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ORKLAND ISLANDS WIND FARM CONCEPT

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TABLE OF CONTENTS

ABSTRACT

This report goes through the design process of three wind turbine concepts and how the best overall concept was chosen for the Orkland Islands wind farm. Through stakeholder analysis and different design criteria, the best concept, which was concept 2, was chosen and visualised through CAD.

A wind farm assessment script on MATLAB was then created to model the expected power output of 150 turbines and to utilise the environmental conditions of Orkland Islands so that the power output can be maximised. From the model, the average power output of the farm is 262MW, but the FLORIS model underestimates the power output to a certain extent, meaning there is a high possibility the actual power output of the farm is closer to the 600MW target. From these calculations, the expected income and expenses were projected and used to calculate an IRR value of 14.29% over 25 years.

1. INTRODUCTION

Renewable energy has been growing in popularity and demand in recent years. With the decrease in supply and increase in price of fossil fuels, as well as one of the UN's Sustainable Development Goals being access to sustainable energy by 2030, it is no surprise that many countries are shifting to renewable sources of energy.

Wind energy is the second most popular source of renewable energy, just behind hydropower. In 2018, the global installed wind power capacity reached approximately 563GW (PowerTechnology.2020) which is about 24% of the world's total renewable energy generation capacity. Despite being a source of sustainable energy, wind farms do have some drawbacks. Despite its decreasing price, wind power still must compete with some sources of energy with lower costs, may not be aesthetically pleasing to some and may even affect surrounding wildlife.

2. DESIGN

This report aims to develop the best possible wind farm layout and choose one of three wind turbine concepts for the Orkland Islands wind farm project to be completed by 2025. To start the project, the different stakeholders were first identified. The full analysis is shown in the Stakeholder Analysis Matrix shown in Table 6.1 in the appendix which shows much they impact and influence the outcome of the project.

2.1. PROBLEM STATEMENT AND DESIGN CRITERIA

To come up with proper concepts, a problem statement and design criteria were first generated. The problem statement that was made is as follows: "To provide renewable energy using wind turbines while keeping formal objections and conflicts to a minimum. The wind farm must be able to meet the specific technical requirements but must also not cause any problems or conflicts with the local community and organisations". This in turn led to making seven design criteria which can be found in Table 2.1. After the design criteria were made, a pairwise comparison matrix was used to rank the importance of each criteria and can be seen in Table 6.2 of the appendix.

Table 2.1 – Design Criteria

Criterion	Criterion Detail
Capital Cost	Total cost must be within the capital of the project
Area	Must only cover a maximum area of 129 km^2
Efficiency	Must be as efficient as possible during use (little energy wasted)
Environmental Impact and Aesthetics	Must have low carbon footprint and must be as visually aesthetic as possible
Maintenance and Lifetime	Should be able to reduce the need for maintenance (maintenance should be done by qualified individuals) and must also have a long lifespan with the flexibility for future upgrades
Total Output	Should provide the required total power output
Creation of Jobs	Should ideally create jobs for the local community

2.2. Concept Idea Generation

Based on the three technical annexes, different concepts for the wind turbines were created and the details of each concept can be seen in Table 2.2 below beside the datum design currently being proposed. Concept 1 is an upscaled version of the current design, giving a rated output of 8MW instead of 4.5MW. Concept 2 uses a concrete/steel hybrid tower, a direct drive nacelle and a gliding yaw bearing. This was done to reduce costs associated with building the tower (Way and Van Zijl. 2015) as well as maintenance costs associated with the nacelle and yaw. Concept 3 replaces the fibreglass blades and nacelle into carbon fibre and uses two blades to cut costs but at the expense of aerodynamic efficiency. All 4 designs are Horizontal Axis Wind Turbines (HAWT) as studies show that HAWTs are the most reliable type of wind turbine (Winslow. 2017).

After generating 3 ideas for the turbines, a Controlled Convergence Performa matrix was used to choose the best design based on the design criteria, with the current proposed design as the datum. The full matrix is shown Table 6.3 in Appendix. The datum design is given a net score of 0 and concepts 1, 2 and 3 are given scores relative to the datum design.

