Design & Computing

Norse Wind Farm Proposal

Nacelle Sub-System focus

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Executive Summary:

The report is split into two sections: Design and Computing. The design aspect of the report considers stakeholder interests, it shows how the wind farm project affects each party and how that party's interests contributes to the decision making of the wind farm (appendix 1). A design criteria lays out a list of requirements the project should aim to meet, it considers a variety of external factors and conditions imposed by the Scottish government and Orkland Island Council. The report aims to satisfy the requirements listed on the design criteria in both design and computing aspects. The design section also contains a pairwise comparison matrix (appendix 3) that discusses different design decisions for the turbine concept as a whole with supplemented 2D designs (appendix 2). A prioritization matrix (appendix 3) ranks the order of importance for each component of the wind turbine so that the turbine's components can be built accordingly. The final design decision concluded that a 110m diameter turbine with a truss support and carbon-fibre blades would be the most ideal turbine design. The computing section of the report used a variety of different inputs through a FLORIS model to calculate the power output of the wind farm throughout the year. The calculations resulted in a planned wind farm consisting of 144 turbines in the Kerrygold location that generates an average of 611 MW of power per annum. The total cost of the project is approximately £459 million and the wind farm generates an estimated £169 million income per annum with an IRR of 8%.

Introduction:

This project aims to design a wind turbine farm on the Orkland islands of Scotland to produce energy from wind power for the local community and the government. The Nordic wind farm site experiences strong winds and provides the project with 104 hectares of land for the turbines. The intention of the project is to design a wind farm that is the most productive and efficient in the world. The project also needs to focus on a sustainable and environmentally friendly wind farm development as the local community is against the construction of the wind farm due to its potential interference with wildlife islands' scenery. The design section of the report considers the turbines' power output, material, nacelle configurations, blade design, blade diameter, height, manufacturing cost and maintenance. Once the overall design of the turbine is finalized, the report focuses on the expected power output for the wind farm as a whole. The wind farm aims to meet the following conditions imposed by the Scottish governments: The farm must meet the expected 600 MW power output with less than 150 turbines and minimize the farm's impact on nature while costing less than the £600 million capital employed into the project. Therefore, the computing part of the report contains different calculations that consider the wind density, speed, direction, turbine wake, turbine diameter and their location on Orkland Islands using a model called FLORIS.

Design section:

Design Criteria:

- Design a wind turbine farm that produces a power output of 600 MW with an estimated GBP 20 million income per annum.
- Minimise the visual pollution caused by wind turbines as far as possible since tourism is one of the islands' main income.

- Ensure that the turbines are built with durable and weather-proof material to reduce the need for frequent maintenance.
- Aim to build as less wind turbines as possible to minimize environmental impact on flora, fauna and RSBP nature reserve while still trying to meet the 600 MW target.
- Ensure the wind turbine is built with either recyclable or sustainable material to ensure the local community's environmental concerns are somewhat satisfied.
- Aim to maximize the project's Return on Capital Employed by generating a healthy yearly income.

Design Decisions:

The pairwise comparison matrix in appendix 3 ranks physical aspects of an ideal wind turbine in the farm in order of their importance which helps decide what features are most important to maximize power output. The 2D sketch in appendix 2 illustrates the rough designs of the development of wind turbine design, they are all designs of Horizontal Axis Wind Turbines (HAWT). The stakeholder matrix in appendix 1 displays each party's involvement on the project as a whole. The power produced by the wind farm is intended to meet the following criteria: high power output, low maintenance costs, low manufacturing costs, high durability, low visual pollution and should be made out of sustainable material. These criteria is then met by ranking what design options are available for the wind turbines. These options are decided between: a vortex generator or no vortex generator, a standard tower or a truss-built tower, glass-fibre blades or standard tubular steel blades, a direct drive nacelle transmission or a single stage gear nacelle transmission and the choice of turbine height.

