linear wind speeds for velocity in Z direction due to the orientation. Output variables were designated as the minimum wind velocity, torque volume, and the volumetric flow rate goals. The scenario section comes up with all possible combinations of the variables. This functionality allowed us to sort through the combinations and select the ones that pertained to our objectives [2].

5.0 Test Rig Data Collection and Analysis

5.1 Wind Probability

As previously mentioned, power produced from wind is proportional to the cube of the wind speed. As such, ascertaining actual power output of the wind turbine test rig requires extensive wind data collection. We are collecting wind data for two reasons: to compare it to RPM of the wind turbine test rig and to figure out how long it would be necessary to obtain an accurate sample size.

A wind speed sensor (also known as an anemometer) was purchased for this very reason. Initially, we narrowed down our options to the Inspeed Vortex Wind Speed Sensor and the Ambient Weather WS-0900-IP Wireless Internet Remote Monitoring Weather Station. We chose

the Inspeed Vortex Wind Speed Sensor because it outputs a pulse for every revolution (a linear relationship of 1 pulse/second to 2.5 mph) at small enough intervals [5]. The Ambient Weather WS-0900-IP Wireless Internet Remote Monitoring Weather Station only produces a graph of its collected data and does not show data points that we need. It also only has intervals from day to day, which are too long for our purposes [6].

In addition, in order to make use of the Inspeed Vortex Wind Speed Sensor, an ESP8266 was programmed to receive wind data from the anemometer. The ESP8266 connects to Wi-Fi and logs data at 10 second intervals to a server in Northern Virginia. The ESP8266 counts the number of times the anemometer makes a full rotation in a 10-second interval, and then divides that number by 10 to obtain the average number of rotations per second. Since 1 rotation/second (Hz) is equivalent to 2.5 mph, the average number of rotation can be converted into MPH by multiplying it by 2.5. We have a website that can access the server, giving us live, up to date information on the wind, as shown in Figure 14:

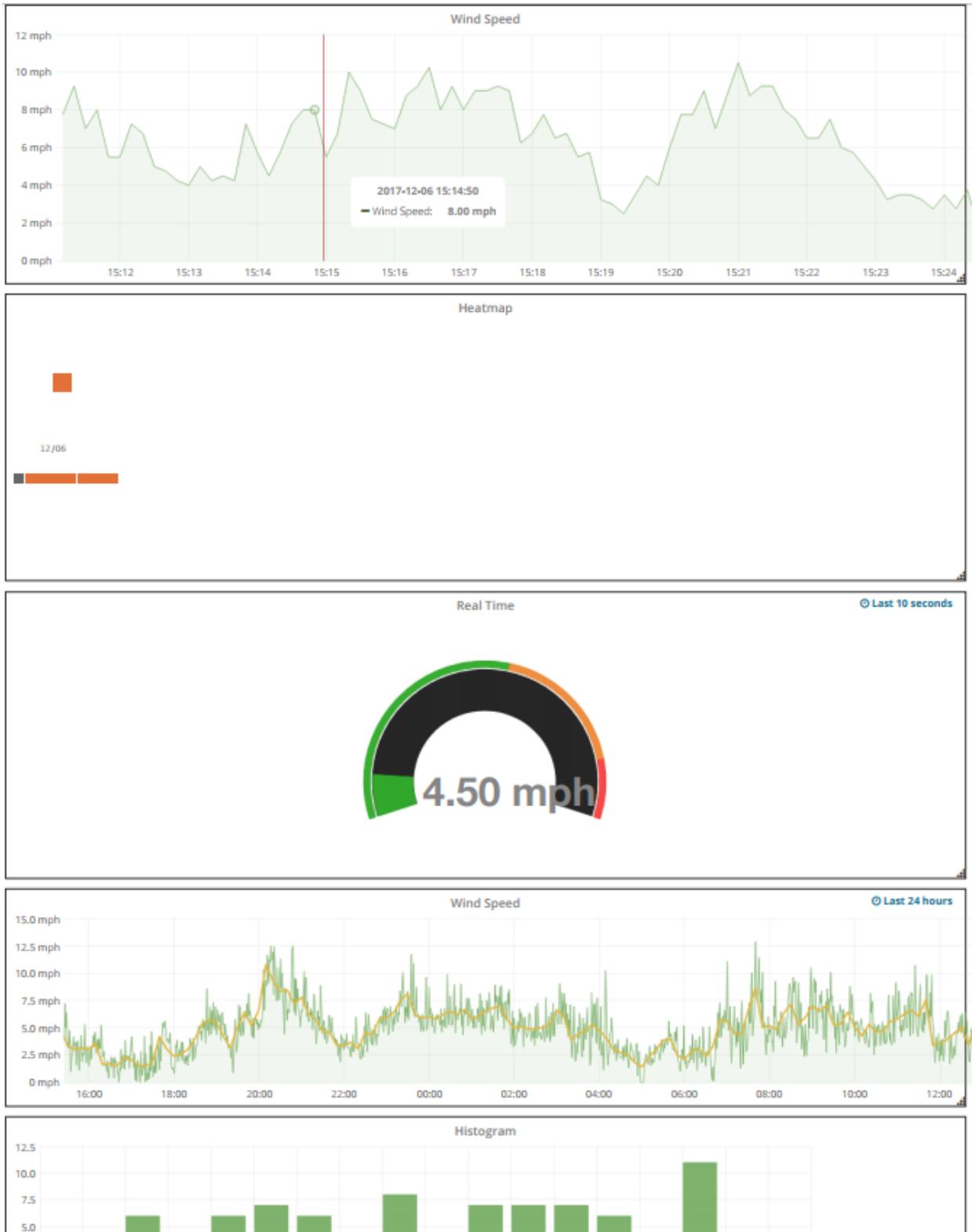


Figure 14 - Wind Speed Data Collection

From the wind data collection, a probability table of the wind speeds can be established, as seen in Table 1:

Table 1 - Probability of Wind Speeds

	Wind Speed (MPH)												
	0	6	9	11	13	15	17	20	22	24	26	29	32
Probability		8.9E-01	8.5E-02	1.6E-02	5.9E-03	2.5E-03	9.8E-04	3.7E-04	6.2E-05	2.1E-05	8.3E-06	4.1E-06	8.3E-06

It is important to note that Table 1 only includes probabilities of wind speed when it is greater than 0. This is because when wind speed is 0, the power output is always 0. Therefore, the probability of 0 wind speed can be ignored.

Though intuitively it may make sense to believe that 32 MPH wind speeds would produce the greatest power output, Table 1 clearly portrays that this statement is not quite accurate. The probability of a 32 MPH wind speed occurring is negligible. In fact, it is more likely for 6 MPH wind speeds to produce the most power, occurring almost 90% of the time.

6.0 Conclusions and Future Considerations

6.1 Electrical Concepts

For someone to use our testing results to optimize their design of a wind turbine, it is necessary to explore topics related to electricity and wind. First and foremost, the central aspects of electricity, namely current, voltage, and resistance, must be defined. Current is the rate at which charged particles pass through a certain point [7]. Direct Current (DC) is current that flows at a steady rate and in a single direction. Alternating Current (AC) is current that flows back and forth in a sinusoidal manner [7]. Voltage is the electrical potential energy difference across a circuit. Resistance is a material property that determines the potential difference given a certain amount of current flowing through it. Therefore, the following equation, known as Ohm's Law, determines resistance:

$$R = \frac{V}{I} \quad (6)$$

Where R is resistance, V is voltage, and I is current. A conductor that has a certain resistance is a resistor [7]. In an electrical device, power is the product of current and voltage, as shown below:

$$P = IV \quad (7)$$

Where P is power, I is current, and V is voltage. Power loss through a resistor is converted into thermal energy, which is not useful for electrical applications, and can be denoted as:

$$P_{Loss} = I^2 R \quad (8)$$

$$P_{Loss} = \frac{V^2}{R} \quad (9)$$

Where R is resistance of the wire, V is voltage, I is current, and P_{Loss} is power loss [7].

6.2 Renewable Energy

Approximately 10% of energy sources is renewable energy in the United States of America. Within this 10%, 23% make up wind-related energy sources. Other renewable energy sources include hydro (60%), biomass (13%), geothermal (4%), and solar (0.3%). However, these renewable energy sources are only about 33.3% efficient, with the remaining 66.7% being lost to thermal losses, powering the plant itself, and power losses in distribution lines. Because renewable energy generators are designed so that they can only run under certain conditions (such as the wind blowing or the sun shining), they often get curtailed when the power supplied is greater than the demand, as opposed to nuclear reactors that will run almost all the time close to maximum power [7].

