

Design of a Wind Turbine Farm for Rochester Institute of Technology

Executive Summary

Rochester Institute of Technology (RIT) is looking to add a wind energy system to the campus to improve sustainability and reduce energy costs. A system was designed using the GE 1.7-100 wind turbine with a hub height of 96 meters. This model was chosen because it performed best under the wind conditions for the specified farm location. Based upon two different modeling methods for power production, each turbine can produce approximately 6.4 GWh per year. The first method used to calculate this value focused on statistical distribution and principles of probability to find the annual power. The second method focused on wind speed values. By using collected data and the specification sheet for the chosen turbine values of power can be found and summed for the year.

Rochester Institute of Technology consumes 80 GWh per year, for the wind turbine farm to produce this amount of power 13 or more turbines would be needed. Because of the limited space available two different arrays were compared, one with four turbines, the other with six. Economic analysis was done including energy inflation and operation and maintenance costs for each turbine model. The 2 by 2 array with GE 1.7-100 96m produced the best result financially delivering 24.3 GW per year for 0.66 \$/kW.

Technical Design Solution

Design Variables

RIT is looking into using wind energy to accommodate some of its energy load to be a more sustainable campus and to reduce its overall energy expenses. A design solution can be made, but many variables and factors must be taken into consideration when creating this solution. In order to create a full design solution three turbine options are compared. The first two turbine options are the GE 1.7-100 with hub heights at 80 or 96 meters and the third option is the GE 1.85-87 with a hub height at 80 meters [1] [2]. The specification sheets for each turbine can be found in Appendices A and B, with important values for analysis in Table 1:

Table 1: Wind Turbine Impactful Values for Calculations

Variable name	Value for the GE 1.7-100 (80 m)	Value for the GE 1.7-100 (96 m)	Value for the GE 1.85-87
Hub height [m]	80	96	80
Rotor diameter [m]	100	100	87
Rated power [kW]	1,700	1,700	1,850

The later wind turbine calculations involve the variable $v_{avg} = 3.63$ m/s, which is the average wind velocity of a location. This is found by taking a data collection of the hourly wind velocities at RIT in 2017 and finding their average. These hourly wind velocities are measured 10 meters above surface level, and is used as a reference height. The average wind velocity must be converted to a velocity at the hub height of the wind turbine for more substantial calculations. This is done through the Equation 1 below:

$$\text{Equation 1: } v_{avg, target} = v_{avg, reference} * \left(\frac{h_{target}}{h_{reference}} \right)^{\alpha}$$

α is a parameter that acknowledges the roughness of the surface that the wind flows over. α can be calculated with Equation 2:

$$\text{Equation 2: } \alpha = \log\left(\frac{v}{v_0}\right) / \log\left(\frac{h}{h_0}\right)$$

Assumptions

Assumptions must be made in order to model the performance of proposed wind turbine systems. Some of these assumptions were given through the proposal, while others were chosen as they were deemed reasonable for this analysis. The list below summarizes the assumptions used in this wind turbine proposal:

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- Annual Energy Consumption for RIT: $80 \cdot 10^6$ kWh
- Energy costs: 0.0961 \$/kWh
- Energy Inflation Rate: 3%
- RIT Discount Rate: 10%
- Annual O&M Costs: 2% of initial costs
- O&M Inflation Rate: 2.5%
- Expected lifetime: 20 years
- Energy losses due to transmission are neglected
- Turbine farm configuration creates an efficiency of 90%
- Noise produced by the turbines will have minimal impact on the area
- All land for the turbines is already purchased and usable
- All local and state laws are followed

Proposed System Plan

In order to begin building a system, it is important to understand the performance of each turbine annually. The performance of a wind turbine can be understood through two different methods. Each method and its results are explained below. Hand calculations for both methods can be found in Appendices F and G and full calculations in the attached Excel Spreadsheets.

Method 1: This method is based on Raleigh's distribution (see Appendix C for details) where the average yearly wind speed is used to determine the probability that the wind speed is between a certain value. Utilizing the given power curve for each turbine, which gives the power output of the turbine at a given wind speed, it's possible to calculate the power output of the turbine for the whole year.