Blade design - The blade design in sketch A of appendix 2 is adopted from the modern concept of a wind turbine and is pretty efficient in the production of energy per rotation in the absence of a vortex generator. However, according to appendix 3 the presence of a vortex generator increases each turbine's power output. A vortex generator is an area on the blade that energizes flow around the surface of the blade, ultimately enhancing each turbine's performance (Froese, 2021). Considering that power output is the second-most important criteria in the matrix, an investment in equipping each turbine with vortex generators will certainly generate a better power output.

Blade material – Most modern turbines are usually made out of tubular steel, although it is a durable material steel is prone to corrosion. With consideration of the Scottish weather on the Nordic islands, rain may cause the turbine to corrode which reduces its durability. Considering that durability is the most important criteria in appendix 3, designing the turbine blades with glass reinforced polyester not only increases its durability, but is also far more recyclable than tubular steel. The glass reinforced polyester can be recycled using thermal decomposition which can result in the production of the same polyester with up to 80% of its original strength. (Recycled glass fibre for cost-effective composites - University of Strathclyde, 2021). The polyester also handles elastic deformation due to high wind velocities much better than steel can which also reduces the risk of any permanent deformation in the blades due to any reason.

Support tower – Sketch C in appendix 2 illustrates a wind turbine support with an integrated truss support attached to the nacelle and rotor. A truss-designed support tower will be able to handle loads caused by wind turbulence better than the standard tower pole. A truss tower resistant to turbulence will be slightly more efficient than a vibrating tower, this is because the turbine loses kinetic energy due vibrations in its support and therefore would factor in as wasted energy. A truss support is also more durable than a single pole support and hence may require less maintenance than the single pole support.

Turbine height – According to the matrix in appendix 3, the 150m turbine would generate the most power relative to the 50 and 100m one but it is important to consider which height is the most economical since there is a limited amount of capital employed into the project. Investing in the 150m turbine wind farm would result in a lesser total number of turbines to reach a certain power output however would cause the most visual pollution out of the three heights and would pose a greater threat to the birds. The 150m turbine would also require expensive and time-consuming maintenance due to its big size. The investment in a 50m turbine wind farm would reduce the visual pollution but would need more turbines to reach a certain power output which would take up a lot of free land. The power output of the 50m turbines is also far less. With both factors taken into consideration an investment in a 100m wind farm seems ideal to balance out maintenance costs, visual pollution and total power output in the wind farm.

Nacelle transmission – The design of the parts in the nacelle is important as this is the component of the wind turbine that turns the kinetic energy from the wind to mechanical energy and essentially electricity. The single stage gear system consists of a lot more parts than the direct drive system due to the existence of a gearbox. It has a longer maintenance duration with a higher maintenance cost due to the possibility of failure of its many parts. A direct drive system is more suitable although it has a higher manufacturing cost as it would need less maintenance than a single gear system with a gearbox. A direct drive system also does not have losses in efficiency due to additional components, these losses could be frictional losses, gear backlash, imprecise motions and wear (Gearboxes vs. direct drive, 2021). Appendix 4 contains a 3D illustration of the chosen direct drive system nacelle and its internal components.

Computing section:

Formulae used:

$$P = \frac{8}{27}\rho v^3 A \tag{1}$$

Where: P = power output (W) | ρ = air density (kg/m^3) | v = wind velocity (m/s) | A = effective area of rotor disk (m^2)

$$v_w(h) = v_{10}\left(\frac{h}{h_{10}}\right)^{\alpha} \tag{2}$$

Where: $v_w(h)$ = velocity of wind (m/s) at height h (m) | h = height of turbine (m) | v_{10} = velocity of wind at h = 10m
α = Hellmann exponent

