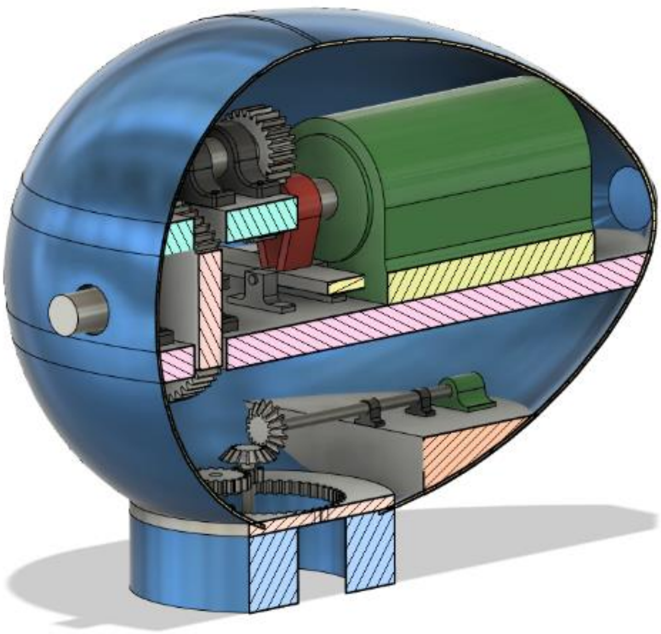
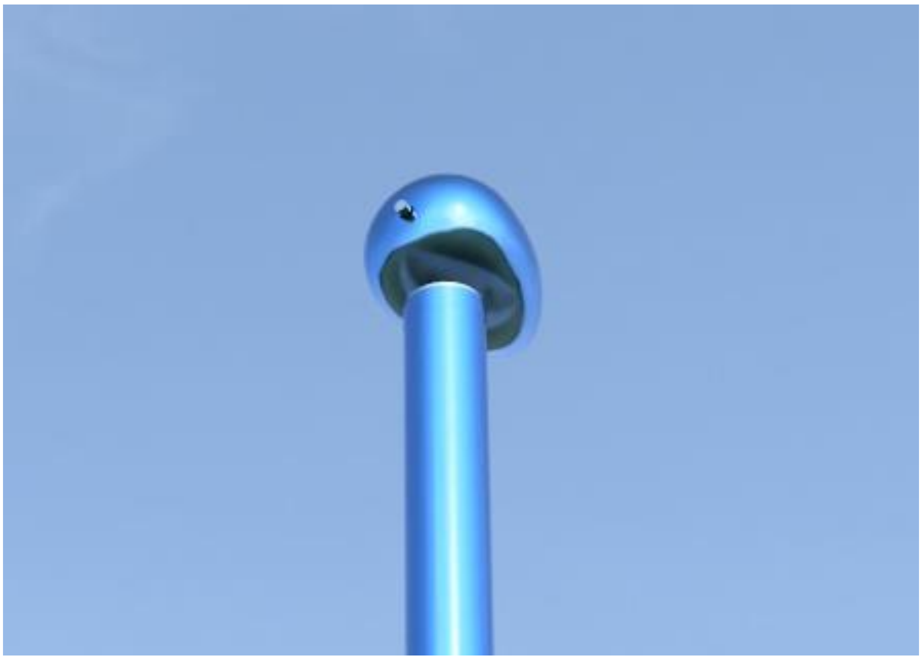
Medium-sized Onshore Wind Turbine for Off-Grid Application





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Contents

Abstract

This report describes a proposal for a medium-sized onshore wind farm taking into account social, environmental, and economic factors such as the aesthetic design, carbon footprint and expected rate of return, combined with the stakeholder and design requirements. A wind farm of 156 three-blade horizontal axis wind turbine (HAWT) was proposed. The nacelle was designed with a blue anodized aluminium shell encompassing a 1:6 spur gearbox and 12.5:1 motorised yaw drive. It was designed to sit at a hub-height of 90m with a three 54m long blades. Using Betz's law, a maximum power output of 4.0MW was calculated for wind velocities between 15 and 25m/s. Locating the wind farm in Kerrygold and calculating the most efficient layout to be a 12x13 grid, the wind farm had a theoretical average yearly power output of 514MW powering over 600,000 homes to give an expected rate of return of 23% for an initial investment of £660 million. However, the proximity of Kerrygold to a nature reserve and the complications associated with building foundations in wetlands may have an impact on the proposal's potential success.

Introduction

Renewable energy is playing a massive role in providing energy to meet the growing demands of the UK population whilst reducing carbon emissions so the UK can achieve 0% net carbon emissions by 2050 (Skidmore, 2019). Wind currently generates up to 26% of the UK's electricity (Dpt. for Business, Energy & Industrial Strategy, 2020) with the greatest growth in offshore wind capacity. The current proposal to build a large onshore wind farm of 150 medium-sized turbines has been overwhelming rejected by the islanders with over 2700 objections to 1100 letters in support. By taking into consideration the many stakeholders and adapting the proposal for the island's unique environment a more successful proposal may be achieved.

Design

Wider Social, Environmental and Economic Context

Wind turbines cut a lot of carbon emissions from the production of electricity but can also have negative impacts. Wind turbine blades cause noise and shadow flicker as they rotate which can be very distracting for local people (World Bank, 2015). The impact of wind farms forming "chains" across the migratory route of birds (Masden *et al*, 2009) can cause major disruption and the new infrastructure can damage the local environment. Also, the burning of fossil fuels during the extraction, processing and transport of raw materials contributes to climate change. Much of this work is undertaken in Newly Emerging Economies (NEEs) for instance China, Brazil, and Guinea are some of the world's largest producers and processors of Bauxite (OECD Global Forum on Environment, 2010) and may have worse environmental standards which could cause harm to the workers, local people, and the immediate environment.

Stakeholders

The main stakeholders in the project are Scottish Power plc and the Orkland community (Appendix 1) who are in direct opposition with each other; therefore the council must try to find a balance between the economic benefits and environmental negatives of the project. The Scottish Government want to grant permission for the project to meet their 500MW renewable energy target but may be lobbied by rival energy companies and local oil and gas sector who may oppose it if their profits decrease consequently. Other stakeholders may include bus companies and commuting workers negatively affected due to many large lorries that may get stuck on rural, narrow roads causing congestion. Finally, the tourism sector and RSPB may oppose the scale of the project and potentially bring legal action against the impact of the turbines on the landscape. The best way to avoid conflicts is through dialogue between the different stakeholders and transparency from Scottish Power so feedback and recommendations for the project can be given.