First a speed is selected (v_{sel}). For analysis, v_{sel} is a whole number that ranges from 0 to 50 m/s. Then, Raleigh's distribution is used to find the probability that a location has that wind moving at that speed. Raleigh's distribution requires the variable c using the equation $c = \frac{2V_{avg}}{\sqrt{\pi}}$. The variable c is then applied to Raleigh's distribution probability equation below. The variable v_{avg} is calculated using a reformatted version of Equation 2, where a new velocity is solved at the height of the turbine hub and the alpha is an average of every alpha from each hour in the year. Equation 3 demonstrates this:

$$\text{Equation 3: } P[v_1 \leq v_{sel} \leq v_2] = \exp\left(-\left(\frac{v_1}{c}\right)^2\right) - \exp\left(-\left(\frac{v_2}{c}\right)^2\right)$$

In this probability equation, v_1 is $v_{sel} - 0.25$ m/s and v_2 is $v_{sel} + 0.25$ m/s. If the range of v_{sel} is infinitely long, the probabilities of each wind speed summed up equals 100%. However, this method only used wind speeds from 0 to 50 m/s, which have a summed probability of 99.8%.

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The probability at v_{sel} is then multiplied 8760 hours/year which results in the amount of hours per year the wind is at the selected speed (h_{sel}). The v_{sel} is then plugged into a turbine energy curve (such as the ones found in Appendices A and B) to find the expected output power (P_{sel}) of the turbine at that wind speed. This expected power is multiplied by the hours per year the wind would be at the selected speed. The result is the amount of energy expected for turbine to produce when the wind speed is at the selected speed ($E_{sel} = P_{sel} * h_{sel}$). When this method is done through every whole wind speed between 0 m/s and 50 m/s, the resulting energies (E_{sel}) are summed up and the total value is the annual energy output of the turbine for all wind speeds. The summary of total energy outputs are shown in Table 2 below. A hand check for the output energy of the GE 1.85-87 at a wind speed of 5 m/s can be found in Appendix F. Table 2 summarizes:

Table 2: Yearly Power Output of 3 Turbine Models Based on Rayleigh Average Speed Distribution (Method 1)

Turbine Model and Height	Annual Energy Output (kWh)
GE 1.7-100 80m	6,040,444
GE 1.7-100 96m	6,501,762
GE 1.85-87 80m	4,905,259

Method 2: This method uses the average wind speed at each hour to find the hourly performance of a wind turbine throughout the entire year. The wind data used is from 2017, with a reference height of 10 meters. The wind speed is given at 10 and 30 meters off ground, so the wind speed at new heights must be found using Equations 1 and 2 as described above. These calculations are done at each hour to provide an accurate total energy output. A curve fit of the energy output for both turbine types was also done to find the power produced based on wind speed. These can be found in Appendix D. These equations are then used to calculate the hourly power output by a turbine, then summed to find the total power output for a year. Table 3 below summarizes the amount of power each turbine produces in a year:

Table 3: Yearly Power Output of 3 Turbine Models Based on 2017 Wind Data (Method 2)

Turbine Model and Height	Annual Energy Output (kWh)
GE 1.7-100 80m	5,983,983
GE 1.7-100 96m	6,398,834
GE 1.85-87 80m	4,914,701

Although each solution method takes a different approach to measuring the performance of the wind turbines, both methods output very similar results. This similarity proves that the resulting annual energy output in each table is a reasonable value.

Wind Farm Sizing

There is a limited area in and around RIT that turbines could be used in, as local regulations require turbines to be at minimum a distance from any property line equal to their height. Two different turbine configurations were tested for their abilities to fit in the available land. The first was a normal two by two array. Because of the limited number of turbines large spacing was possible keeping the system efficiency high, 95%. The other system tested was a two by three array of turbines. The side to side spacing was kept the same but the front to back distance was lowered. Because of this change in distance, the system efficiency dropped to 85%. The graph showing turbine efficiency can be found in Appendix E. It can be seen that lowering the spacing between the turbines to increase the amount of possible turbines has a negative effect on the efficiency of the overall farm. Because of the lack of data on unique wind turbine configurations it is assumed that a simple square array is the most efficient. The land being used is currently farmland and trees, it is assumed that this land will be functional and is owned by RIT.

Economic Analysis

The cost of turbines was found by using assumptions from above and values from Table 4 below:

Table 4: Assumed Costs Values for Compared Wind Turbine Models

Turbine Model and Height	Initial Cost [\$]	Turbine 1 [\$/kW]	Turbine 2&3 [\$/kW]	Turbine 4+ [\$/kW]	Tower Cost [\$/kW]
GE 1.85-87 80m	400,000	2,000	1,800	1,600	250
GE 1.7-100 80m	400,000	2,500	2,200	1,900	250
GE 1.7-100 96m	400,000	2,500	2,200	1,900	350

These values are then used to find the total cost the system and then find a the cost per kWh for each potential system, described by Table 5:

Table 5: Cost of Different Turbine Configurations and Models for Total System and per Watt

Turbine Model and Height	2 x 2 Array [\$/array]	2 x 2 Array Power [kW]	2 x 2 Array [\$/kW]	2 x 3 Array [\$/array]	2 x 3 Array Power [kW]	2 x 3 Array [\$/kW]
GE 1.7-100 80m	15,785,000	22,739,138	0.69	22,245,000	30,518,317	0.73
GE 1.7-100 96m	15,955,000	24,315,573	0.66	22,415,000	32,634,058	0.69
GE 1.85-87 80m	14,182,500	18,675,865	0.76	20,102,500	25,064,977	0.80

Once the total cost was found for each system it was divided by the annual power generated to get the cost per kilowatt. The best performing system was a 2 by 2 array using the GE 1.7-100 96m, with a cost of 0.66 \$/kW and a total cost of \$15.96 million dollars.

Before calculating the Simple Payback, Net Present Value, and the Internal Rate of Return, the d' and Present Value Function (PVF) of the energy production and O+M must be found. This is done in Equations 4, 5, 6, and 7 below over an analysis of 20 years:

$$\text{Equation 4: } d_{Turbine} = \frac{d-e}{1+e} = \frac{.1-.03}{1+.03} = 0.0679$$

$$\text{Equation 5: } PVF(d_{Turbine}, n) = \frac{(1+0.0679)^{20}-1}{0.0679(1+0.0679)^{20}} = 10.76 \text{ years}$$

$$\text{Equation 6: } d_{O\&M} = \frac{d-e}{1+e} = \frac{.1-.025}{1+.025} = 0.0731$$

$$\text{Equation 7: } PVF(d_{O\&M}, n) = \frac{(1-0.0731)^{20}-1}{-0.0731(1-0.0731)^{20}} = 10.34 \text{ years}$$

Simple Payback

The simple payback period of the installation is the ratio of the initial cost of the system to the annual energy savings in dollars produced by the system, minus the O+M cost. More applicably, it is the number of years it will take before the system has generated enough cost savings to recoup the initial investment. Simple payback period is calculated in Equation 8:

Equation 8:

$$\text{Simple Payback Period} = \text{Initial Cost } (\Delta P) [\$] / (\text{Net Annual Savings } [\$/\text{year}] - O + M [\$/\text{year}])$$

$$SPP = \$18,020,000 / ((\$2,374,314/\text{yr}) - (\$360,400/\text{yr})) = 8.95 \text{ years}$$

Net Present Value

Net present value (NPV) shows the current dollar value of an investment. This is done by first calculating the annual savings in electricity costs and operations and maintenance costs in Equation 9, 10, 11, 12, 13, and 14. The savings are based upon the difference in costs of the renewable option and the traditional option, in this case gas. By subtracting the two values the difference, or delta, shows how beneficial one method is over the other.

Equation 9:

$$\Delta A_{\text{saving}} = \text{Cost of electricity} * (\text{Electricity Generated} - \text{Electricity Consumed})$$

$$\Delta A_{\text{saving}} = \$0.0961/\text{kWh} * (\$24,706,699 - 0 \text{ kWh}) = \$2,374,314/\text{year}$$

$$\text{Equation 10: } O\&M_{\text{Turbine}} = 2\% * \text{Initial Cost}$$

$$O\&M_{\text{Turbine}} = 0.02 * \$18,020,000 = \$360,400$$

$$\text{Equation 11: } O\&M_{\text{Grid}} = \$0$$

$$\text{Equation 12: } \Delta A_{O\&M} = O\&M_{\text{Wind}} - O\&M_{\text{Grid}}$$

$$\Delta A_{O\&M} = \$360,400 - \$0 = \$360,400$$

$$\text{Equation 13: } \Delta A_{O\&M} = O\&M_{\text{Wind}} - O\&M_{\text{Grid}}$$

$$\Delta P = P_{\text{Turbine}} - P_{\text{Grid}} = \$18,020,000 - 0 = \$18,020,000$$

$$\text{Equation 14: } NPV = \Delta P + \Delta A_{\text{saving}} PVF(d_{\text{energy}}, n) + \Delta A_{O\&M} PVF(d_{O\&M}, n)$$

$$NPV = -\$18,020,000 + (\$2,374,314/\text{yr})(10.76 \text{ yrs}) - (\$360,400/\text{yr})(10.34 \text{ yrs}) = \$3,811,310$$

Internal Rate of Return

The internal rate of return calculates the discount rate at which the NPV equals zero. This is useful in determining how the investment may compare to other potential investments and repurposing Equations 9-14 above. By manipulating the discount rate in the spreadsheet calculator, this value for d can be found:

$$NPV = \$0 \text{ when } d = 12.656\%$$

Environmental and Regulatory Analysis

An important factor for wind farm land selection is municipal site regulation. The Rochester, NY zoning regulation requires that a wind turbine system must be set back a distance from any property line equal to or greater than its height [3]. In the case of this project design, each GE 1.7-100 turbine is 146 m tall, so every turbine in the wind farm must be at least 146 m from any property line. A minimum distance of 150 m was used for wind farm location as it ensures all parts of the wind farm meet the distance requirement.