$$\mu = (1-k_m)(1-k_e)(1-k_{e,t})(1-k_t)(1-k_w)(C_p) \tag{3}$$

$$\mu = (1-0.0015)(1-0.0075)(1-0.065)(1-0.025)(1-0.065)(0.35) = 0.296 = 29.6\%$$

Where: μ = efficiency | k_m = mechanical losses of the blades and gearbox (0 – 0.3%) | k_e = electrical losses of the turbine (1-1.5%) | $k_{e,t}$ = electrical losses of transmission to the grid (3-10%) | k_t = percentage of time out of order due to maintenance (2-3%) |k_w = wake losses due to neighboring turbines and terrain topography (3-10%) | C_p = turbine efficiency (30-40%)

$$Actual\ power\ output = \mu \cdot Theoretical\ Power \tag{4}$$

Equation 2 considers the different wind velocities at the top and bottom of the rotor to give an average wind gradient and then put into equation 1 for power output. The Hellmann exponent differs based on the location of where the wind hits the turbine and therefore the different locations produce a different power output. After calculating the theoretical power output, the efficiency of the turbine is calculated using equation 3, the actual turbine power output is then calculated using equation 4. The power output calculation in table 1 indicates that the Kerrygold location consisting of open wetland and marshes clearly offers the best theoretical power and will be the location of where the turbines are built. The wind farm also does not occupy the entire area of Kerrygold, leaving enough space for the natural flora and fauna without disrupting the nature at other sites of the Islands. The high theoretical power in this location allows the farm to successfully generate more than 600 MW of power and over £ 169 million annual income.

Table 1: Calculation of theoretical power output for four different locations

Location	Hellmann Exponent (α)	v_{10} (m/s)	$v_w(h)$ (m/s)	Theoretical Power (W)	Theoretical Power (MW)
Deltling	0.11	8.3	10.69247128	4216725.6	4.2
Collinfirth	0.27	8.3	15.45532323	12734205.1	12.7
Kerrygold	0.40	8.3	20.84865738	31258766.8	31.3
Nestling	0.06	8.3	9.52967506	2985189.1	3.0

Wind farm computing:

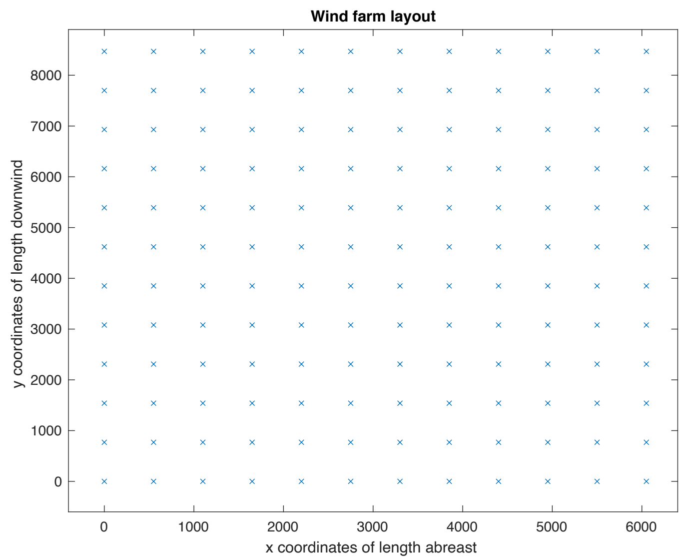

Figure 3: Wind farm layout

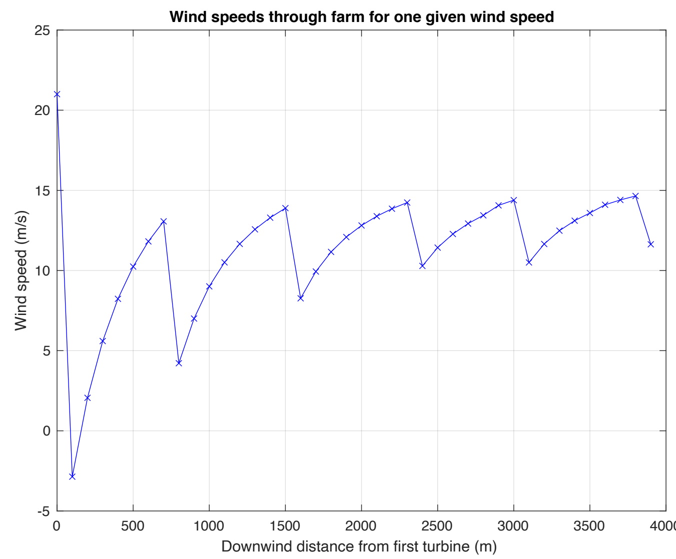

Figure 4: Variation in wind speed for one given speed for turbines in the same row

Figure 3 displays an aerial view of the wind turbine layout in Kerrygold. The graph displays a 12 x 12 matrix with a x7 turbine diameter distance between each turbine downwind and x5 turbine diameter distance between each turbine abreast.

Figure 4 shows how the wind speed varies for turbines placed in the same row due to factors such as wake. The graph uses a constant speed and oncoming flow direction. The constant speed value used in the graph is 21 m/s which is the average median speed for all 12 months.

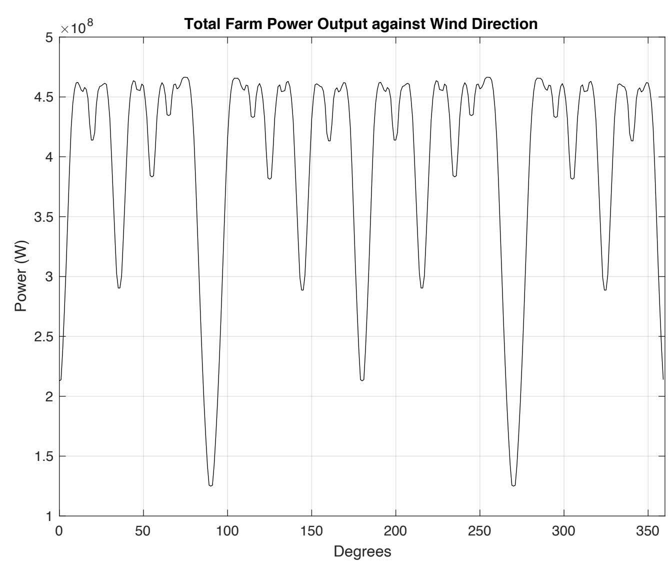

Figure 5: Variation of power output with oncoming flow direction

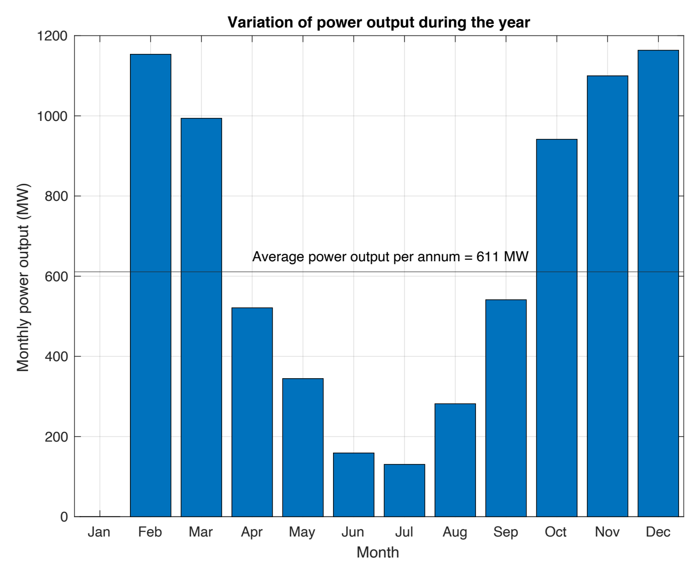

Figure 6: Actual power output per month throughout the year

Figure 5 displays the effect of changing oncoming flow direction to the power output for a sample turbine in the wind farm. The graph shows that the power output varies drastically based on different wind directions, measured in degrees in this case.

