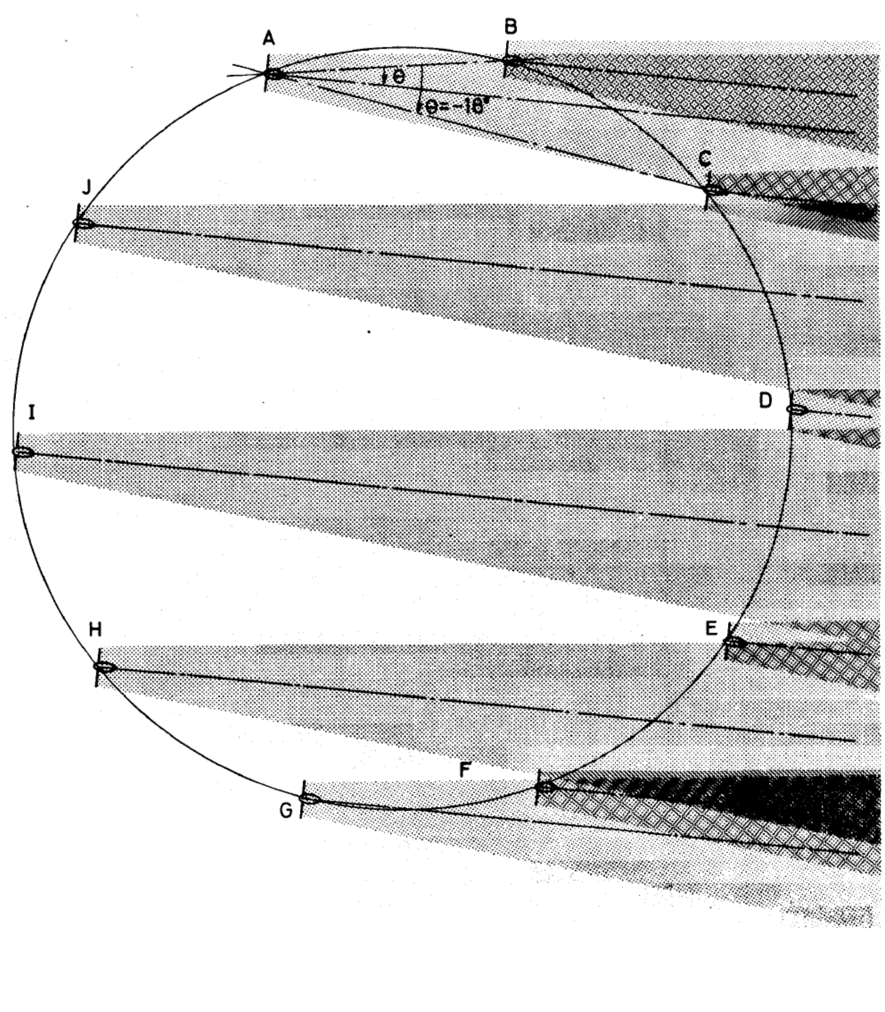
Wind Turbine Placement Based on Wind Direction

Zachary Wright
ME 706 - Renewable Energy
Course Project
University of New Hampshire - 2020



List of Tables

List of Figures

Background

The orientation and placement of wind turbines based on the wind direction has been a topic of interest to me ever since analyzing the Block Island Wind Farm located in Rhode Island. The off-shore wind farm has the turbines placed in a linear path parallel to Block Island, this seems conventional if the wind is constantly in the direction perpendicular to the linear placement, which would be an onshore or off-shore wind. While this is the case most of the time if the wind were to change in the direction of the turbine placement the efficiency and power output would dramatically decrease caused by turbine wake and turbulence of upwind turbines. In my analysis I will analyze the placement of turbines in different orientations and the effect of the power output. I will also incorporate different wind directions to demonstrate real life changing of wind directions. The power output of the overall farm will be compared to the proposed available power the turbines would produce if there was no turbulent wake affecting downstream turbines.