Design Requirements

Following a brainstorm to develop as many ideas as possible (Appendix 2a), three main ideas were selected and sketched (Appendix 2b): a large three-blade HAWT with a motorised yaw system and tubular steel tower, a medium-sized two-blade HAWT with a passive yaw system and trussed tower and a small Savonius wind turbine with 2 scoops and no yaw system. Seven design requirements (Appendix 3a) were created to differentiate between the designs. Economic requirements such as the *cost*, *reliability* and *productivity* had to be weighed against *environmental* and *sustainability* requirements. Physical requirements such as *aesthetics* and potential maximum *structural* size of the wind turbine were also important considerations to ensure the design met the needs of the stakeholders. By weighting the design requirements in a table (Appendix 3b), the most important requirement was found to be productivity, which was defined to be the power output per unit area of land for a wind farm, with a score of 26%. Across all criteria the three-blade HAWT had the greatest score of 37%, predominantly due to the high productivity and reliability of the three-blade wind turbine. However, the three-blade HAWT scored poorly in sustainability and environmental criteria so this must be mitigated when developing the idea.

Developing the Idea

A 3D model of the three-blade HAWT nacelle was built in Fusion 360 to implement the solutions to the weighted design criteria (Figure 1) accompanied by technical orthographic projections (Figure 2). To minimise the visual impact of the wind turbine it was anodized in blue to improve the aesthetics to improve the reliability criterion of the wind turbine. However, this may have a detrimental impact on the bird population so the blade tips would be bright orange to reduce the likelihood of bird impacts if the blades were designed. To simulate the aesthetics of the wind turbine in an outdoor environment, a rendered version of the entire nacelle was created (Appendix 5) which blended in effectively into the environment.

The nacelle shell is aerodynamic to reduce the transverse forces acting on the tower and reduce turbulent effects downstream. A motorised yaw drive was designed to rotate the nacelle to always face towards the prevailing wind and featured a bevel gear driving an annular gear which rotated on a thrust ball bearing to achieve a total step-down of 12.5:1. The body of the nacelle will be made of a recycled aluminium alloy as this will reduce the weight without compromising the strength too much. A band brake will also be used to prevent rotation of the shaft during periods of strong winds.

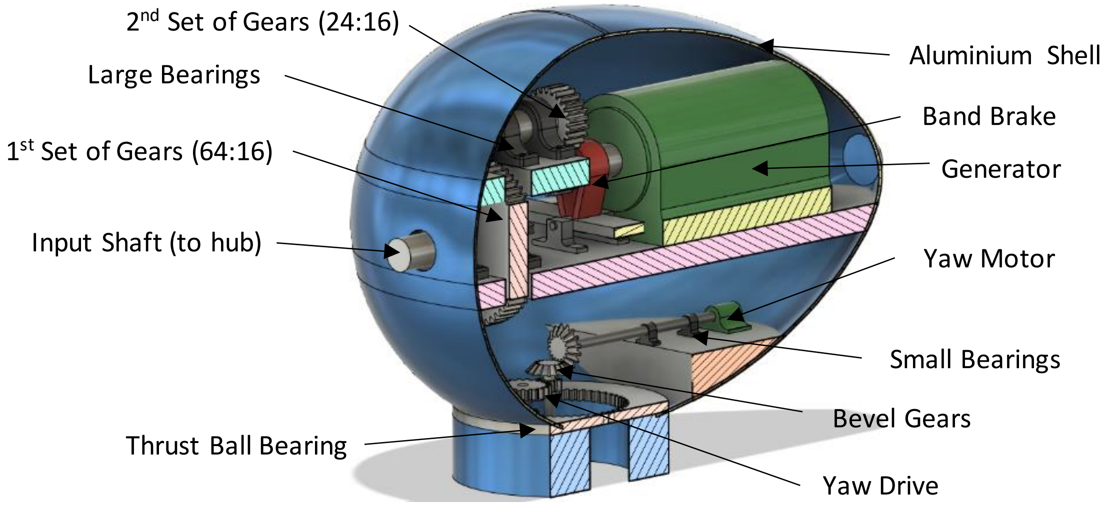

Figure 1: 3D Model of Nacelle

Since aluminium can be reused multiple times, it was chosen over the single use composites, as recycling reduces the carbon emissions by 96% (Hillman *et al*, 2015) which will in-turn greatly reduce the time for the wind turbine to reach overall net zero emissions for the entire life cycle. The length of the blades will be 60% of the 90m hub height as this is similar to current wind turbines (Yang, Chen and Pang, 2018) to give a diameter of 108m.

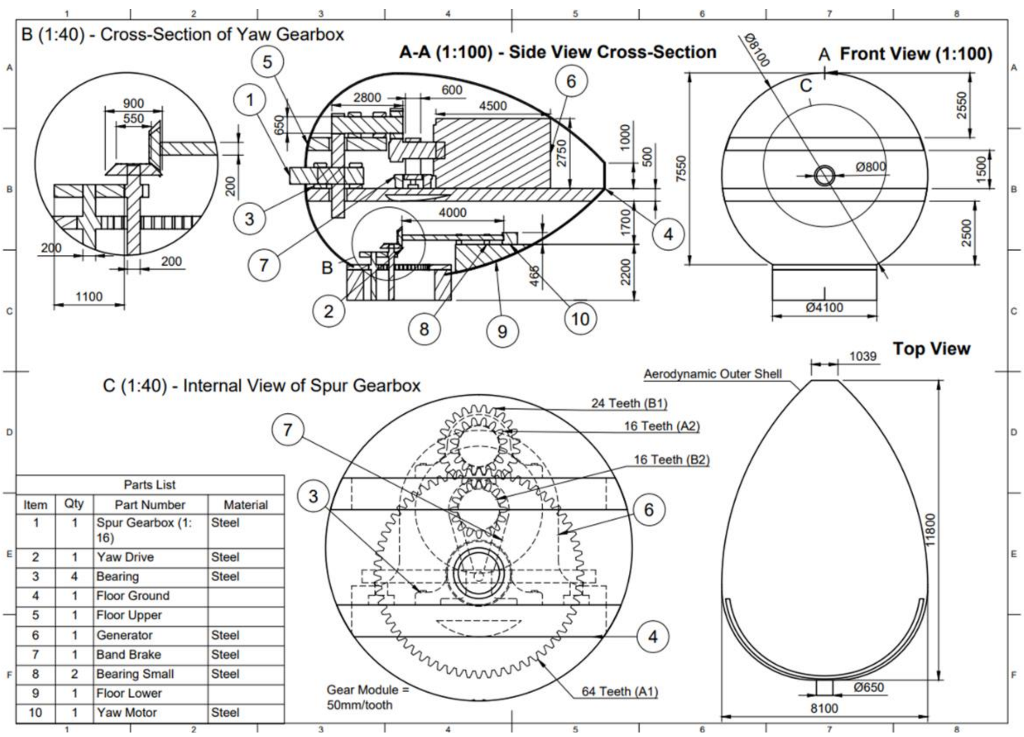

Figure 2: Technical Drawing of Nacelle

Computing

Validation Checks

To check the validity of the FLORIS model, it had to be compared against readings from experimental tests. In the power validation test (Appendix 6a), the FLORIS model under predicted the normalised power output for the downstream turbines. This was most noticeable for the second turbine in the row which had greater actual normalised power of 0.7 compared to a theoretical power of 0.55.