To incentivize the use of renewable energy, the United States government has created Renewable Energy Certificates (RECs). RECS are technology and environmental (non-energy) attributes that represent proof that 1 megawatt-hour (MWh) of electricity was generated from an eligible renewable energy resource, that can be sold separately from the underlying generic electricity with which they are associated. REC owners can retire them in exchange for financial compensation. In this sense, there is an incentive to use renewable energy such as wind power. There are three ways to purchase RECS: through a Power Purchase Agreement, directly through a utility, and through an independent market [8].

Incentivizing renewable energy ultimately brings up the question of who will be willing to purchase it. We have identified an important, potential customer: wind turbine installation companies who could use our flow simulation and data collection to help them find potential locations to install wind turbines.

A second potential customer is the US military. In remote bases and posts in Afghanistan, the military uses gasoline generators to power their camps. However, it takes roughly two gallons of gasoline to transport one gallon of fuel [9]. To put this into monetary terms, the military must spend up to \$400 to airdrop one gallon of gasoline [10]. A way to help reduce these high costs is to use wind power to produce electricity and our models could help predict electrical output in new bases where known wind data is limited.

The military uses about 70% of its gasoline consumption to transport the remaining 30% of gasoline. At remote bases, the military uses gasoline generators [9].

6.3 Wind Turbine Electric Machines

Wind turbines (and most other machinery that generates electricity) work in a way such that it is powered by a fluid in motion (in this case the wind) which passes through and spins the wind turbine blades, thus spinning the shaft. The generator then uses the energy from the rotating shaft to produce electricity [11]. The wind turbine's ability to produce electricity begins with Faraday's Law. Faraday's law is the derivative of magnetic flux (the integral of a magnetic field over the area that it occupies) with respect to time (known as induction), and this induces a voltage with a current in a closed conducting loop. Faraday's Law leads into the Hall effect. A Hall effect is when a magnetic field perpendicular to a conductor strip that carries current produces voltage across the conductor strip [7].

A synchronous machine has a grouping of conductors known as an armature that are positioned in such a way that they can be moved through a magnetic field and induce voltage. Typically, armatures are placed in stationary stators that are close to a rotating magnetic field, which is either created through a permanent magnet or field windings. Conductors receive DC current from the more popularly used field windings that can either be spiraled around slow-

spinning salient poles or found in faster moving rotating rotors. The following equation shows how the speed of those rotors is determined: is shown below:

$$N(\text{rpm}) = \frac{120f}{p} \quad (10)$$

Where N is the rotor speed, f is the output frequency, and p is the number of poles [7]. In general, three-phase synchronous machines convert mechanical torque to electrical power when connected to the grid. Its rotor must spin at the same speed as other grid generators [11].

In addition to synchronous machines, there are also induction machines. Induction machines do not operate at synchronous speed with a load. There are two types of induction machines: wound rotor induction generators (WRIG) and squirrel cage induction generators (SCIG) (made up of a copper/aluminum cage that is similar to one that is used for a pet squirrel). A WRIG, which can operate at a controlled speed, supplies AC (with varying frequency) to the rotor and the stator responds with 60 Hz of AC (frequency of the grid in the United States of America). The frequency within the rotor always tries to maintain this 60 Hz by balancing out the supplied AC frequency. If the rotor spins with a frequency of 65 Hz, the supplied AC frequency responds with 5 Hz in the opposite direction. WRIGs require exciters, brushes, and slip rings. A SCIG has its rotor shorted. The stator, as usual, is connected to the grid which has AC running through it. This AC in the stator allows for the rotor to spin when torque is applied, thus outputting AC voltage back into the grid at the same frequency it was inputted (60 Hz) [11].

6.4 Research on Existing Residential Wind Turbines

DC household wind turbines currently dominate the residential wind energy market.

From data of current DC household wind turbines on the market, we ascertained the efficiency,

as a percentage of 59.26% (The Betz Limit), for a 400-Watt wind turbine, 600-Watt wind turbine, and 1500-Watt wind turbine. Figure 15, Figure 16, and Figure 17 below show power (in Watts) versus wind speed (in MPH) provided by the manufacturer of the 400-Watt, 600-Watt, and 1500-Watt wind turbine.