Table 2.2 – Wind Turbine Design Concepts

Design	Datum	Idea 1	Idea 2	Idea 3
Type	HAWT	HAWT	HAWT	HAWT
Output (MW)	4.5	8	4.5	4.5
Tower Material	Steel	Steel	Concrete/Steel Hybrid	Steel
Tower Height (m)	90	150	100	100
Blade Material	Fibreglass	Fibreglass	Fibreglass	Carbon Fibre
Number of Blades	3	3	3	2
Blade Diameter (m)	110	150	110	110
Nacelle Type	Single Stage Gear System	Single Stage Gear System	Direct Drive System	Single Stage Gear System
Nacelle Material	Fibreglass	Fibreglass	Fibreglass	Carbon Fibre
Yaw Type	Roller Yaw Bearing	Roller Yaw Bearing	Gliding Yaw Bearing	Roller Yaw Bearing

2.3. Concept Evaluation

From the Controlled Convergence Matrix, it is seen that Concept 2 is the best choice, with a net score of 2. Concept 3 is tied with the datum, while Concept 1 comes in last with a net score of -2. Concept 2 is able to significantly cut down on manufacturing costs as steel-concrete towers usually cost around 42% of pure steel towers (Way and Van Zijl. 2015). It is also able to cut down on maintenance costs due to the reduction of flange connections and use of a gliding yaw bearing and direct drive system. Despite Concept 2 having more of a short-term negative impact to the environment due to the larger amount of CO2 produced when manufacturing the materials compared to the datum, it can be paid back to the environment during the turbine's whole lifetime and can even still be considered carbon-negative since it is expected to operate for a relatively long period and produces almost zero carbon emissions when generating electricity (Glennie.2016).

2.4. Concept Visualisation

Based on the chosen concept, a visualisation of the nacelle was generated using Fusion 360 and the 2D technical drawing can be seen in Figure 2.1. The nacelle utilises a direct drive system and has a casing with a square cross-section of 13m x 13m and a length of about 18.5m. It has a main shaft connecting the rotor hub and the generator which has a diameter of 2m and a length of 15m. The shaft is held in place by a support behind the generator. Although the nacelle has a gliding yaw system, it was not modelled in the CAD visualisation as the model focuses on the nacelle itself.

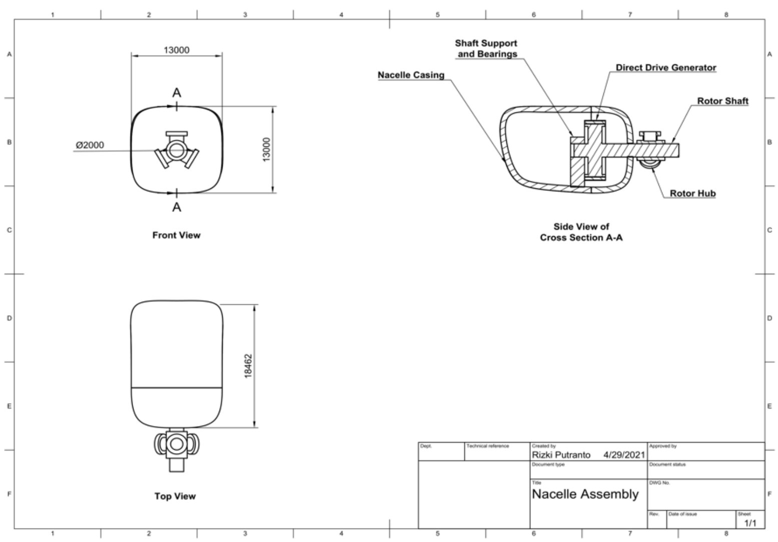


Figure 2.1 - 2D Nacelle CAD Technical Drawing

3. Computing

After the final concept was chosen, a wind farm assessment was carried out in MATLAB using the FLORIS model, which calculates the power produced by wind turbines, as well as the speed a user-specified point.

3.1. Validation

Two validation scripts were first made to plot data from the FLORIS model against known experimental data as can be seen in Figures 6.1 and 6.2 in the appendix. Figures 6.1(a) and 6.1(b) plots data for the varying speeds across a wind tunnel. The former shows the actual normalised speeds downstream a turbine in a wind tunnel, compared against data modelled by FLORIS for the same conditions shown by the latter. Figure 6.2 plots data for normalised power produced by FLORIS against data provided for Horns-Rev wind farm in Denmark for ten turbines placed linearly.