In the speed validation test (Appendix 6b), the FLORIS model severely under predicted the wind speed within three blade diameters of the previous turbine and predicted a negative wind speed at around 0.1 diameters downstream but a maximum wind speed at the turbine. However, from five diameters onwards, the FLORIS model quite accurately predicts the wind speed. Wake losses occur because the wind speed downstream is slower than the freestream wind speed, so a lower power output is achieved downstream.

Wind Farm Location

The location chosen was Kerrygold as it had the greatest area and the most preferable Hellmann exponent giving it by far the greatest power output. It was also preferable to only build at one site to reduce logistical difficulties as all the necessary infrastructure can be built in one place. Kerrygold is also low-lying so incoming planes to the nearby airport should not be affected by the height of the wind turbines. It is also marshland so the Whimbrel bird species should not be impacted, as their ground nests are located in ling heather on sloping banks to avoid flooding (Massey *et al*, 2016). However, the foundations of the wind turbine may have to be adapted to this problematic ground type. A grid layout was chosen as the relief and shape of the area was approximated to be flat and rectangular. Kerrygold is nearby to a nature reserve which may cause a conflict with stakeholders such as the RSPB and the community, however the massive increases in power output at Kerrygold would reduce carbon emissions dramatically, so the wider environmental benefits outweigh the local problems.

Main Turbine Plots

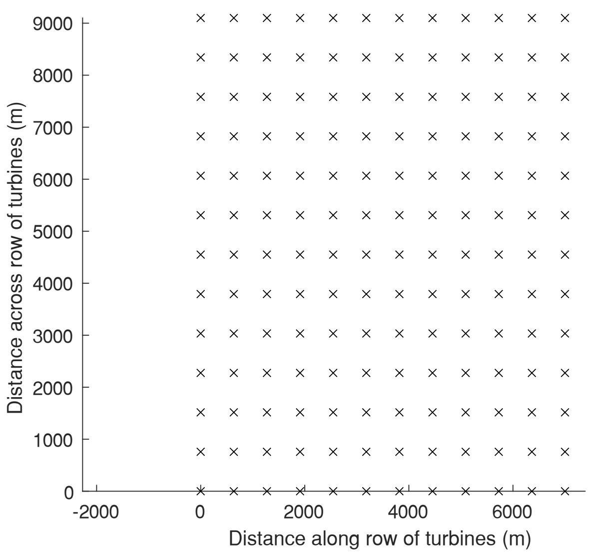

Figure 3: Layout of Wind Farm

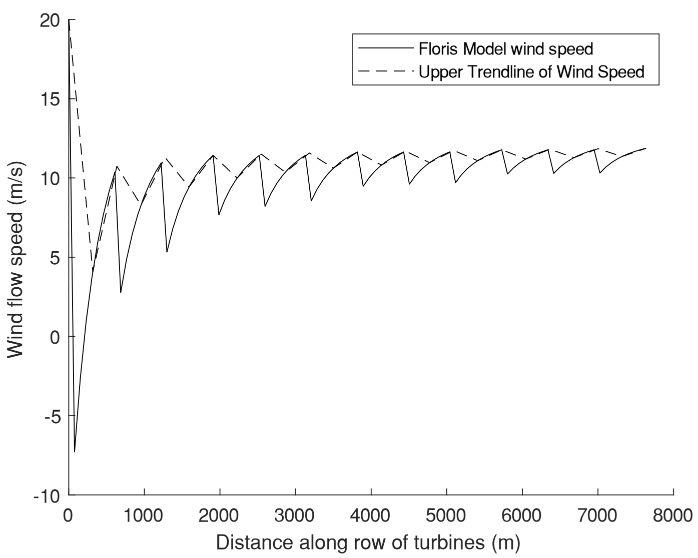

Figure 4: Wind Speeds Along Row of Turbines

For all the plots except the power across the year and spacing algorithm, a constant westerly prevailing wind of 8.3m/s at 10m above the ground was used. The turbines were arranged so that a 12x13 grid could perfectly fit into the chosen location of Kerrygold (Figure 3) which was approximated to be 7000x9100m (~6400ha), to give a spacing in-between turbines of 636 and 758m respectively (5.9 and 7 diameters). The grid is aligned north-to-south in the y-direction.

As shown in the speed validation task, the calculated wind speed was invalid below three diameters behind the turbine. As wind speed varies along a row of turbines it decreases rapidly after each turbine, so wind speeds were taken at the turbine and the midpoint between turbines to produce a rough trendline which probably reflects a more realistic wind speed. The wind speeds behind each wind turbine were identical due to the symmetry of the grid so a 2D plot (Figure 4) was chosen to ensure that the program runs quickly by only calling FLORIS 100 times instead of 10,000 times.