Another important factor for wind farm land selection is noise pollution and its effects on the environment. Even if turbines are hidden from view and safely far away, their noise can still be heard. It was found that with the 150 meter minimum rule, the most sound a person would hear would be as loud as a normal AC unit [4]. Because this is the maximum noise pollution, it is assumed that the 150 meter rule results in negligible noise pollution to the surrounding environment.

The preferred land that would be used for the 2 by 2 wind farm is the plot of farm land directly south of and bordering the main campus of RIT (visual plan can be found in Appendix H). It is the most suitable land as it can be easily purchased and managed by RIT and its proximity to the campus would result in less maintenance and less energy losses transporting the wind farm electricity to the campus. However, environmental factors must also be taken into account when selecting the location of the wind farm. RIT is built on and surrounded by wetlands, which are sensitive but vital habitats to a variety of plants and animals. Because of this, the wind project design must include acquiring a general construction permit under the New York State Department of Environmental Conservation and developing a Stormwater Pollution Prevention Plan approved by the State Pollutant Discharge Elimination System program [5]. Following these regulations ensures that the proposed wind farm causes minimal effects on the wetland environment it will be built on. The wind farm and its construction will also be monitored to minimize the threat to bird safety and their migration patterns, threat of construction cleanup, and threat of potentially harmful vibrations from the turbine foundations.

Conclusions

Rochester Institute of Technology consumes 80 GWh per year. This value can be reduced by implementing wind turbines in the local area. Because of the lack of usable area smaller array sizes had to be considered, a two by two and two by three configuration were tested. Two different calculation methods were used to compare the power output of three different turbines in the different array configurations. From these values the best was chosen, GE 1.7-100 96m with a two by two array formation, which produced 24.3 GW per year for 0.66 \$/kW. This system will cost \$15.9 million and take 8.95 years to pay back.