From Figure 6.2, the normalised powers for both the FLORIS model and actual data are equivalent for the first turbine, but the power modelled by FLORIS decreases rapidly downstream along the wind farm and plateaus right before the third turbine to about 51% of the power output of the first turbine and continues until the last turbine. The Horns-Rev data shows a similar trend but the decrease in power is less than what was modelled by FLORIS and there is a similar, but less pronounced plateau of normalised power before the third turbine. The power output continues to decrease slightly until the final turbine, at which it produces just under 55% of the power of the first turbine.

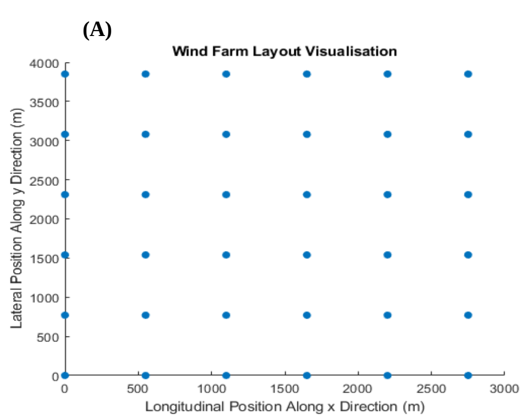
Looking at Figures 6.1(A) and 6.1(B), the wake modelled by FLORIS is shorter, narrower, and less smooth than the wake produced by the actual turbine. Like the power output, the normalised speeds modelled by FLORIS at certain points are lower than the actual data, with the lowest speeds from FLORIS being around 20% of the initial oncoming wind speed while the lowest speed from actual data is about 55%.

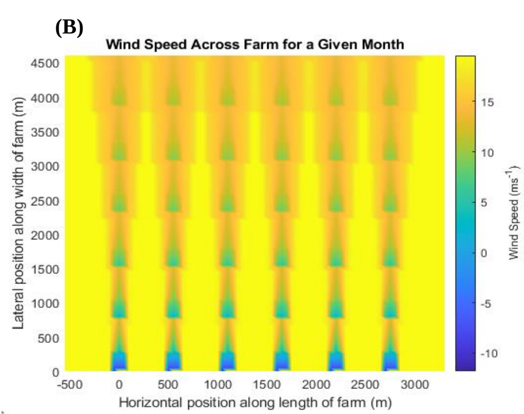
Overall, it can be seen that the FLORIS model does not accurately model the wind speeds and power outputs but does give a good overview of what is to be expected. The experimental data clearly shows the weaknesses and limitations of FLORIS when used as a standalone model which is important to take note of when assessing the Orkland Islands wind farm design.

3.2. Wind Farm Assessment

After completing the FLORIS validation, a MATLAB script was created to generate 4 plots of data as shown by the examples below in Figure 3.1 below. Figure 3.1(A) shows a plot of the expected grid layout of the wind farm for a specific location while considering the total usable area of each location. Users can obtain this by first running the MATLAB script and then entering one of the four locations of where they would like to conduct the entire assessment. However, KerryGold will not be used due to the presence of important flora and fauna in the area as well as bordering the site of a RSBP nature reserve. Building the farm in KerryGold will most likely result in more backlash from the local community and organisations, who are also stakeholders in the project.

Figure 3.1(B) then shows a plot of the varying wind speeds across the farm, shown by the gradient of colours, for one given oncoming wind speed during a user-specified month and wind direction, which can be repeated. Figure 3.1(C) is then generated, which plots the total power output across the year for each month as well as the possible variations through the mean, 25th and 75th percentile wind speeds. Figure 3.1(D) shows the final graph which plots how the power output varies with a changing wind direction for a user-specified month and can also be repeated for different months. It is worth noting that Figure 3.1(D) shows a rapid increase in the power output when the wind direction shifts slightly from the four cardinal directions, and in some cases may increase by a factor of two. This can be taken advantage of in practice by monitoring the wind direction across the year and adjusting the yaw angles accordingly so that the wind turbines do not directly face the cardinal directions and thus the power output can be maximised.