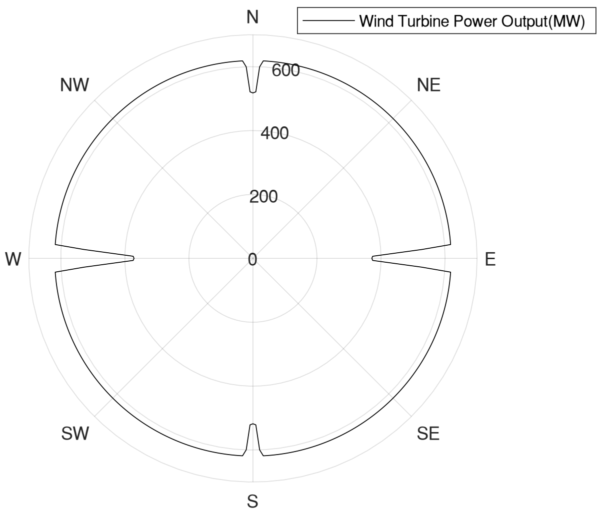

Figure 5: Power Output of Wind Farm Variation with Prevailing Wind Direction

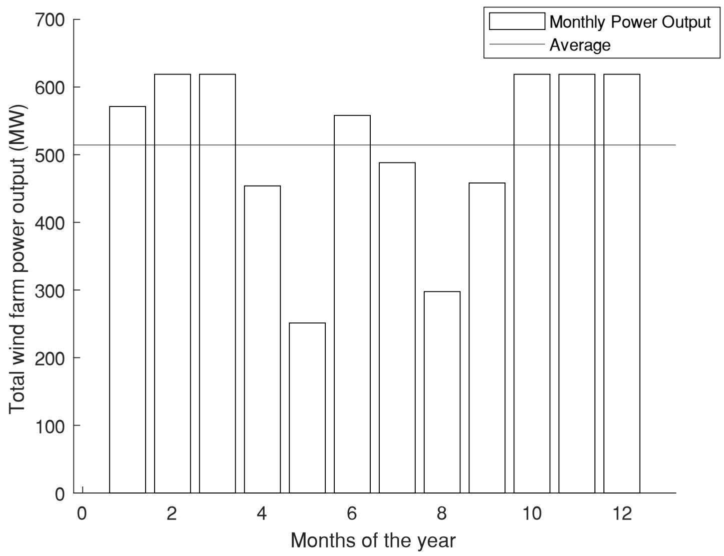

Figure 6: Power Output of Wind Farm across the year

As the wind direction varies, the total power output of the wind farm was plotted in figure 5. There are minima for wind directions that travel directly along or across rows as this is when the spacing between turbines is at its smallest, so the wake losses are the greatest. This is especially true in the east-to-west direction as the spacing is only 5.9 diameters. However, at all other angles the power output is smooth because the speed of the wind throughout the farm at all these angles is greater than 15m/s. Due to a lower efficiency at greater speeds, the power curve remains constant beyond this wind speed (Appendix 7a) and consequently the total power output does not change. The total power was plotted for each month for varying wind speeds and directions (Figure 6). Similarly to the varying wind direction plot, a maximum value of 618MW was achieved in 5 different months due to a wind speed greater than 15m/s throughout the farm and a yearly average of 514MW was calculated. In January, a lower wind farm power output was calculated because the freestream wind speed was greater than the 25m/s shutdown speed (Appendix 7b and 7c), so the first turbine did not operate. June and July had much greater power outputs than expected due to a preferable wind direction which reduced the wake losses.

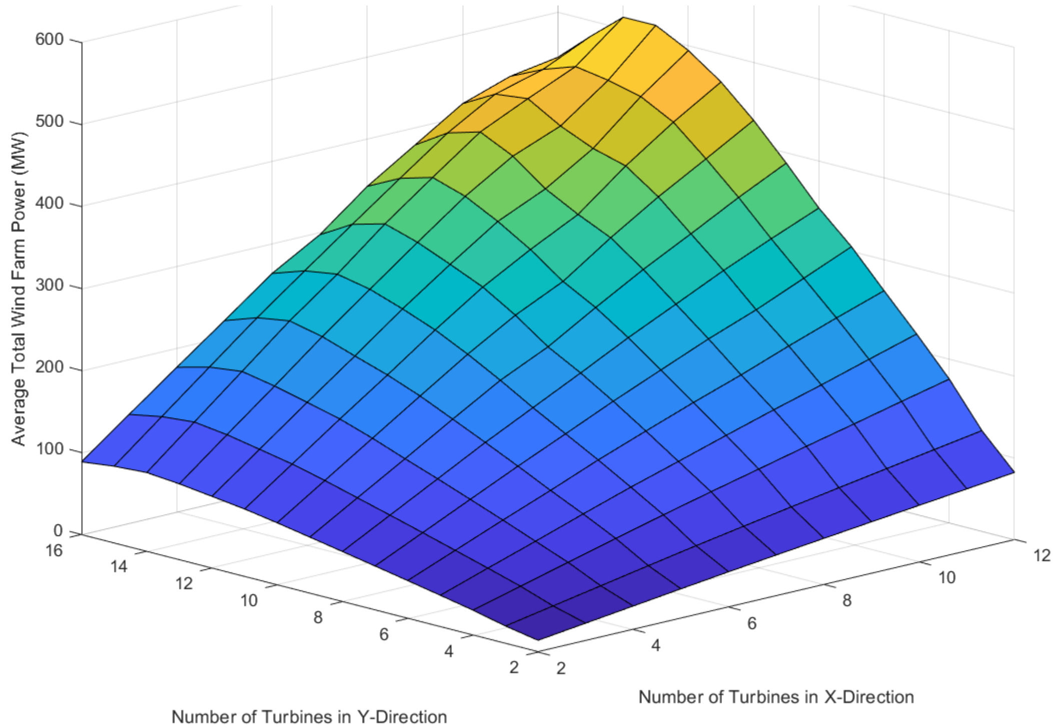

Figure 7: Average Yearly Power Output Varying with Number of Turbines in X and Y Direction

Due to wake losses, increasing the number of turbines beyond a certain point will decrease the average wind farm power throughout the year. This is further complicated by the changing wind direction throughout the year so the optimum spacing for the rows and columns in the grid is different. The code for the monthly wind farm power was run for all possible grid layouts (Figure 7). This gave an optimum layout of 12x13 wind turbines which was iteratively used to plan out the grid (Figure 3). Figure 7 shows that increasing the number of turbines in the x-direction always increases power whereas increasing the number of turbines in the y-direction above 13 decreases power. The average prevailing wind direction is almost directly south so the spacing between turbines in the y-direction is very important to reduce the wake losses. In the x-direction it is more beneficial to have as many turbines as possible because the benefits of an extra row in the y-direction outweighs the extra wake losses in the x-direction.

Economic Viability

Assuming an initial cost of £660 million for 156 turbines, the project should break even within 4 years (Appendix 8) at an expected internal rate of return of 23%, powering on average over 600,000 homes. 2.25TWh of electricity will be generated per year which will prevent over 500,000 tonnes of CO_2 equivalent entering the atmosphere a year from gas (Dpt. for Business, Energy & Industrial Strategy, 2020a, 2020b).

Conclusion

In conclusion, the wind farm design will provide a large amount of renewable energy which will contribute greatly towards meeting Scotland's renewable energy budget and reducing the amount of CO_2 released into the atmosphere. In order to address the concerns of the stakeholders, the nacelle has been designed to have minimal visual impact and have an aerodynamic shape to improve the efficiency of the farm. The hub-height of the turbine will be 90m and have a diameter of 108m, giving a maximum power output of 3.97MW per turbine. In a grid layout of 12x13 situated in Kerrygold, generating on average 514MW to produce a total of 2.25TWh a year. The benefits of increased productivity to generate more green energy at Kerrygold outweighed the local environmental damage. However, a greater understanding at what altitude the island birds fly at and the migratory routes the birds take would ensure the wind farm has minimal impact on the wildlife to give a better insight into the viability of the wind farm being located at Kerrygold, reducing conflict between stakeholders.