Electricity (W) Produced at Different Wind Speeds (MPH)

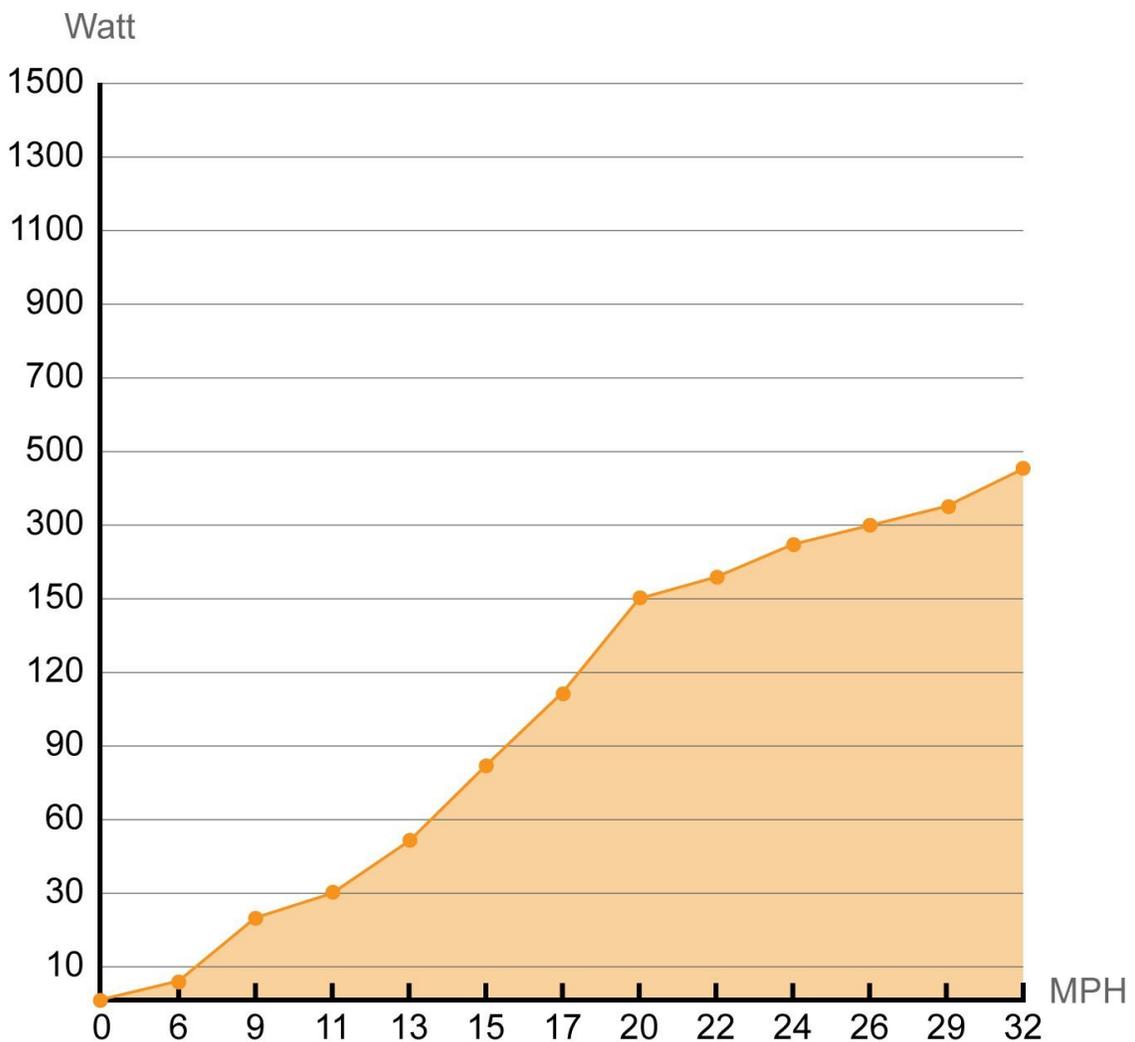


Figure 15 - 400-Watt DC Wind Turbine Power Output vs Wind Speed [12]

Electricity (W) Produced at Different Wind Speeds (MPH)