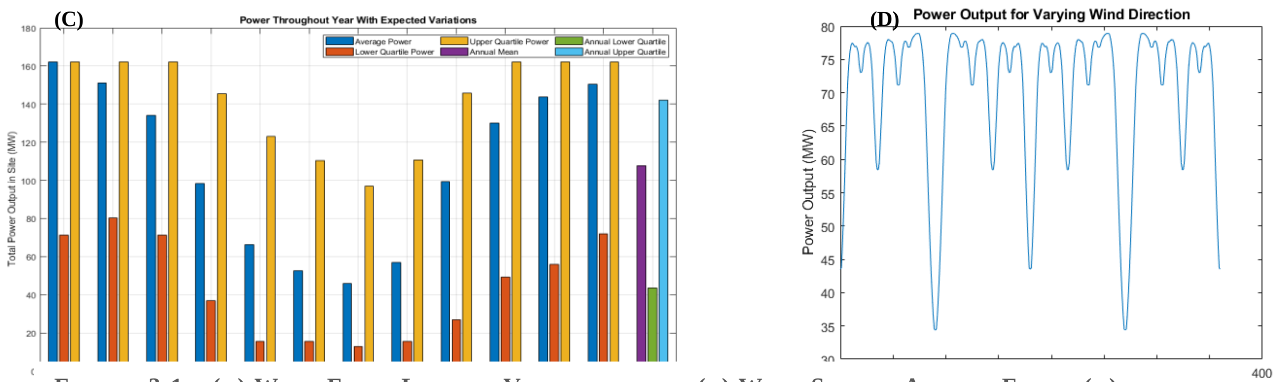


FIGURE 3.1 – (A) WIND FARM LAYOUT VISUALISATION, (B) WIND SPEEDS ACROSS FARM, (C) POWER VARIATIONS THROUGHOUT YEAR, (D) POWER OUTPUT FOR VARYING WIND SPEEDS

3.3. POWER OUTPUT

Table 3.1 shows the average power output throughout the year for the mean, 25th percentile and 75th percentile wind speeds as modelled by FLORIS. It is important to note that these numbers are an average across the whole year and not representative of each month. The average value is heavily affected by the large variations in wind speeds between every month, with the stronger winds present during the autumn and winter months and the calmer winds during the spring and summer months. A full assessment in MATLAB using the provided code is needed to obtain a better understanding of the power outputs per month.

It should also be noted that the power output modelled by FLORIS can be significantly lower than what is actually produced as shown in the validation. Obtaining the actual power output may only be possible by building and collecting data from actual wind farms instead of models.

TABLE 3.1 – AVERAGE POWER OUTPUT THROUGHOUT YEAR

Location	Overall Average Power (MW)	Average 25th Percentile Power (MW)	Average 75th Percentile Power (MW)
Deltling	130.43	42.5	231.83
Collinfirth	107.59	43.63	142
Nestling	24.07	7.76	44.3
TOTAL	262.09	93.89	418.13

3.4. FINAL COSTS

Table 3.2 below shows an Excel table used to calculate the Interal Rate of Return (IRR) of 14.29% for the project, utilising the XIRR function. The cash flow is the summation of different incomes and expenses per year, and the details can be found in Tables 6.4(A), 6.4(B) and 6.4(C) in the appendix. From the calculations, the project would be able to breakeven after eight years and start making profit afterwards. However, it is important to note that this calculation makes a lot of assumptions, including a rough estimation of the full load period of 2000 hours. It also assumes a typical lifespan for turbine equipment of about 25 years (Renewables First. n.d). A more detailed breakdown of the costs is needed to obtain a more accurate cash flow and IRR value.

Period	Cash Flow	Net Flow
1/1/2025	-£ 695,769,853	-£ 695,769,853
1/1/2026	£ 74,015,750	-£ 621,754,103
1/1/2027	£ 77,986,065	-£ 543,768,038
1/1/2028	£ 82,092,486	-£ 461,675,552
1/1/2029	£ 86,339,437	-£ 375,336,115
1/1/2030	£ 90,731,480	-£ 284,604,635
1/1/2031	£ 95,273,321	-£ 189,331,314
1/1/2032	£ 99,969,815	-£ 89,361,499
1/1/2033	£ 104,825,971	£ 15,464,472
……		
1/1/2049	£ 208,996,249	£ 2,505,453,851
1/1/2050	£ 217,506,253	£ 2,722,960,104

IRR	14.29%	

TABLE 3.2 – OVERALL CASH FLOW AND IRR VALUE (REFER TO APPENDIX FOR FULL TABLE)

4. CONCLUSIONS AND RECOMMENDATIONS

After thorough analysis, it is apparent that Concept 2 is best suited for the wind farm as it provides the best compromise across the aforementioned design criteria. Although it may not meet the 600MW power output expectation throughout the whole year according to FLORIS, it will be able to reach it during periods of faster wind speeds, particularly during the winter and autumn months. Using this design, the project will roughly be able to breakeven after its eighth year of operation and continue to make profits afterwards.