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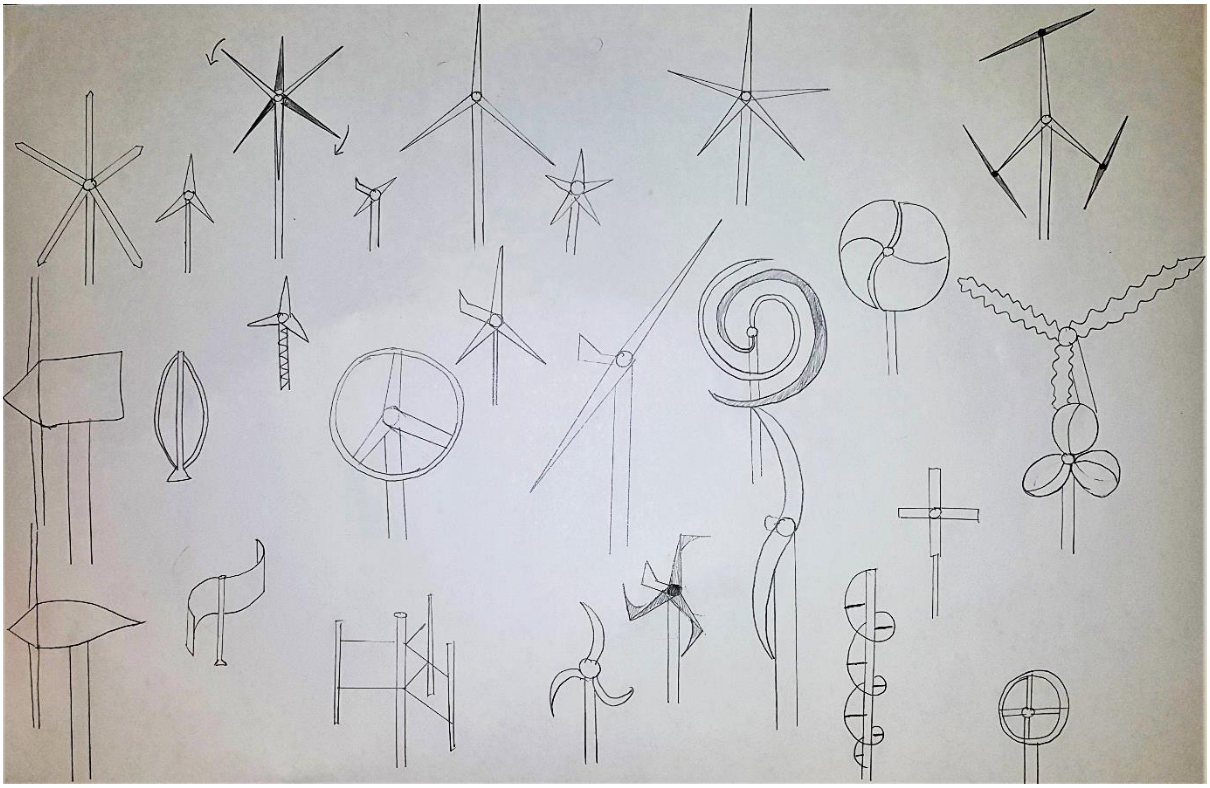
Appendices

Appendix 1 – Stakeholder Analysis

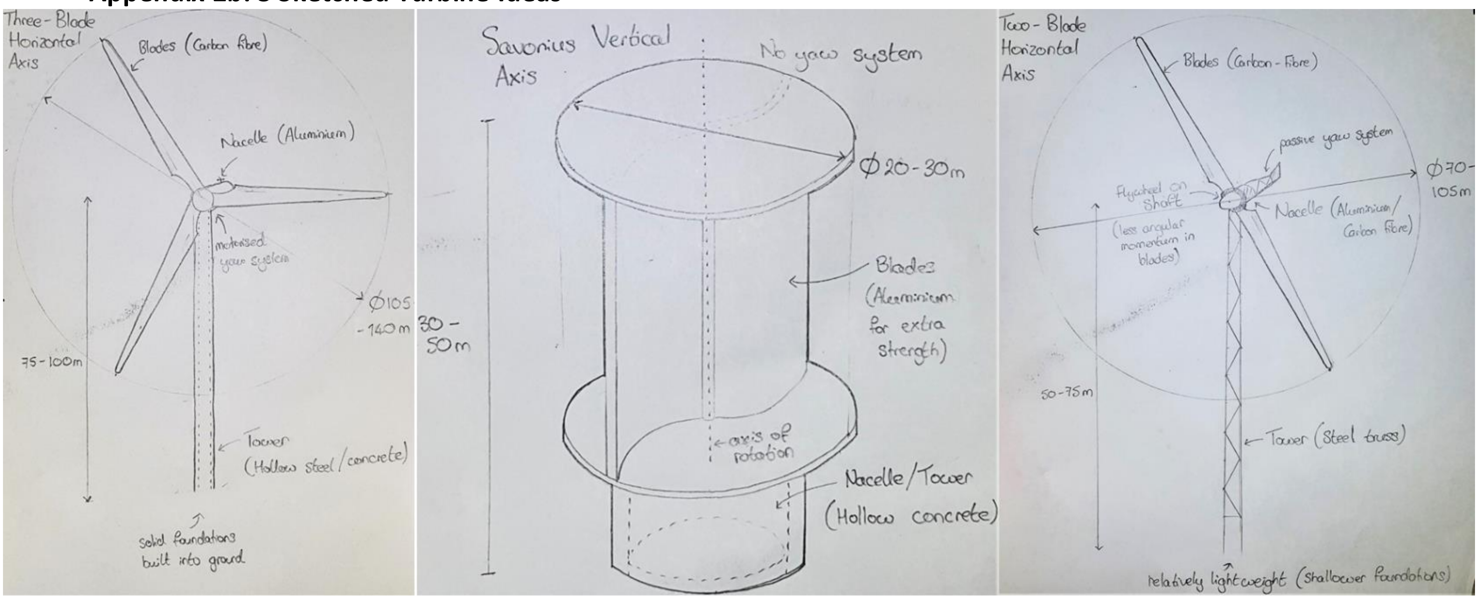
Stakeholder Name	Impact	Influence	What is important to the stakeholder?	How could the stakeholder contribute to the project?	How could the stakeholder block the project?	Strategy for engaging the stakeholder
Scottish Power Renewables	High	High	Making a profit on their investment	Build a large onshore wind farm	Decide not to proceed with project	Backing from community/council for project
Orkland Community	High	Medium	Maintaining the environment	Give feedback to ensure wind farm is sustainable	Protest against the construction	Monthly group feedback sessions
Government (Energy Minister)	Medium	High	Meeting the renewable energy budget target	Grant permission for the project to go ahead	Deny permission for the project to go ahead	Quarterly meetings with council
Orkland Island Council	High	High	Balance between economic benefits and environmental negatives of project	Explain to the community the benefits of the project	Explain to the community the negatives of the project	Weekly updates with energy company
RSPB Scotland	Medium	Medium	Protecting bird species/habitat	Give advice on how to minimise impact on birds	Bring legal action against the project	Quarterly meetings
Rival Energy Companies	Medium	Low	Making profit from their projects	Share knowledge on their issues with projects	Lobby the government to reject plans	Dialogue between the companies
Bus companies/ Commuting workers	Medium	Low	Roads that are not congested	Give feedback on construction-caused traffic	Complain to council about congestion	Traffic management plan
Tourism Sector	Medium	Medium	Generating income from tourists	Offer feedback on the design of the proposed wind farm	Complain to council about tourism decline	Quarterly meetings
Local oil/gas industry	High	Low	Directly/Indirectly generate income from fossil fuels	Understand how they can benefit from the new wind turbine industry	Lobby government to protect jobs	Quarterly meetings