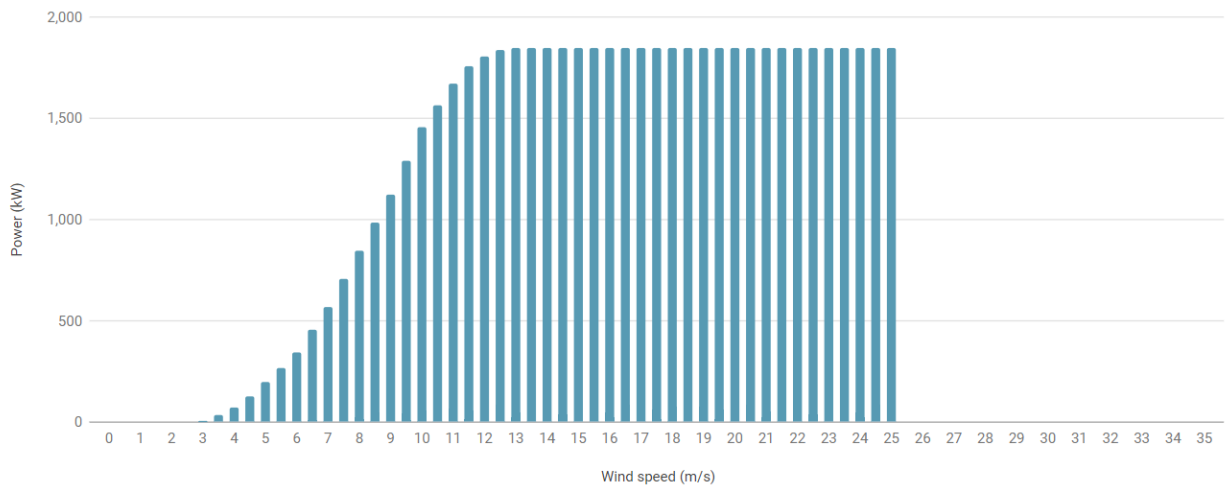
References

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- [2] The Wind Power. "GE Energy 1.85-87 Wind Turbine," [Online]. Available: https://www.thewindpower.net/turbine_en_611_ge-energy_1.85-87.php
- [3] eCode360. "Article XXV: Accessory Solar Energy Systems," [Online]. Available: <https://ecode360.com/12723276#:~:text=A%20system%20shall%20be%20set,a%20maximum%20of%20155%20feet>
- [4] Siemens Digital Industries Software. "Not in My Backyard: How Annoying is Wind Turbine Noise?" [Online]. Available: <https://blogs.sw.siemens.com/simcenter/not-in-my-backyard-how-annoying-is-wind-turbine-noise/>
- [5] Rochester Institute of Technology (RIT). "Wetlands and Stormwater Management," [Online]. Available: <https://www.rit.edu/ehs/wetlands-and-stormwater-management>
- [6] Statistic How To. "Weibull Distribution: Definition, Examples," [Online]. Available: <https://www.statisticshowto.com/weibull-distribution/>

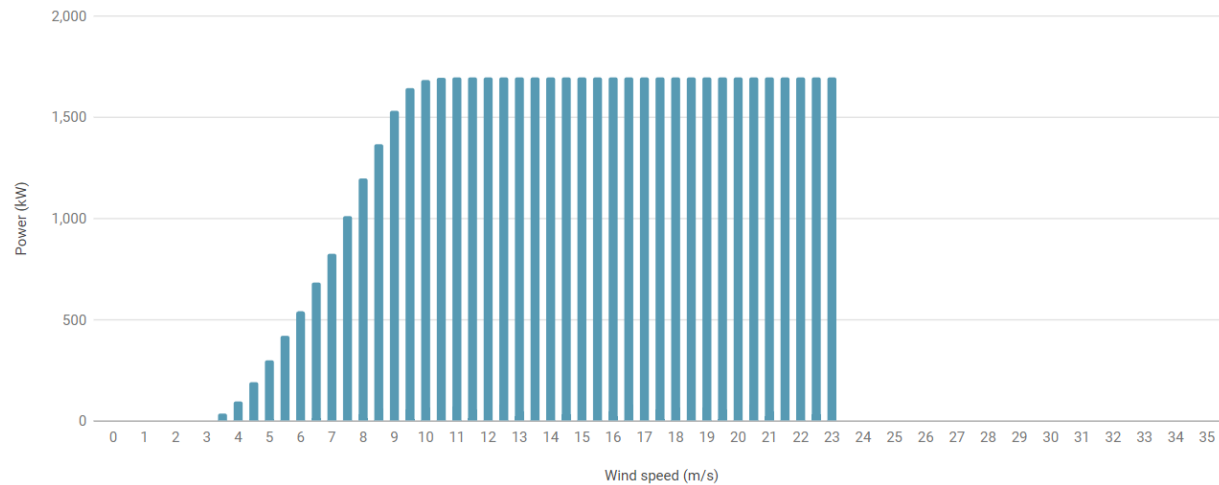
Appendices

Appendix A - 1.85-87 Spec Sheet

- Manufacturer: [GE Energy \(Etats-Unis\)](#)
- Model: 1.85-87
- Rated power: 1,850 kW
- Rotor diameter: 87 m
- No more available
- Wind class: IEC S
- Offshore model: no
- Swept area: 5,945 m²
- Specific area: 3.22 m²/kW
- Number of blades: 3
- Power control: Pitch
- Commissioning: 2012
- Cut-in wind speed: 3 m/s
- Rated wind speed: 13 m/s
- Cut-off wind speed: 25 m/s
- Gear box: yes
- Gear ratio: 107
- Type: ASYNC DF
- Number: 1
- Voltage: 690 V
- Hub height: 80 m

Power curve**Appendix B - 1.7-100 Spec Sheet**

- Manufacturer: [GE Energy \(Etats-Unis\)](#)
- Model: 1.7-100
- Rated power: 1,700 kW
- Rotor diameter: 100 m
- No more available
- Wind class: IEC S
- Offshore model: no
- Swept area: 7,854 m²
- Specific area: 4.62 m²/kW
- Number of blades: 3
- Power control: Pitch
- Commissioning: 2013
- Minimum rotor speed: 9,65 rd/min
- Maximum rotor speed: 17,9 rd/min
- Cut-in wind speed: 3,5 m/s
- Rated wind speed: 11 m/s
- Cut-off wind speed: 23 m/s
- Gear box: yes
- Gear ratio: 111
- Type: DFIG
- Number: 1
- Voltage: 690 V
- Minimum hub height: 80 m
- Maximum hub height: 96 m