Despite KerryGold having the fastest wind speeds throughout the year, it is not a viable site to build the wind farm on due to the presence of important flora and fauna in the area as well as bordering the site of a RSBP nature reserve. The wind speeds in this area may even exceed the cut-off speed at times, meaning turbines placed in this area will not be able to produce power during these times. This means that spreading the turbines across Deltling, Nestling and Collinfirth is the best option to maximise the power output across the year.

If, for any reason, the designed wind farm fails to achieve the desired results, the best possible solution would be to build more turbines in Nestling as the current layout only uses approximately 25% of the area in Nestling. It would also be possible to move some turbines to KerryGold and scale them down in size so that the wind speeds at the hub height will not exceed the cut-off. However, the RSBP and local community must agree to a possible compromise, such as painting the wind turbines black so that the chances of a bird strike are decreased and taking great care when building in that area so that the flora and fauna will not be affected.

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6. Appendix

Table 6.1 – Stakeholder Analysis Matrix

Stakeholder Name	**Contact Person** *Phone, Email, Website, Address*	**Impact** *How much does the project impact them? (Low, Medium, High)*	**Influence** *How much influence do they have over the project? (Low, Medium, High)*	**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 Energy plc		High	High	EnsuriShg the project's completion	Listening to concerns and input from opposing sides to be able to reach an agreement		
Orkland Islands Council		High	High	Ensuring that the conflicting sides reach an agreement	Organising meetings between the leaders/spokesperson of the two sides to discuss any agreements or compromises that can be made		
Scottish Government		Medium	High	Ensuring the project's completion while not having any major conflicts due to the project	Provide funds for the project	Not give consent to build the project	Giving regular updates on the progress of the project
RSPB Scotland		Medium	Medium	Making sure the wind farm does not affect the bird population	Address concerns to the conflicting parties to sort out any issues	Objecting the project's construction	Arranging regular meetings and taking note of their concerns
Orkland Community Campaign Group		Medium	Medium	Making sure the construction of the wind farm project does not continue	Stopping any legal actions taken and sort out issues through meetings	Taking legal action against the construction of the project	Arranging regular meetings and taking note of their concerns

TABLE 6.2 – PAIRWISE COMPARISON MATRIX

Pairwise Comparison Matrix

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

Criteria		Capital Cost	Area	Efficiency	Environmental Impact and aesthetics	Maintenance and Lifetime	Total output	Creation of jobs		
	X	1	2	3	4	5	6	7	Total	%
Capital Cost	1	X	3.00	1.00	1.00	0.33	1.00	1.00	7.33	13
Area	2	0.33	X	0.33	0.33	0.33	1.00	1.00	3.33	6
Efficiency	3	1.00	3.00	X	1.00	1.00	3.00	3.00	12.00	21
Environmental Impact and aesthetics	4	1.00	3.00	1.00	X	3.00	3.00	3.00	14.00	24
Maintenance and Lifetime	5	3.00	3.03	1.00	0.33	X	3.00	3.00	13.37	23
Total output	6	1.00	1.00	0.33	0.33	0.33	X	1.00	4.00	7
Creation of jobs	7	1.00	1.00	0.33	0.33	0.33	1.00	X	4.00	7
		7.34	14.04	4.00	3.33	5.33	12.00	12.00	58.03	100
		12.6	24.2	6.9	5.7	9.2	20.7	20.7	100	58.03

TABLE 6.3 – CONTROLLED CONVERGENCE PERFORMA MATRIX

CONTROLLED CONVERGENCE PROFORMA

	DATUM	Idea 1	Idea 2	Idea 3
CRITERIA				
Capital Costs	0	-	+	+
Area	0	0	0	0
Efficiency	0	+	+	-
Environmental Impact and Aesthetics	0	-	-	-
Maintenance and Lifetime	0	-	+	+
Total Output	0	0	0	0
Creation of Jobs	0	0	0	0
∑ +				
∑ -				
∑ S				
Net Score	0	-2	2	0
Rank	2	3	1	2

TABLE 6.4 – (A) ESTIMATES FOR PROJECT COSTS (B) ESTIMATES FOR ANNUAL CASH FLOW (C) FULL CASH FLOW AND IRR TABLE

(A)