Appendix 2 - Hand-drawn sketches of wind turbine ideas

Appendix 2a: Brainstorm of Turbine Ideas



Appendix 2b: 3 Sketched Turbine Ideas



Appendix 3 – Design Requirements

Appendix 3a: Description of Design Criterion

	Criterion	Criterion Detail
1	Productivity	Power output per unit area of land for a wind farm
2	Cost	Cost for materials & construction
3	Reliability	Variations in maintenance costs and power output
4	Aesthetics	The visual impact on the landscape
5	Sustainability	Total carbon footprint of design
6	Environmental	Direct impact on ecosystem e.g. birds
7	Structural	Needs to be strong and scalable

Appendix 3b: Weighting of Multiple Design Criterion

=*Much* More Important	=*More* Important	The =*Same*	=*Less* Important	=*MuchLess* Important
9	3	1	0.333	0.111

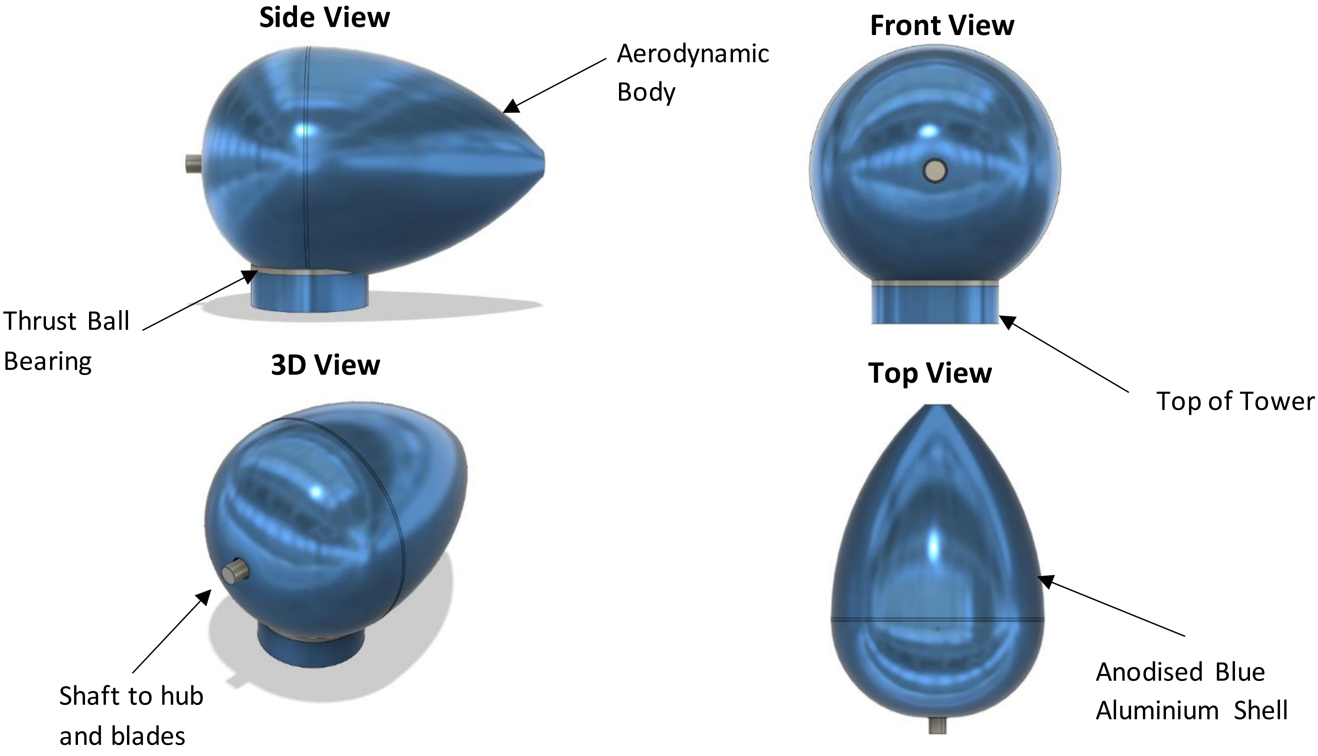
Criteria		Productivity	Cost	Reliability	Aesthetics	Sustainability	Environmental	Structural		
	X	1	2	3	4	5	6	7	Total	%
Productivity	1	X	3.00	3.00	3.00	1.00	3.00	3.00	16.00	26
Cost	2	0.33	X	1.00	3.00	0.33	1.00	1.00	6.66	11
Reliability	3	0.33	1.00	X	3.00	1.00	3.00	3.00	11.33	19
Aesthetics	4	0.33	0.33	0.33	X	1.00	0.33	3.00	5.33	9
Sustainability	5	1.00	3.03	1.00	1.00	X	0.33	0.33	6.69	11
Environmental	6	0.33	1.00	0.33	3.03	3.00	X	1.00	8.70	14
Structural	7	0.33	1.00	0.33	0.33	3.03	1.00	X	6.03	10
		2.67	9.36	6.00	13.36	9.36	8.66	11.33	60.75	100
		4.4	15.4	9.9	22.0	15.4	14.3	18.7	100	60.75