Currently in the US there is only one operational offshore wind turbine, Block Island Wind Farm, RI. However, there is 44,000 tera-watt hours of electricity generation potential along the US coastlines. [2] This poses the question, if there is so much potential resource, why are we not taking advantage of that. The answer is simple, money, off-shore wind farms are very expensive and if not designed correctly could end up not being profitable at all. The materials to build the turbine, lease or purchase of land to place them and maintenance rack up a large capital cost. This is why it is extremely important to make sure all tests and analysis are done correctly and effectively or else the farm could underproduce and cost millions of dollars which will evidently hurt the wind turbines reputation and make future plans even more difficult to get approved.

An alternative way of analyzing the power output loss due to turbulent wake is using a change in temperature gradient between the wind and the turbine blade. While not included in this analysis this is another area of interest that could help maximize the power output of offshore wind turbine farms. This idea is that how does the difference in temperature between the wind and turbine blade affect the drag, power output and downstream wake turbulence. If you were able to use the excess heat generated from the mechanical parts of the turbine and use a fluid to transfer the heat to the ends of the blades, would it affect the boundary layer and evidently the drag or power output. The answer is unknown but the idea is there and will be saved for a later analysis but still could be related to this analysis.

My goal is to take all the uncertainties and risks involved in offshore wind farms, analyze them and find the best solution to these issues. This will mitigate any potential problems from arising while building these farms and help grow the market by ensuring a safe investment with minimal risks.

1. Abstract

The design and placement of a wind farm is critical to the power output of the farm. We continue to develop and innovate new, more efficient turbines capable of a nameplate capacity upwards of 8 Megawatts. However, this is individual turbines, if placed in a farm with multiple turbines and the orientation did not account for the effect of turbulent wake caused by up stream turbines, can result in the farm only producing a fraction of the expected power output. This is the reason the development of not only the turbines are needed but also how the wake and wind direction affects the overall farm performance. Ideally, the maximum number of turbines in the leased land area is desired, but accounting for losses, the farm may be able to produce more power with less turbines that are placed in effective locations. In this analysis the focus was on turbines with a rotor diameter of 150 meters with 12 turbines in the farm, similar to the Block Island wind farm. Accounting for turbulent wake caused by upstream turbines, a distance between turbines of 500 meters results in a 75% wind velocity recovery, this was used as a minimum distance. A maximum recovery of 90% velocity was accounted for at a distance of 1,200 meters, any distance greater than 1,200 meters would recover the wind velocity at a rate that would require more land then the effective use of the recovered wind. In order to account for changing wind direction two cases were analysed, random in all directions and in a single direction. The first case with no dominant single direction, where the wind was equal in all directions was analyzed and determined the best orientation was a circular placement of turbines with a diameter between turbines of 1,200 meters. For the case where the wind is in a single direction with slight variation in either direction under 45 degrees, the best placement is linear rows of turbines perpendicular to the initial wind direction, with row spacement of 1,200 meters. For these two cases the design provided will result in the maximum power output of the overall farm.

2. Introduction

Wind turbines are usually located in concentrated groups for many reasons, most commonly for geographical reasons. When building a wind farm the land suitable to put the turbines must be leased or purchased and that land is analyzed to ensure the farm outputs maximum power possible. In order to do this, the turbines are placed so that the largest number of turbines possible can fit. At the same time, the orientation of the turbines must be examined to determine the best location to minimize down stream turbulent wake. This is because turbulent wake causes downstream turbines to produce less power and causes a larger loading on them. To maximize the power output, the turbines would be ideally placed in a line perpendicular to the wind and each row to be placed far enough behind the first one to ensure a fully recovered wake. This will allow each turbine to achieve the maximum possible output of power and concentrate the most number of turbines in the alloted land mass.

This is an ideal case and the wind rarely ever maintains a constant direction as it is constantly changing. In order to analyze this to help provide the best possible orientation for a 12 turbine wind farm with rotor diameters of 150 meters. The direction of wind will be analyzed in three directions to act as a real life example of changing wind.

3. Methods

In order to analyze how the turbulent wake of an upstream turbine affects the velocity down wind, the Jensen Model is used derived from a balance of momentum equation where the radius of the wake is proportional to distance downstream;

$$U(x) = U_{\infty}[1 - \frac{2}{3}(\frac{r}{r+\alpha x})^2] \qquad \text{[i]}$$

Where U is the velocity, U_{∞} is the far upstream velocity, r is the rotor radius, x is the distance from the turbine and αis the entertainment constant. [1]

The new wind velocity U(x) will be used when analyzing the power output of the turbine using the equation below;

$$P(U) = \frac{1}{2}\rho A U^3 \qquad \text{[ii]}$$

Where P is the power output in Watts, ρis the air density, A is the rotor disk area, U is the velocity at the turbine. Equation [ii] shows that the power is related to the velocity cubed, therefore the power is affected by the wind velocity heavily. A minor decrease in velocity that may be overlooked can result in a major power loss.