Cost per Turbine (70%)	£	3,246,926
Overall Cost per Turbine (100%)	£	4,638,466
Total Cost for 150 turbines	£	695,769,853
Annual O&M Costs for 150 Turbines	£	30,000,000
Annual Power Produced (kWh)		1350000000
Orkland Power Demand (kWh)		42550000

(B)

Period	Revenue per year from Tariffs	Annual O&M Costs	Orkland Demand Percentage (%)	Power Exported (kWh)	Annual Export Tariffs	Total Cash Flow per Year
1/1/2026	£ 189,000,000.00	£ 30,000,000	3.152	1307450000	£ 84,984,250.00	£ 74,015,750.00
1/1/2027	£ 194,670,000.00	£ 30,000,000	3.152	1307450000	£ 86,683,935.00	£ 77,986,065.00
1/1/2028	£ 200,510,100.00	£ 30,000,000	3.152	1307450000	£ 88,417,613.70	£ 82,092,486.30
1/1/2029	£ 206,525,403.00	£ 30,000,000	3.152	1307450000	£ 90,185,965.97	£ 86,339,437.03
1/1/2030	£ 212,721,165.09	£ 30,000,000	3.152	1307450000	£ 91,989,685.29	£ 90,731,479.80
1/1/2031	£ 219,102,800.04	£ 30,000,000	3.152	1307450000	£ 93,829,479.00	£ 95,273,321.04
1/1/2032	£ 225,675,884.04	£ 30,000,000	3.152	1307450000	£ 95,706,068.58	£ 99,969,815.46
1/1/2033	£ 232,446,160.57	£ 30,000,000	3.152	1307450000	£ 97,620,189.95	£ 104,825,970.61
1/1/2034	£ 239,419,545.38	£ 30,000,000	3.152	1307450000	£ 99,572,593.75	£ 109,846,951.63
1/1/2035	£ 246,602,131.74	£ 30,000,000	3.152	1307450000	£ 101,564,045.62	£ 115,038,086.12
1/1/2036	£ 254,000,195.70	£ 30,000,000	3.152	1307450000	£ 103,595,326.54	£ 120,404,869.16
1/1/2037	£ 261,620,201.57	£ 30,000,000	3.152	1307450000	£ 105,667,233.07	£ 125,952,968.50
1/1/2038	£ 269,468,807.61	£ 30,000,000	3.152	1307450000	£ 107,780,577.73	£ 131,688,229.88
1/1/2039	£ 277,552,871.84	£ 30,000,000	3.152	1307450000	£ 109,936,189.28	£ 137,616,682.56
1/1/2040	£ 285,879,458.00	£ 30,000,000	3.152	1307450000	£ 112,134,913.07	£ 143,744,544.93
1/1/2041	£ 294,455,841.74	£ 30,000,000	3.152	1307450000	£ 114,377,611.33	£ 150,078,230.41
1/1/2042	£ 303,289,516.99	£ 30,000,000	3.152	1307450000	£ 116,665,163.56	£ 156,624,353.43
1/1/2043	£ 312,388,202.50	£ 30,000,000	3.152	1307450000	£ 118,998,466.83	£ 163,389,735.67
1/1/2044	£ 321,759,848.57	£ 30,000,000	3.152	1307450000	£ 121,378,436.17	£ 170,381,412.41
1/1/2045	£ 331,412,644.03	£ 30,000,000	3.152	1307450000	£ 123,806,004.89	£ 177,606,639.14
1/1/2046	£ 341,355,023.35	£ 30,000,000	3.152	1307450000	£ 126,282,124.99	£ 185,072,898.37
1/1/2047	£ 351,595,674.05	£ 30,000,000	3.152	1307450000	£ 128,807,767.49	£ 192,787,906.57
1/1/2048	£ 362,143,544.27	£ 30,000,000	3.152	1307450000	£ 131,383,922.84	£ 200,759,621.44
1/1/2049	£ 373,007,850.60	£ 30,000,000	3.152	1307450000	£ 134,011,601.29	£ 208,996,249.31
1/1/2050	£ 384,198,086.12	£ 30,000,000	3.152	1307450000	£ 136,691,833.32	£ 217,506,252.80

(C)