Appendix 3c: Pairwise Comparison Matrix

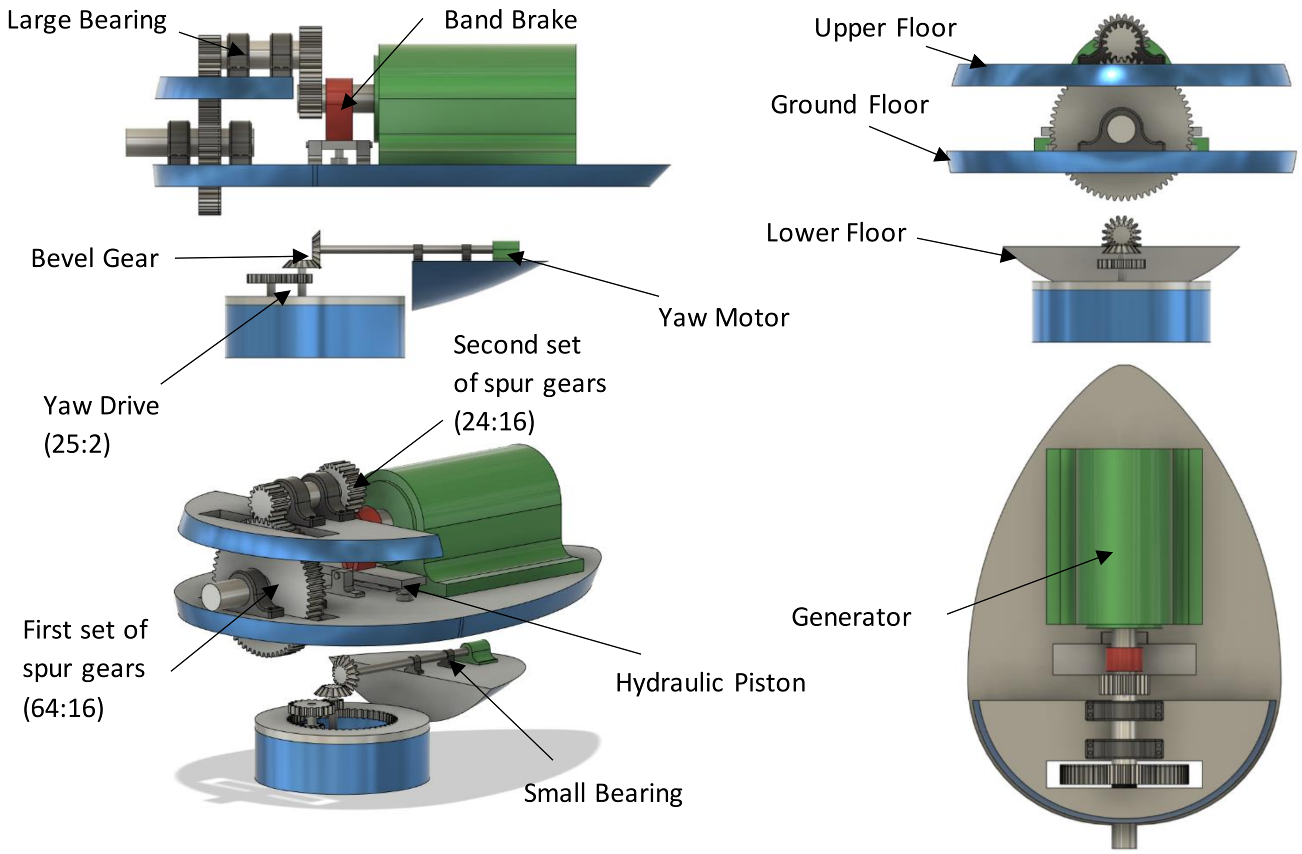
	Criteria	Productivity	Cost	Reliability	Aesthetics	Sustainability	Environmental	Structural		
	Weights	0.263	0.110	0.187	0.088	0.110	0.143	0.099		
Options		1	2	3	4	5	6	7	Total	%
3 blade horizontal	1	3	2	3	1	1	1	3	2.21	37
2 blade horizontal	2	2	3	2	2	2	2	2	2.11	35
Savonius vertical	3	1	1	1	3	3	3	1	1.68	28

Appendix 4 – Orthographic Projections of Nacelle

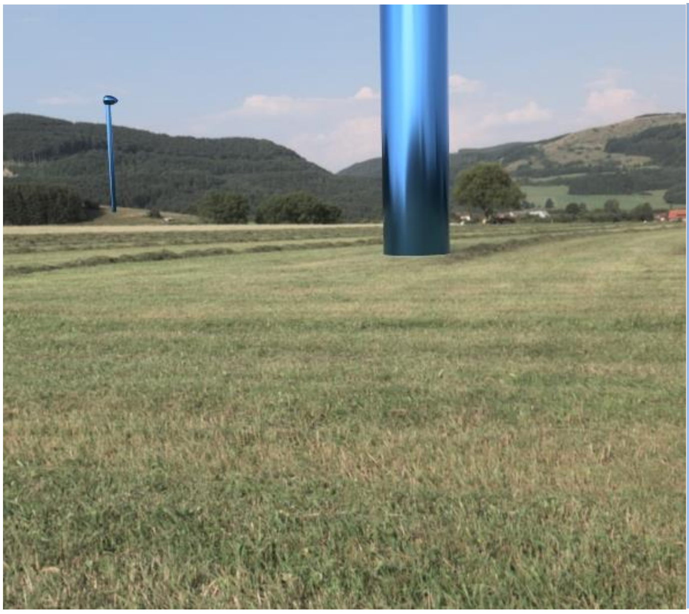
Appendix 4a: Orthographic Projection of Nacelle