For the analysis of a 150 meter rotor diameter and a constant wind velocity of 15 m/s the theoretical power output for each turbine is 38 Megawatts and will be used to compare the actual power output.

When analysing the power output of a wind turbine farm there are many variables to account for, including wind velocity and spacing distance between turbines. The main variable that is unable to be controlled is the wind direction. To account for changing wind directions data from Block Island is used. While the wind direction is constantly changing it is predominantly in a certain direction with a variance of direction in either direction from that one point. Using "WINDFINDER" [3] statistic analyzing Block Island wind direction and strength, there is mainly a westerly wind with a slight northwest and southwest varicen. This is shown in the figure below;

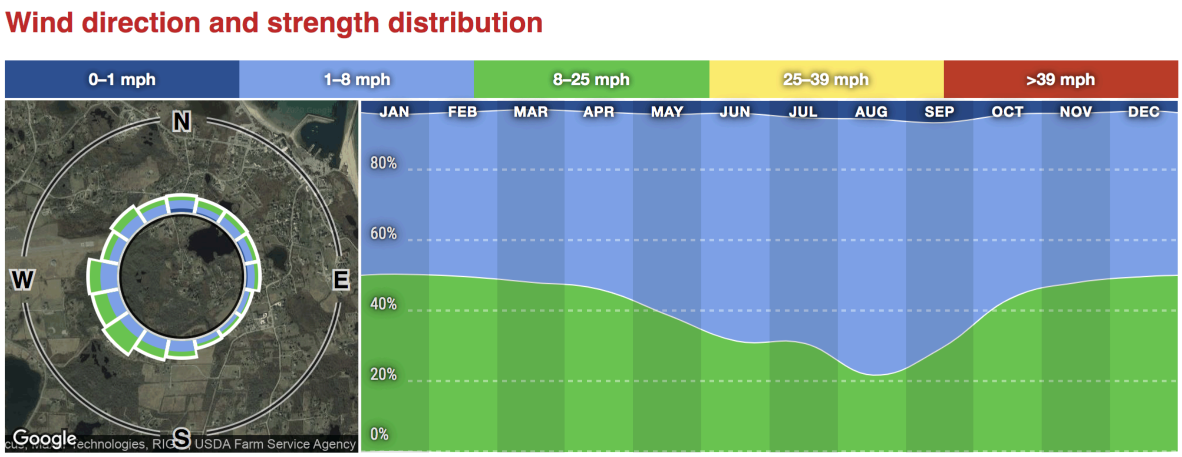


Figure 1 - Block Island Wind Direction and Strength [3]

4. Results

Equation [i] is used to analyze how far downstream (x) is in order to recover the wind velocity to 90% of the upstream wind velocity. $0.9 = 1 - \frac{2}{3}(\frac{75}{75+\alpha x})^2]$results in $(0.1)\,x = \frac{75^2}{0.15} - 75^2$and results in $x = 1,187\ m$. A table of the percent recovery and the corresponding distance (x) is shown below.

Percent Recovered (%)	Distance (m)	Velocity (m/s)
99	5,371	14.85
90	1,187	13.5
80	619	12
70	368	10.5

Table 1 - Percent Velocity and Distance...

The same concept for Table 1 is used to analyze the percent of the upstream wind velocity as a function of streamline distance. This is shown in the graph below:

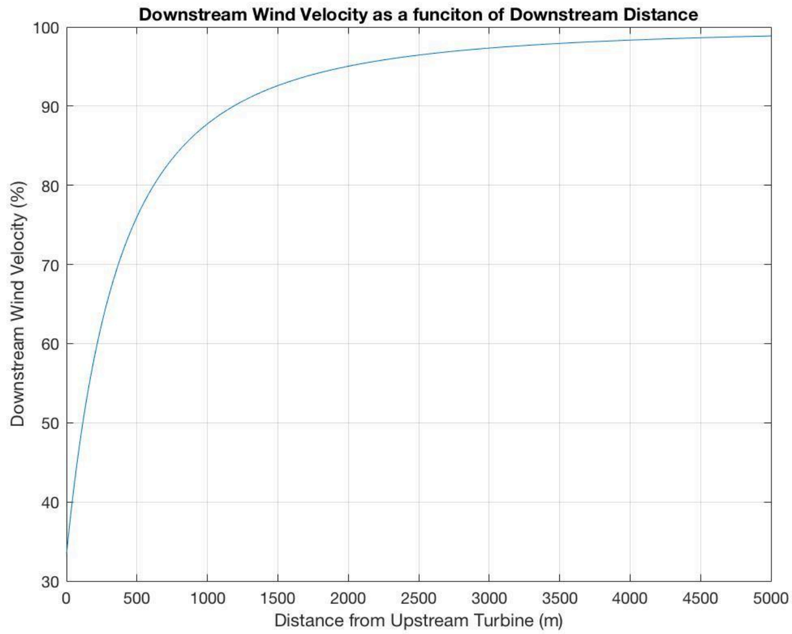


Figure 2 - Wind Velocity Percent as a function of Streamline Distance

This figure shows that the more distance away from the upstream turbine results in a larger velocity recovery. If you put the turbine under 500 meters from the head turbine, the wind velocity will only recover 75% of the upstream wind velocity. While, to achieve over 90% recovery there must be 1,200 meters between turbines. After 90% recovery you are sacrificing a much larger distance for such minimal velocity recovery. For this analysis, a focus on a minimum distance of 500 meters for 75% recovery and a maximum of 90% recovery for 1,200 meters will be used to compare different orientation methods.

Continuing to use the Jenson Model equation [i] and similar to Figure 2, an analysis of percent upstream wind velocity recovery as a function of the turbine rotor radius with a constant streamline distance of 500 meters and 1,200 meters to meet the 75% and 90% recovery is shown below;