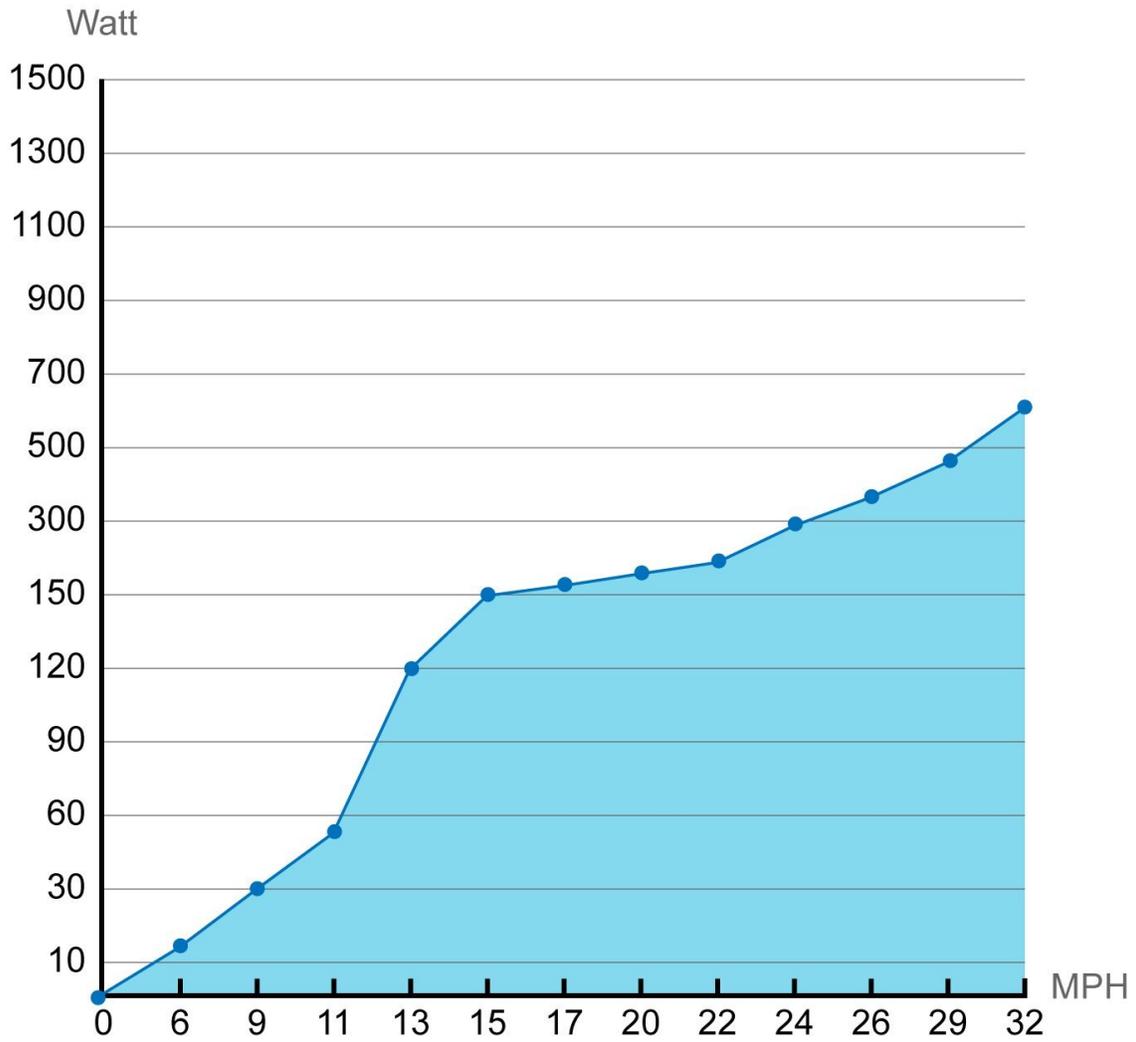


Figure 16 - 600-Watt DC Wind Turbine Power Output vs Wind Speed [13]

Electricity (W) Produced at Different Wind Speeds (MPH)