Appendix 4b: Orthographic Projection of Internal Components of Nacelle

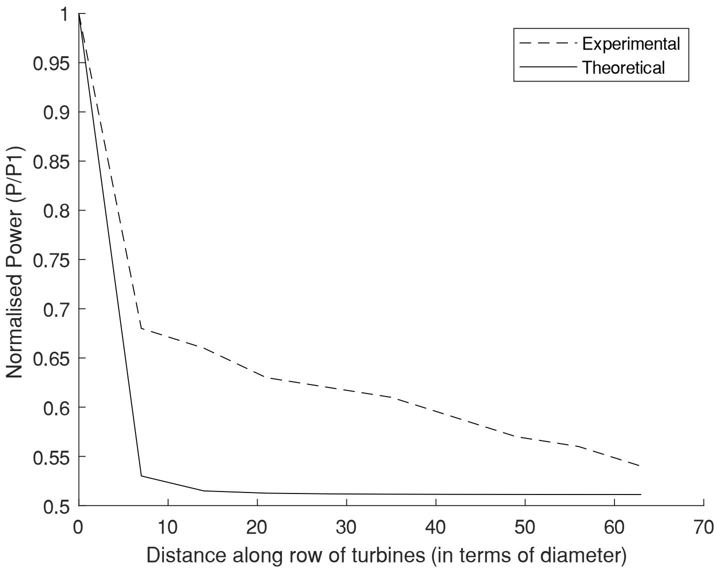


Appendix 5 – Visualisations of Nacelle in a Possible Location

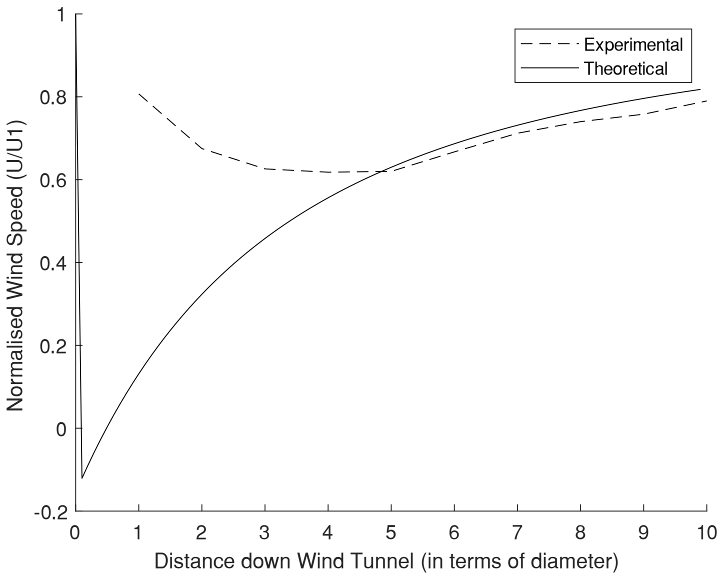


Appendix 6 – Code Validation

Appendix 6a: Power Validation

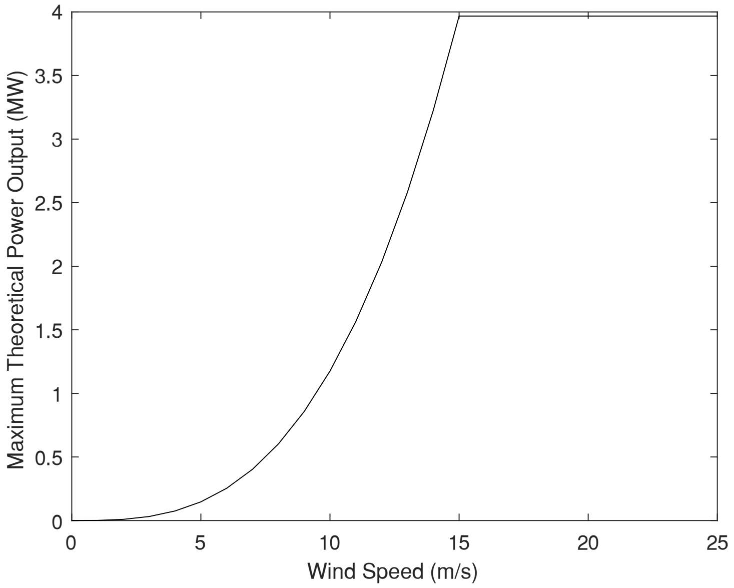


Appendix 6b: Speed Validation

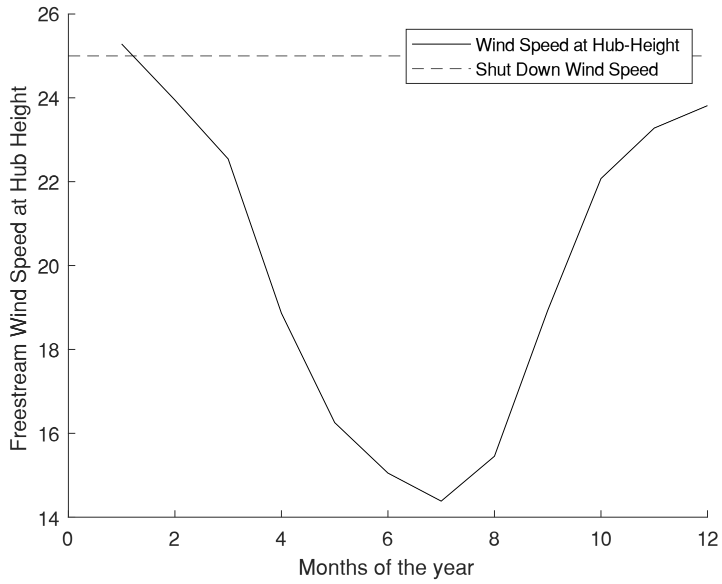


Appendix 7 – Other Wind Farm Plots

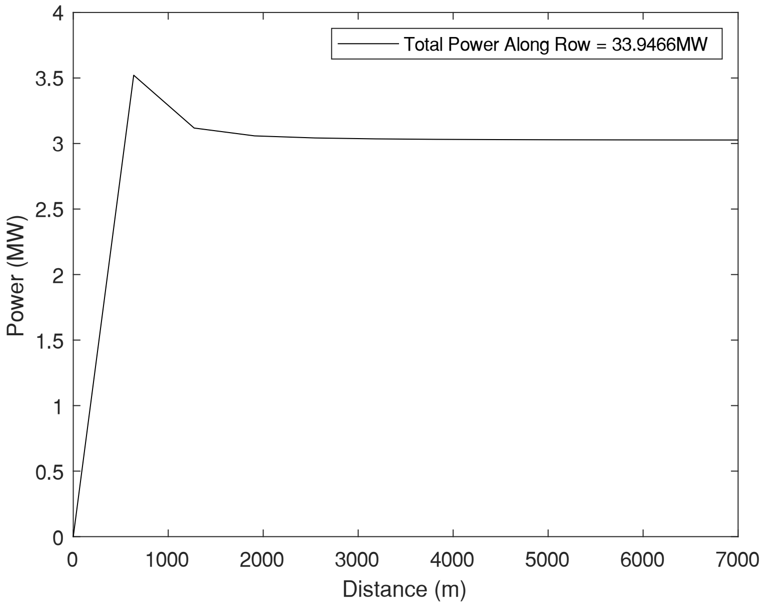
Appendix 7a: Power curve



Appendix 7b: Monthly Freestream wind speed



Appendix 7c: Power Along Row for January



Appendix 8 – Economic Viability