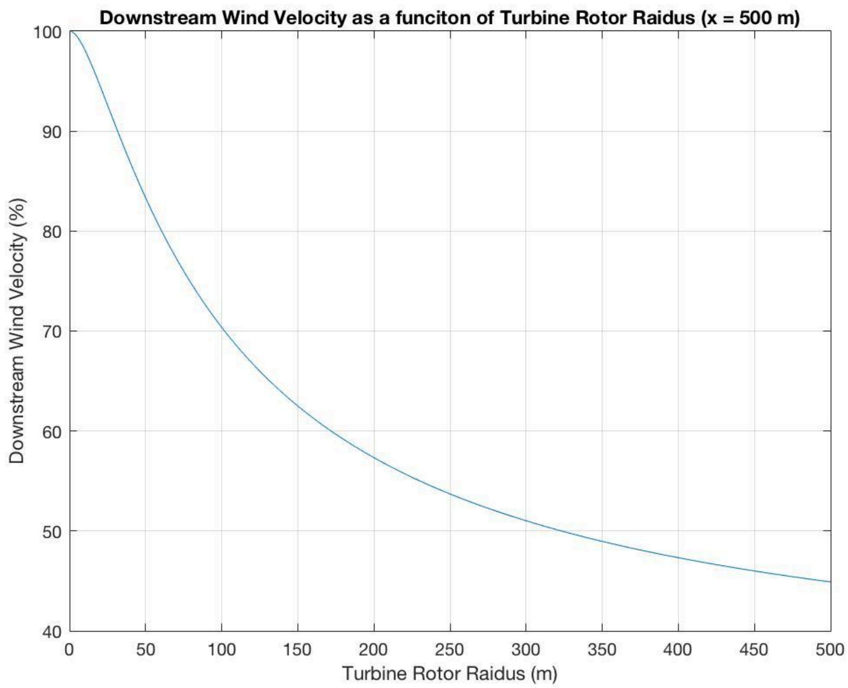


Figure 3 -Wind Velocity as a function of Rotor Radius at 500 meters

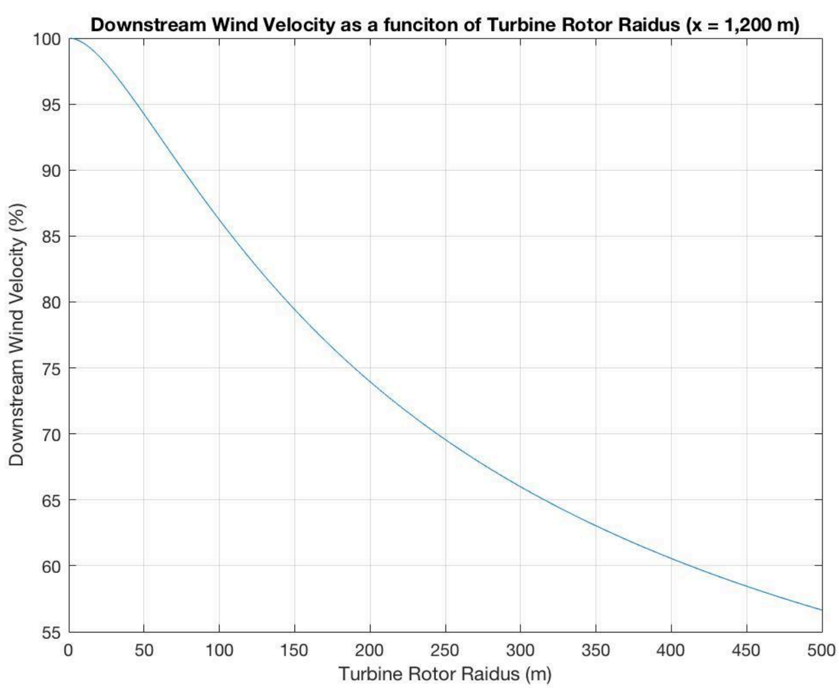


Figure 4 -Wind Velocity as a function of Rotor Radius at 1,200 meters

Figure 4 shows that at close distances (500 meters) the velocity is dramatically decreased as the rotor radius is increased. For our analysis using a turbine with a radius of 75 meters the wind velocity is recovered as expected at 75%. Similar to Figure 4, the velocity is recovered 90% for a 75 meter radius turbine. These figures show that the more distance between turbines the less effect the radius has, this results in a decision between distance and rotor radius.

This poses the question, is it beneficial to use smaller turbines that have smaller radius with a smaller effect on downstream velocity and try to pack them into a closer area. This issue with this is that would result in more materials and installation of the turbines, along with maintenance of many more turbines. The most efficient turbine size and the relative distance downstream must then be compared to the cost of construction and installation so that the power output is compared to the cost.

Using equation [ii] the power output is analyzed as a function of the velocity at the turbine rotor and the power output as a function of the streamline distance, which is relative to the velocity. The power output of a single turbine as a function of wind velocity can be seen the the graph below;

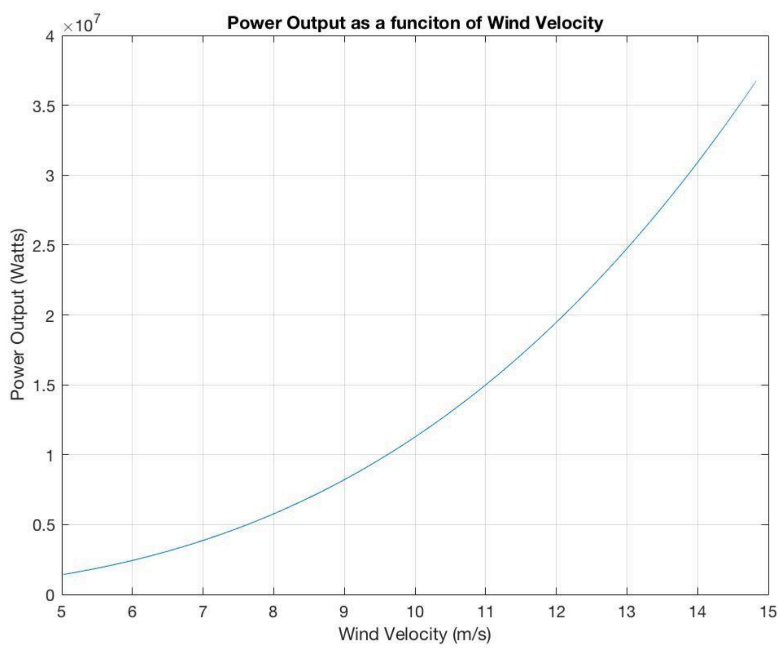


Figure 5 - Power Output as a function of Wind Velocity

As you would expect, the power output is related to the wind velocity cubed. In reality there is a cut in and cut out speed for the turbines to operate out. This is to prevent any damages that can be caused when operating a turbine at very large wind speeds. Also, the cut in speed is to ensure the wind is strong enough to output a reasonable amount of power.