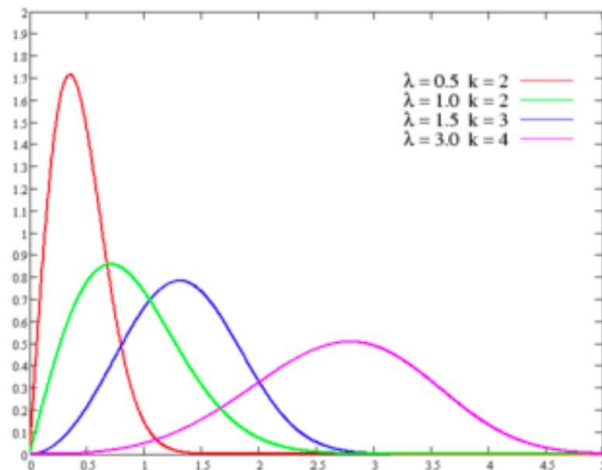
Power curve

Appendix C - Fundamentals of Raleigh's Distribution

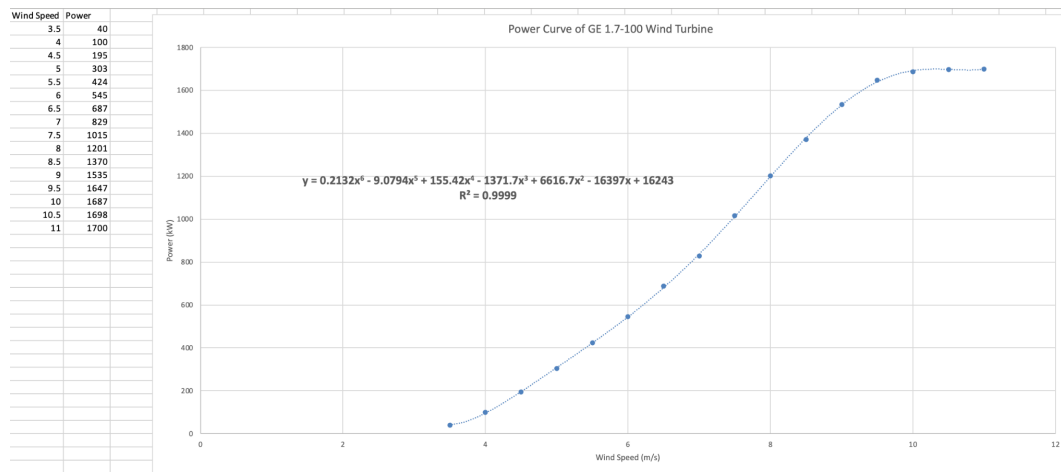
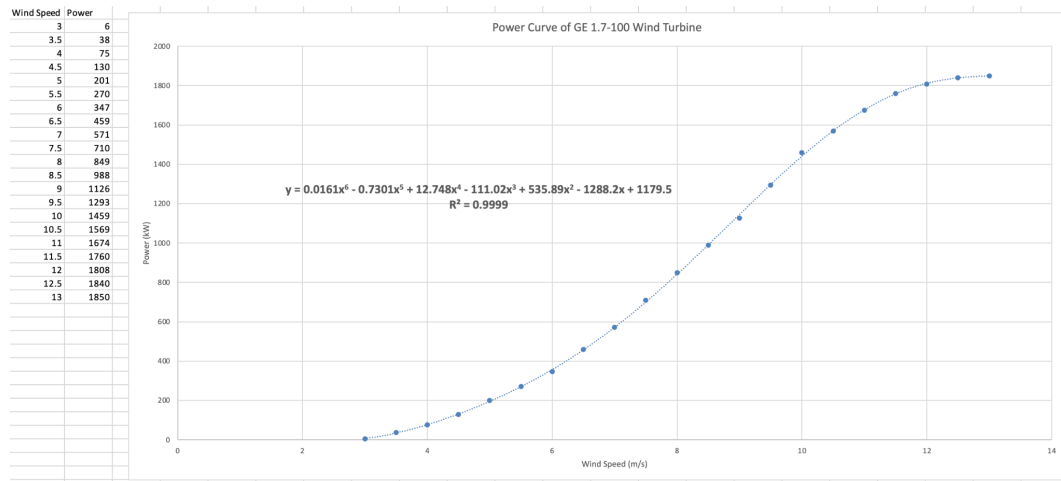
Raleigh's distribution is based on a more general Weibull distribution. The Weibull Distribution follows the equation shown below, where v is wind speed, k is the shape factor, and c is the scale parameter.