Figure 6 displays how the power output varies throughout the year as per the months. Different months have different densities and wind velocities, hence the power output also varies. Analyzing the graph as a whole, January experiences average median wind speeds greater than 25 m/s (the cut off speed) and hence produces 0

MW of power. The summer months experience less wind while the winter months generate a lot more power since it is significantly windier. Finally, the graph displays an average power output from the 12 months which is 611 MW.

Conclusions and Recommendations:

The design section of the report explores the different options for the turbine design through pairwise and prioritization comparisons, idea generation through 2D sketches, and a comprehensive consideration of stakeholder groups with direct interest into the project, attached in appendix 1. The selection of HAWT with vortex generators, glass-fibre blades, truss-tower design, 110m turbine diameter and a direct drive nacelle configuration aims to maximize power output and meet the report's design criteria. These design decisions supplement the construction of a wind turbine farm that is sustainable, efficient and environmentally friendly. The finalized turbine design meets the criteria relating to minimizing visual pollution, using durable and weather-proof material, reducing impact on flora and fauna and the use of sustainable material.

The computing section of the report uses the FLORIS model to calculate the power output of the farm per annum and displays different computations (Figure 1 – 6). The selection of 144 turbines each with a 110m diameter in the Kerrygold location successfully fulfills the 600 MW per annum requirement. The cost of wind farm is £459 million and it generates an annual income of £169 million, this successfully satisfies the requirements of the Scottish government and Orkland Island Council. In conclusion the Norse wind farm project successfully generates the required power output per annum while still taking major environmental and stakeholder impacts into consideration.

References:

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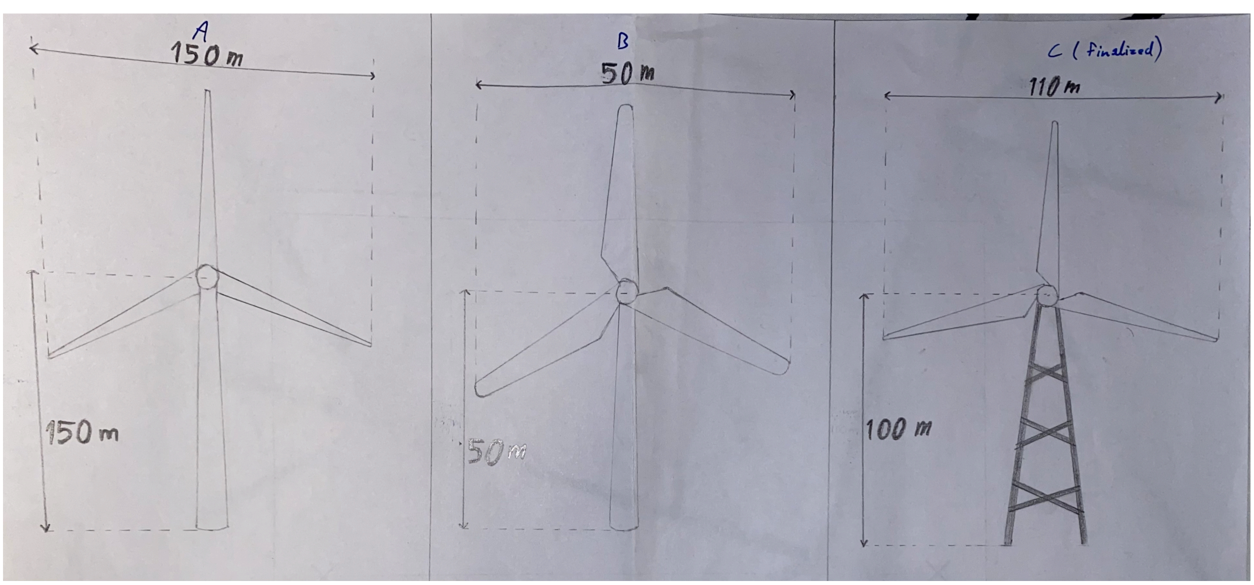
Appendices