With equation [ii] we can also analyze the power output as a function of streamwise distance, this is shown in the graph below;

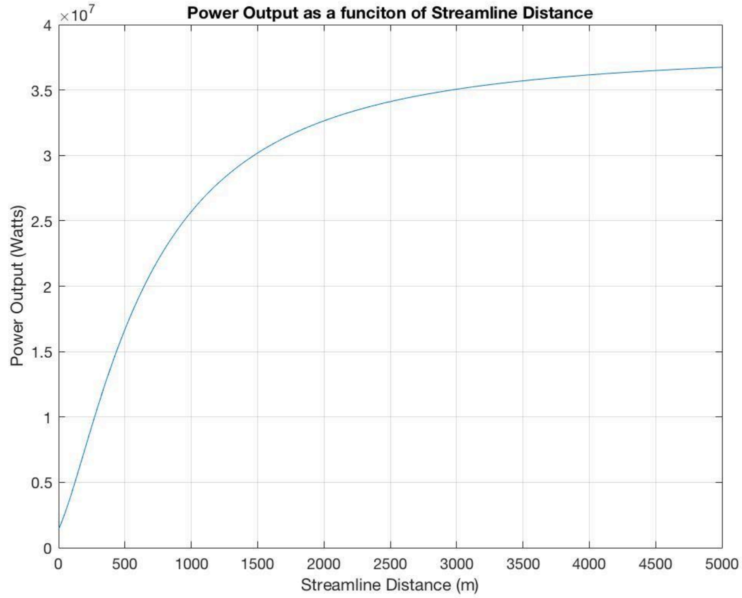


Figure 6 -Power Output as a function of Streamline Distance

Figure 6 is similar to the wind velocity as a function of distance as they are related. However, at 500 meters in the streamwise direction, the wind velocity is recovered 75%, but the power output is 16.7 Megawatts. When compared to a distance of 1,200 meters where the velocity is 90% recovered, the power output is 27.9 Megawatts. A difference of 700 meters and 15% wind velocity recovery results in a 60% of the power output. As you can see the power output is never equal to 38 Megawatts, which is the theoretical power output. This is because of losses and the wind velocity not able to fully recover to 15 m/s.

This is only analyzed for a single turbine, in a farm this would be multiplied by the number of turbines in operation. If we are using a farm similar to Block Island with 12 turbines placed 500 meters apart the farm would output 200.4 Megawatts of power. While the same farm is analyzed with 1,200 meters space between turbines the farm would output 334.8 Megawatts of power. This is compared to the theoretical power in the turbine farm; 456 Megawatts. This is analyzing the farm with the turbines placed in a line in the direction of the wind. This would be a very unconventional placement of turbines but is useful when dealing with large farms to determine how far back to place rows of turbines.

While accounting for space between rows of turbines, this is not the only variable affecting the power output of the farm. The wind direction is needed to be accounted for in the analysis as it is constantly changing. For an extreme case where the wind is not a majority in one direction but evenly distributed in all directions. The optimal design would be a circle of turbines with a diameter between turbines equal to the distance of full recovery. For our case, if a 90% wind velocity recovery distance of 1,200 meters would result in 7 turbines operating at the full potential with a wind speed at the rotor of 15 m/s while 5 of the 12 turbines would be operating at 90% wind velocity at the rotor. This would be the result of any wind direction around the circle inline of a front wind turbine and 7 turbines in the shape of a half circle achieving unobstructed wind velocities. A schematic of this orientation is shown below;