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^k\right)$$

The figure below shows the distribution under different k values. The Weibull distribution with $k = 2$ is known as Raleigh's Distribution and is commonly used as a statistical distribution tool for finding wind speed in an area over time [6].



Appendix D - Curve fits for Wind Turbines

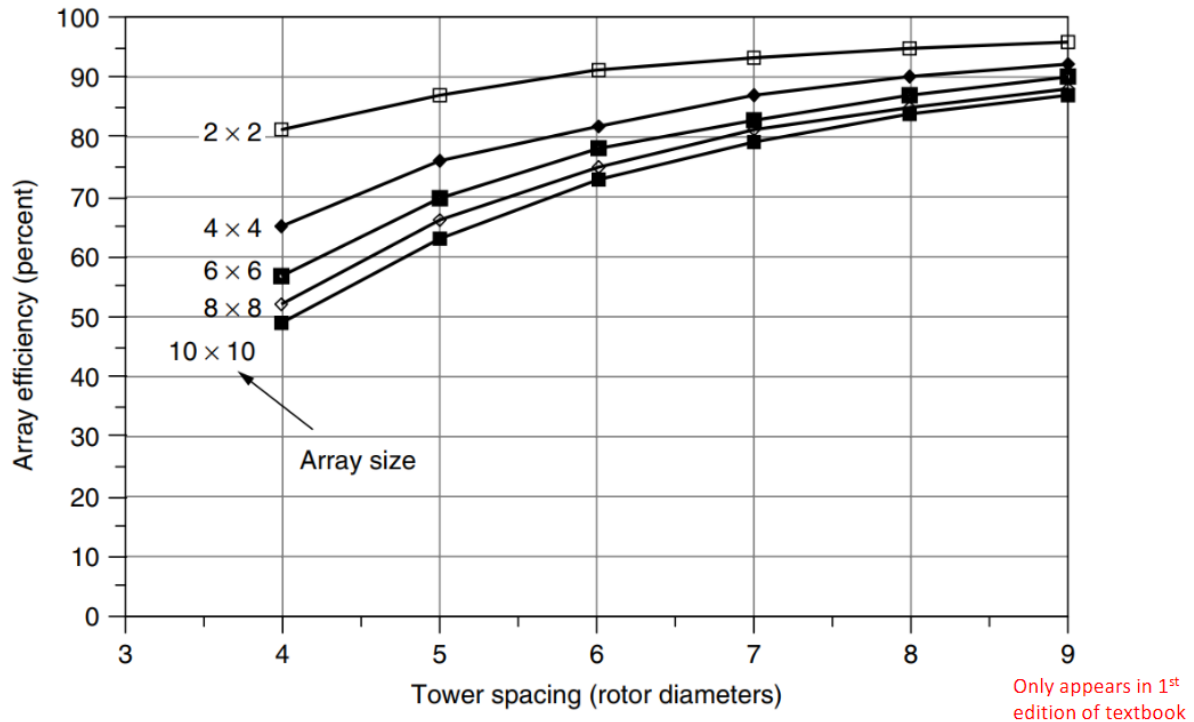


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Appendix E - Array Efficiency

Spacing Impact on Array Efficiency



Appendix F - Hand Check for Method 1 output energy of the GE 1.85-87 at 5 m/s

$$c = \frac{2v_{avg}}{\sqrt{\pi}} = \frac{2 \cdot 6.24 \text{ m/s}}{\sqrt{\pi}} = 7.04 \text{ m/s}$$

The “c” calculated above is a constant that only changes based on the turbine height.

$$P[v_1 \leq v \leq v_2] = \exp\left(-\left(\frac{v_1}{c}\right)^2\right) - \exp\left(-\left(\frac{v_2}{c}\right)^2\right)$$

$$P[4.75 \text{ m/s} \leq v \leq 5.25 \text{ m/s}] = \exp\left(-\left(\frac{4.75 \text{ m/s}}{7.04 \text{ m/s}}\right)^2\right) - \exp\left(-\left(\frac{5.25 \text{ m/s}}{7.04 \text{ m/s}}\right)^2\right) = 6.09\%$$

$$h = P * \text{hrs/year} = 6.09\% * 8760 \text{ hrs/year} = 533.38 \text{ hrs/year}$$

The turbine power is 201 kW at 5 m/s, which is extracted from the power curve for GE 1.85-87.

$$E_{sel} = \text{Turbine power} * h_{sel} = 201 \text{ kW} * 533.38 \text{ hrs/year}$$

$$E_{sel} = 107194 \text{ kWh/year}$$

The hand check predicts that the GE 1.85-87 will output 107194 kWh per year from the time that the wind speed is at 5 m/s, which matches the value from the actual Method 1 model.