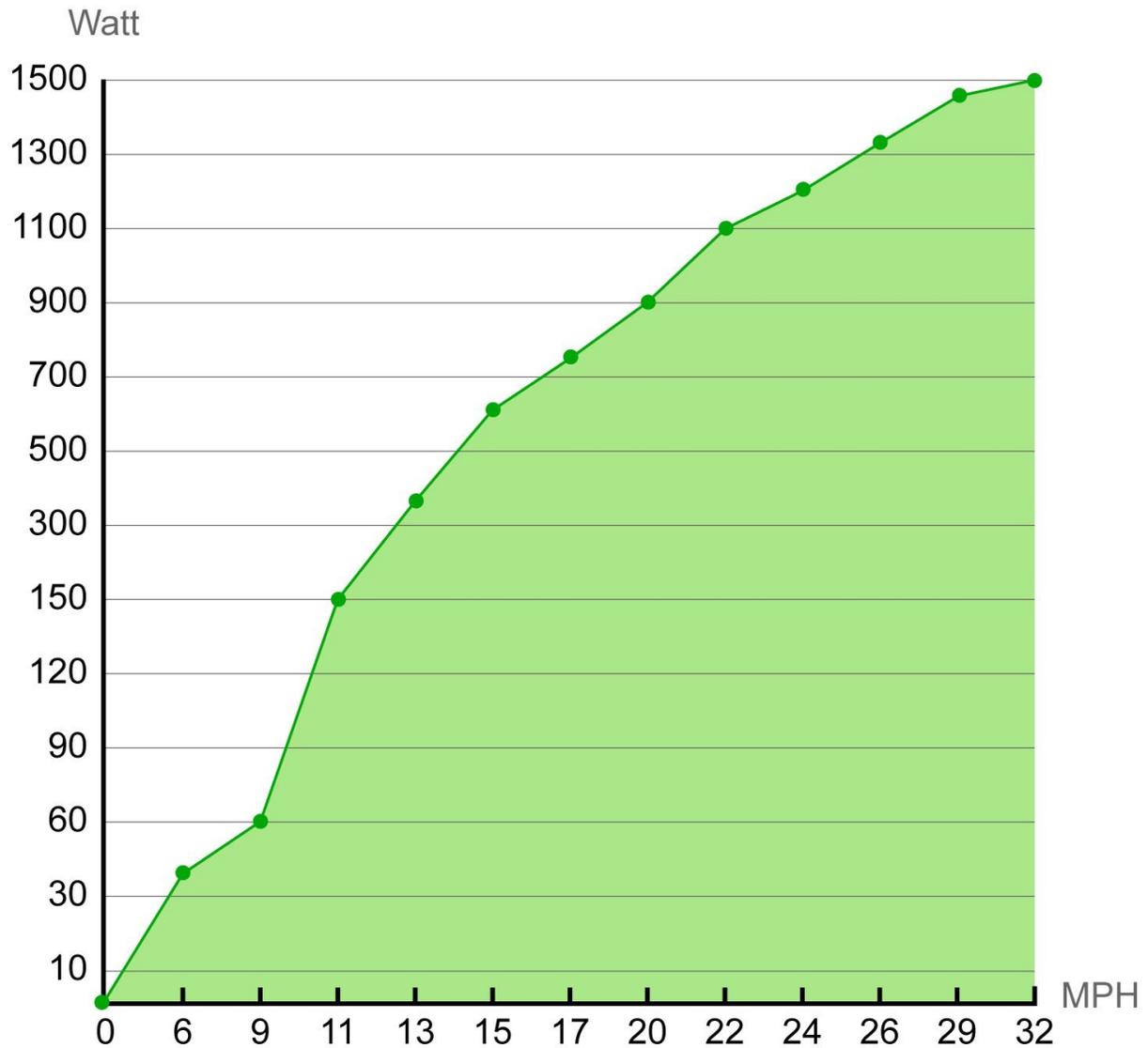


Figure 17 - 1500-Watt DC Wind Turbine Power Output vs Wind Speed [14]

The manufacturers did not provide an efficiency for each turbine. We calculated the efficiency of each wind turbine based on the data provided and conducted a trial-and-error process to find the estimated curve that best matched the rated curve to ascertain each one's efficiency. For each wind speed shown above, we calculated a power output with a theoretical

efficiency and blade area. We adjusted the efficiency until we achieved a minimum R^2 value for power output. Figure 18, Figure 19, and Figure 20 show the graphs related to this process:

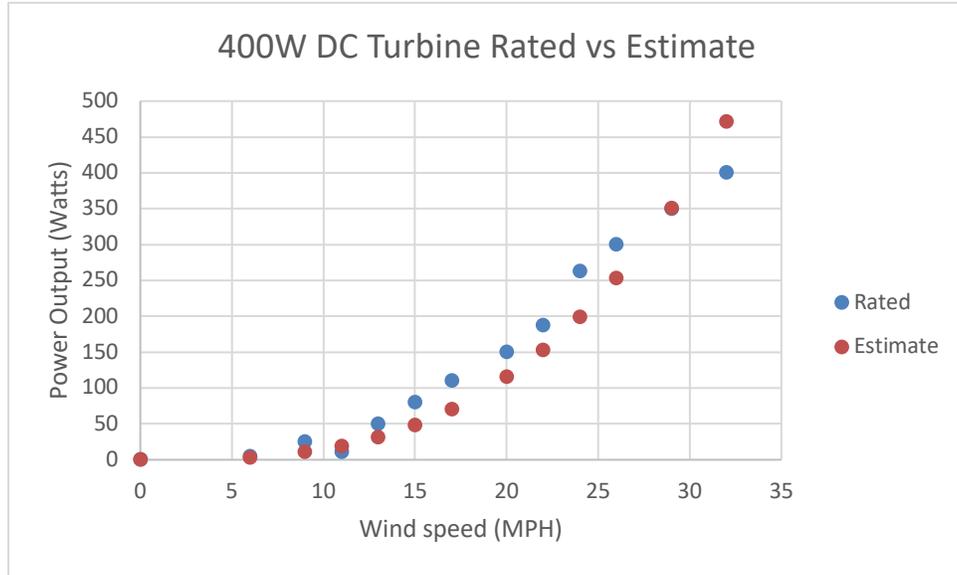


Figure 18 - 400W DC Turbine Rated vs Estimate

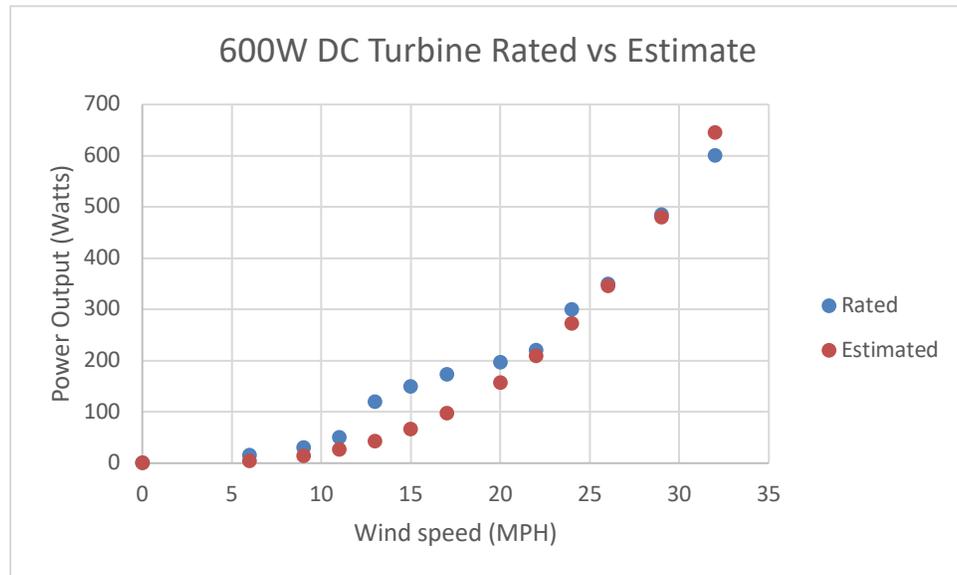


Figure 19 - 600W DC Turbine Rated vs Estimate

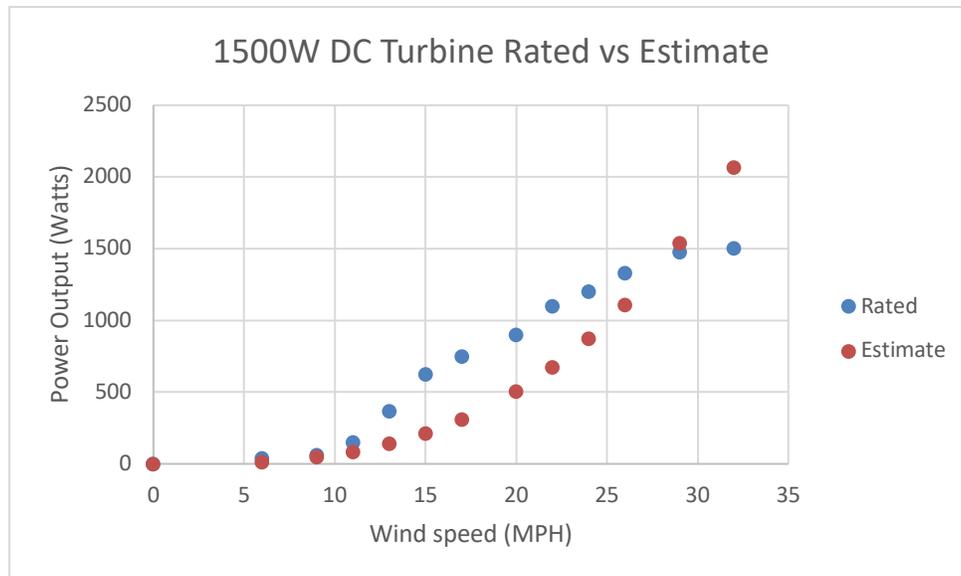


Figure 20 - 1500W DC Turbine Rated vs Estimate

For the 400-Watt wind turbine, the efficiency is 38% of the maximum efficiency of 59.26%. For the 600-Watt wind turbine, the efficiency is 45% of the maximum efficiency. And for the 1500-Watt wind turbine, the efficiency is 85% of the maximum efficiency. This is data provided by the manufacturer and so these efficiencies may not be completely accurate. Ascertaining these efficiencies for new wind turbine prototypes can be made possible through the use of SolidWorks Flow Simulation, which is another reason why companies and organizations would value the work done for this MQP.

6.5 Present Value of Money

As with any venture, it is important to understand the finances of the undertaking. It is equally important to know that the value of money in the future is worth less today. This is due to the fact that money could be invested today and it could increase in value as a result. Given that nominal amounts of money throughout time do not necessarily have the same value, the present value can provide a form of standardization. This value can be obtained through the following equation:

$$P = \frac{F}{(1 + i)^n} \quad (11)$$

Where P is the present value, F is the future value, i is the interest rate, and n is the number of years [7]. As of December 9, 2017, the interest rate is at 2.378% [15]. For the purposes of our MQP, it is necessary for the wind turbine's investment interest rate to be greater in order to be successful venture. The cost of wind turbines is typical upfront. Their return on investment usually occurs after a number of years, which is why the present value of money is important for wind turbines.