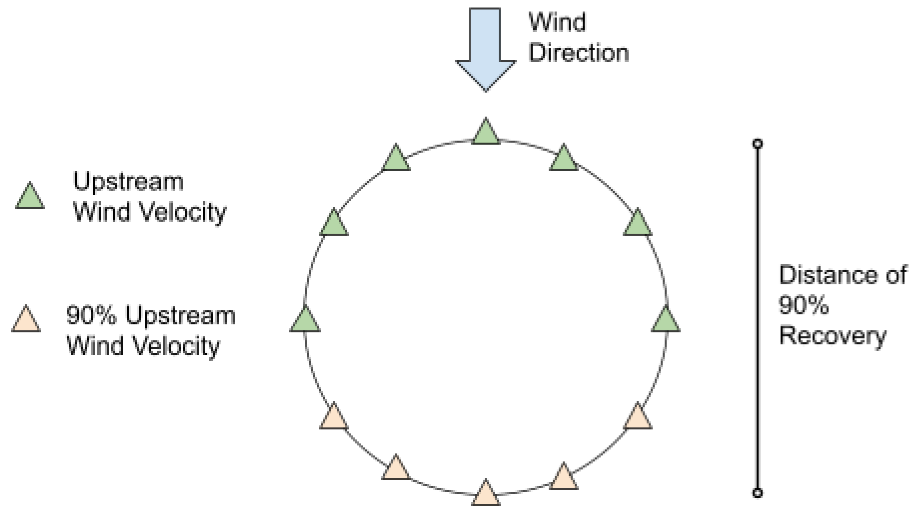


Figure 7 - Farm Orientation for Randomized Wind Directions

As you can see in Figure 7 if the wind is in any direction inline with a wind turbine the overall farm will result in the maximum power output. With a minimum of only 5 turbines affected by upstream turbulent wake. Overall, this farm would theoretically produce 405.5 Megawatts of power with any wind direction, compared to the theoretical maximum output of 456 Megawatts.

When analyzing wind direction, the data in Figure 1 will be used to predict a real life changing of wind. For our case, three directions will be used, west, northwest and southwest, with wind blowing towards west 50% of the time and both northwest and southwest at 25% of the time. For the optimal case of a circle will result in the same power output for all three directions.

For the case of linear rows of turbines that are perpendicular to the west wind and placed 1,200 meters away from each other, the power output would actually be increased with the wind variation. This is because when the wind is in the southwest direction the distance from the streamline turbine is increased and can be seen in the schematic below.

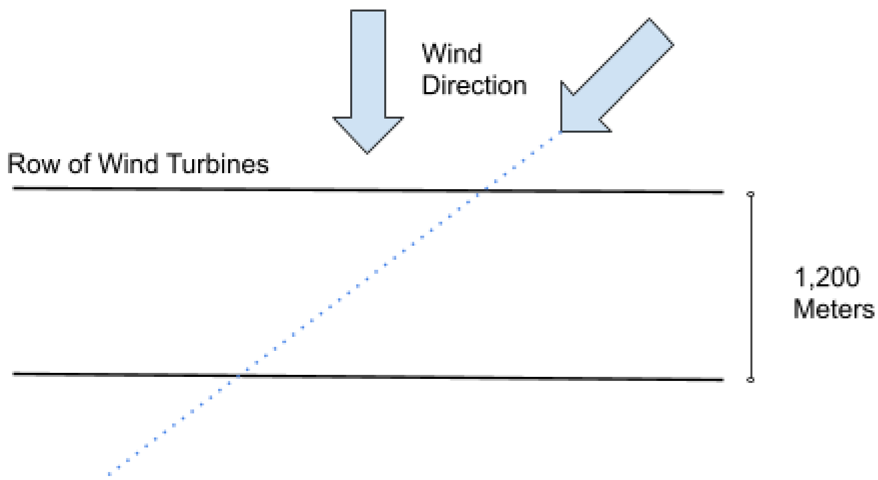


Figure 8 - Farm Orientation for Single Direction Wind

As you can see the distance between turbines is increased when the wind is a 45 degree adjusted direction. There are 2 rows of 6 turbines with the specification used in this analysis for 50% in the perpendicular direction and 25% in either 45 degree adjusted direction. Using geometry the streamline turbines for the 45 degree adjusted wind are 1697 meters behind the lead turbine and will be used when calculating power output. 31.3 Megawatts

Wind Direction	Row One Power (MW)	Row Two Power (MW)
West (50%)	228	167.4
SouthWest (25%)	228	187.8
NorthWest (25%)	228	187.8

Table 2 - Wind Direction and the relative Power Output

Table 2 shows that the power output of this orientation would be 405.6 Megawatts. This seems ideal, however this does not account for wind direction that is parallel to the linear wind turbine rows. If accounting for that direction the overall power output is dramatically decreased as in a line the turbines are placed under 500 meters apart. Also, there are many turbines in a row so the wake will be affected by multiple turbines and will compound to decrease the velocity and power output. This case is ideal if the wind is only in these three directions.