Appendix 1: Stakeholder matrix

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 PLC	High	High	To produce substantial energy via the wind turbines.	Provide funding for research and development of the turbines.	Cancelling the partnership agreement with Orkland Island Council	Producing a large amount of energy from the turbines for the local community.
Local community	High	Medium	Protecting agriculture like nature reserves and seabird colonies. Visual pollution.	Offer moral support and provide acceptance of the project running in their hometown.	Try and cancel the project by complaining to the Orkland Island Council. Going on strikes.	Keep the community up to date about the progress of the project and offer jobs.
Orkland Island Council	High	High	Community's voice is heard and that they are not dissatisfied with the wind turbine projects. 20 million pounds per annum towards their trust	Allowing access to their islands and permission to work on their land.	Denying access for any construction on their islands.	Displaying the project's benefits for the local community in terms of jobs and production of clean energy.
Scottish government	Low	High	The financial advantages of the wind farm project	Provide funding for the project.	Withdraw any funding for the project.	Keep the government about-to-date about the progress of the project and any news.
RSPB Scotland	Medium	Medium	Protecting agriculture like nature reserves and seabird colonies.	Not encouraging the local community against the project.	Has the strength to start protests and strikes against the project.	Ensuring that the birds and their habitats are safe during the construction of the wind turbines.

Appendix 2: Hand-drawn wind turbine concepts



Appendix 3: Pairwise comparison and prioritization matrix

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

Criteria		Power output	Maintenance	Visual pollution	Durability	Recyclable	Manufacturing cost	Environmental impact		
	X	**1**	**2**	**3**	**4**	**5**	**6**	**7**	Total	%
Power output	**1**	**X**	9.00	9.00	3.00	9.00	3.00	9.00	42.00	34
Maintenance	**2**	0.11	**X**	3.00	0.11	0.33	0.33	1.00	4.89	4
Visual pollution	**3**	0.11	0.33	**X**	0.11	0.33	0.11	0.33	1.33	1
Durability	**4**	0.33	9.01	9.01	**X**	9.00	9.00	9.00	45.35	37
Recyclable	**5**	0.11	3.00	3.00	0.11	**X**	1.00	1.00	8.23	7
Manufacturing cost	**6**	0.33	3.00	9.01	0.11	1.00	**X**	3.00	16.46	13
Environmental impact	**7**	0.11	1.00	3.00	0.11	1.00	0.33	**X**	5.56	4
		1.11	25.35	36.02	3.56	20.67	13.78	23.33	123.82	100
		0.9	20.5	29.1	2.9	16.7	11.1	18.8	100	123.82

	Criteria	Power output	Maintenance	Visual pollution	Durability	Recyclable	Manufacturing cost	Environmental impact		
	Weights	0.339	0.039	0.011	0.366	0.066	0.133	0.045		
Options		**1**	**2**	**3**	**4**	**5**	**6**	**7**	Total	%
Vortex generator	**1**	10	3	1	6	3	10	1	7.29	10
No Vortex generator	**2**	7	2	1	6	3	7	1	5.84	8
Truss tower	**3**	1	8	5	11	3	9	1	6.18	9
Standard tower	**4**	1	6	3	6	3	6	1	3.85	5
Glassfibre blade	**5**	9	11	1	11	9	10	5	9.68	13
Tubular steel blade	**6**	7	8	1	5	4	7	8	6.09	8
Direct drive system	**7**	9	3	1	8	2	10	1	7.62	11
Single stage gear system	**8**	9	8	1	7	2	7	1	7.05	10
50m height	**9**	2	2	1	7	1	6	2	4.29	6
100m height	**10**	7	4	4	6	1	8	4	6.08	8
150m height	**11**	11	8	8	5	1	11	8	7.85	11

Appendix 4: 3D CAD visualization of turbine nacelle