6.6 Flow Simulation Final Results

From the SolidWorks Flow Simulation, we inputted data about our wind turbine test rig blades to calculate power output if we harnessed its power. Table 2 shows the torque values at different RPMs and wind speeds in inch-pounds:

Table 2 - Raw Data Output From Flow Simulation

	RPM	Wind Speed				MPH
		0	6	9	11	
Rotation speed	10	0	-6	-13	-19	Units: in*lb
	50	0	-8	-13	-19	
	75	0	-6	-17	-23	
	100	0	-3	-16	-26	
	125	0	2	-12	-24	
	150	0	8	-7	-19	
	250	0	42	29	16	
1000	0	828	818	810		

Positive values of torque mean that the wind turbine is a load and negative values of torque means that the wind turbine is a generator. As such, positive values of torque will become

0 because the wind turbine could be built such that it shuts off when it starts consuming power.

Table 3 shows the true torque values:

Table 3 - True Torque Values of Flow Simulation

		Wind Speed				MPH
		0	6	9	11	
Rotation speed	RPM					
	10	0	-6	-13	-19	Units: in*lb
	50	0	-8	-13	-19	
	75	0	-6	-17	-23	
	100	0	-3	-16	-26	
	125	0	0	-12	-24	
	150	0	0	-7	-19	
	250	0	0	0	0	
1000	0	0	0	0		

As previously stated, power in a rotational setting is the product of torque and angular velocity. Table 4 converts the torque values to the corresponding power outputs in watts:

Table 4 - Power Output of Flow Simulation

		Wind Speed (MPH)				Output Units:
		0	6	9	11	
Rotation Speed (RPM)	10	0	-1	-2	-2	Watts
	50	0	-5	-8	-11	
	75	0	-6	-15	-21	
	100	0	-3	-19	-30	
	125	0	0	-18	-35	
	150	0	0	-12	-34	
	250	0	0	0	0	
	1000	0	0	0	0	
Max Power		0.0	5.7	19.2	35.0	

At the bottom of Table 4, there is the predicted maximum power. This maximum power was calculated through the power in the wind equation while incorporating the Betz limit and some efficiency.

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