If the wind is in a single direction or varies 45 degrees in either direction of the point perpendicular to the turbine rows, the best orientation is in linear rows perpendicular to the main wind direction with a distance between rows relaitve to the diresed wind velocity recovery desired, for our case we used 1,200 meters for a 90% recovered wind. While if the wind varies in a more uncertain direction, like West, North and South, the optimal orientation is to organize the turbines in a circular or curvature pattern with a distance relative to the desired wind velocity recovery, is between turbines, or the diameter of the circle.

5. Conclusion

In order for wind turbine farms to be built there is a large amount of analysis on the specific size and design of the farm before work can be done. A main focus of analysis is the wind direction and how it affects the overall power output of the farm or how to orientate the placement of turbines to achieve the maximum power output based on the most common wind directions. Turbines cause a turbulent wake that follows the streamwise wind direction and decreases the power output and increases the load on the downstream turbines. The main focus is on the distance between turbines, as the velocity is a function of the distance and recovers a certain percentage based on how far away from the head turbine you are. This is used when calculating the power output of the farm as the power output is a function of wind velocity cubed. This shows how crucial it is to try and recover as much of the velocity as possible. However, the distance needed to make a full recovery is exponential and over 5,000 meters, for most farms this would result in using more land then the farm would see worth based on how many turbines can fit in the area. Due to this the maximum wind velocity is desired to be recovered while maintaining a reasonable total area. For this case, a minimum of 75% recovered at 500 meters and a maximum of 90% recovered at 1,200 meters were used to keep a reasonable area and still a profitable power output. This is based on a 150 meter rotor diameter wind turbine used in the analysis, these figures are different based on other rotor sized turbines.

When designing a wind farm the distance between turbines is crucial but there are also other factors affecting the power output. An example is the orientation or how the turbines are placed with respect to the rest of the farm. Following the analysis, this depends on how frequent the wind is in a single direction. If the wind is mostly in a single direction with a varied angle of 45 degrees, the best orientation is linear rows of turbines placed perpendicular to the wind direction with spacing of the rows based on the desired wind velocity recovery, for our case 90% and 1,200 meters. While, if there is a less predictable wind direction, in the sense that it is in multiple directions greater than 90 degrees with respect to one direction, the optimal orientation is a circular or curved placement with a distance between turbines based on the desired velocity recovered. This will prevent a line of turbines with a smaller distance between them from being dramatically affected when the wind is in the direction parallel to the row.

6. Future Analysis

The future of the analysis of determining the best design and orientation of turbines in a turbine farm to produce the maximum possible power output is to examine different variables that affect the power output of a farm. For example, adjusting the hub height of the turbines downstream so that they are taller and out of the turbulent wake of the upstream turbines.

Another related analysis is how the distance perpendicular to the streamwise distance (left or right of head turbine) is affected by the upstream turbine wake. If you place a turbine 500 meters behind but also 500 meters to the right will the power output be dramatically increased? Another topic of interest that relates to this, is to heat up or cool down the turbine blades to have a temperature gradient between the turbine blade and wind. This will affect how the wind passes around the turbine and may affect the drag and wake of the turbine.

References

[1] Jensen, N. O. (1983). A note on wind generator interaction. Risø National Laboratory. Risø-M, No. 2411

[2] https://www.energy.gov/eere/articles/

[3] https://www.windfinder.com/windstatistics/block_island

[4] https://doi.org/10.1016/j.rser.2016.01.113. - S J Andersen et al 2014 J. Phys.: Conf. Ser. 524 012161

[5] Barthelmie RJ; Pryor SC; Frandsen ST; Hansen KS; Schepers JG; Rados K; Schlez W; Neubert A; Jensen LE; Neckelmann S (2010)

[6] J. Atmospheric and Oceanic Technology 27:1302–1317