Appendix G - Hand Calculations for Method 2

Hour 55 of the year is chosen randomly as the hand calculations. It also has a wind speed greater than 3.5 m/s and less than 11 m/s, which is important to ensure the curve fits produce active results. The wind speed is 5.31 m/s at the reference height of 10 m. Equations 1 and 2 are used to calculate alpha, and the wind speed at both 80 m and 96 m:

$$\alpha = \log\left(\frac{6.59}{5.31}\right) / \log\left(\frac{30}{10}\right) = 0.197$$

$$v_{target} = v_{reference} * \left(\frac{h_{target}}{h_{reference}}\right)^{0.197}$$

$$v_{80m} = 5.31 \text{ m/s} * \left(\frac{80 \text{ m}}{10 \text{ m}}\right)^{0.197} = 7.99 \text{ m/s}$$

$$v_{96m} = 5.31 \text{ m/s} * \left(\frac{96 \text{ m}}{10 \text{ m}}\right)^{0.197} = 8.29 \text{ m/s}$$

Using the curve fit from Appendix D, power for each of the 3 turbine models is found. Results can be checked against the specifications sheet in Appendices A and B:

GE 1.7-100 @ 80m:

$$P = 0.2132 * (7.99)^6 - 9.0794 * (7.99)^5 + 155.42 * (7.99)^4 - 1371.7 * (7.99)^3 + 6616.7 * (7.99)^2 - 16397 * (7.99) + 16243 = 1197.3 \text{ kW}$$

****In line with 1201 kW @ 8 m/s from spec sheet****

GE 1.7-100 @ 96m:

$$P = 0.2132 * (8.29)^6 - 9.0794 * (8.29)^5 + 155.42 * (8.29)^4 - 1371.7 * (8.29)^3 + 6616.7 * (8.29)^2 - 16397 * (8.29) + 16243 = 1308.2 \text{ kW}$$

GE 1.85-87 @ 80m:

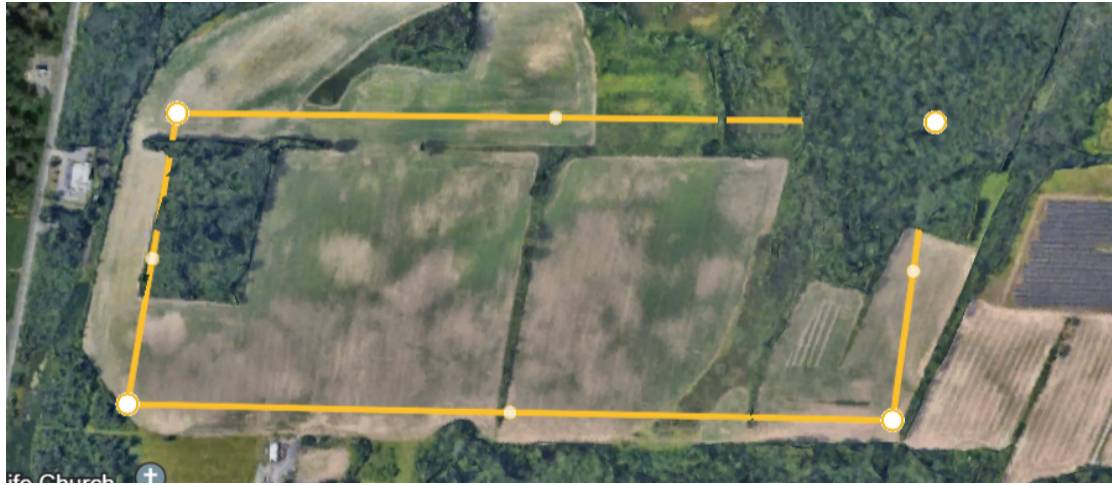
$$P = 0.0161 * (7.99)^6 - 0.7301 * (7.99)^5 + 12.748 * (7.99)^4 - 111.02 * (7.99)^3 + 535.89 * (7.99)^2 - 1288.2 * (7.99) + 1179.5 = 838.1 \text{ kW}$$

****In line with 849 kW @ 8 m/s from spec sheet****

All calculations are in line with calculated values and those provided from the specifications sheet. Slight error is due to the precision of excel, but is close enough to be valid.

Appendix H - Wind Turbine Formation Maps

2 x 2 Array



2 x 3 Array