Period	Cash Flow	Net Flow
1/1/2025	-£ 695,769,853	-£ 695,769,853
1/1/2026	£ 74,015,750	-£ 621,754,103
1/1/2027	£ 77,986,065	-£ 543,768,038
1/1/2028	£ 82,092,486	-£ 461,675,552
1/1/2029	£ 86,339,437	-£ 375,336,115
1/1/2030	£ 90,731,480	-£ 284,604,635
1/1/2031	£ 95,273,321	-£ 189,331,314
1/1/2032	£ 99,969,815	-£ 89,361,499
1/1/2033	£ 104,825,971	£ 15,464,472
1/1/2034	£ 109,846,952	£ 125,311,424
1/1/2035	£ 115,038,086	£ 240,349,510
1/1/2036	£ 120,404,869	£ 360,754,379
1/1/2037	£ 125,952,968	£ 486,707,347
1/1/2038	£ 131,688,230	£ 618,395,577
1/1/2039	£ 137,616,683	£ 756,012,260
1/1/2040	£ 143,744,545	£ 899,756,805
1/1/2041	£ 150,078,230	£ 1,049,835,035
1/1/2042	£ 156,624,353	£ 1,206,459,389
1/1/2043	£ 163,389,736	£ 1,369,849,124
1/1/2044	£ 170,381,412	£ 1,540,230,537
1/1/2045	£ 177,606,639	£ 1,717,837,176
1/1/2046	£ 185,072,898	£ 1,902,910,074
1/1/2047	£ 192,787,907	£ 2,095,697,981
1/1/2048	£ 200,759,621	£ 2,296,457,602
1/1/2049	£ 208,996,249	£ 2,505,453,851
1/1/2050	£ 217,506,253	£ 2,722,960,104

IRR	14.29%	

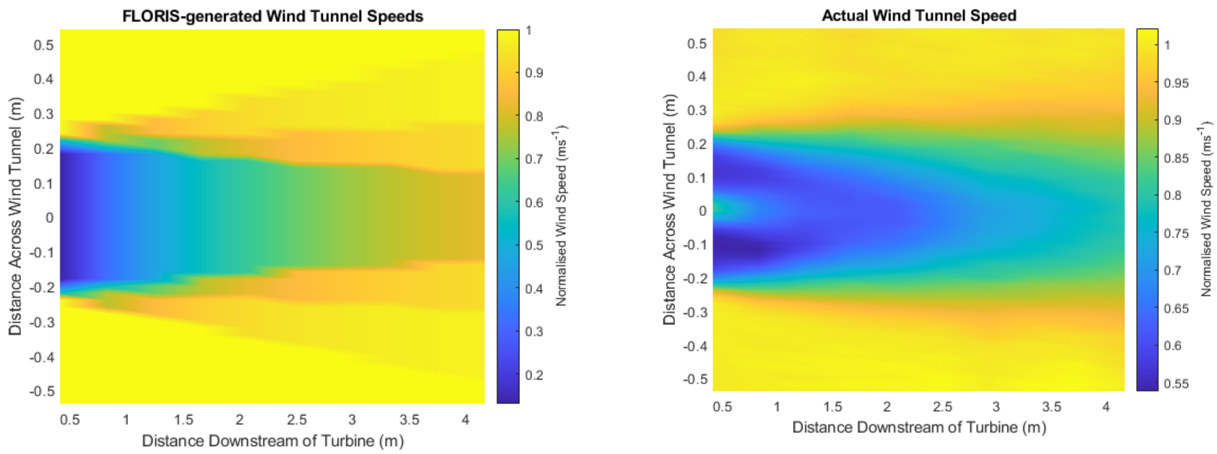

FIGURE 6.1 – (A) FLORIS-GENERATED WIND SPEEDS AND (B) ACTUAL WIND SPEED DATA

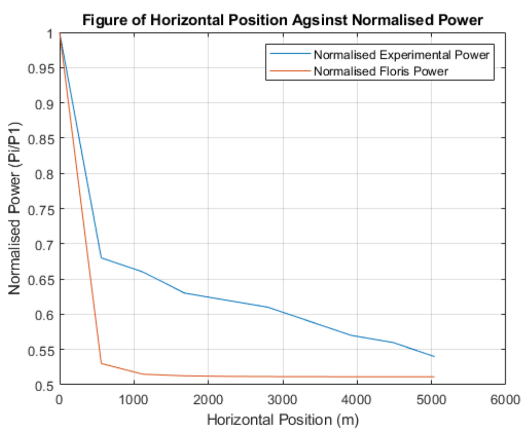

FIGURE 6.2 – COMPARISON OF ACTUAL NORMALISED POWER AND NORMALISED FLORIS POWER

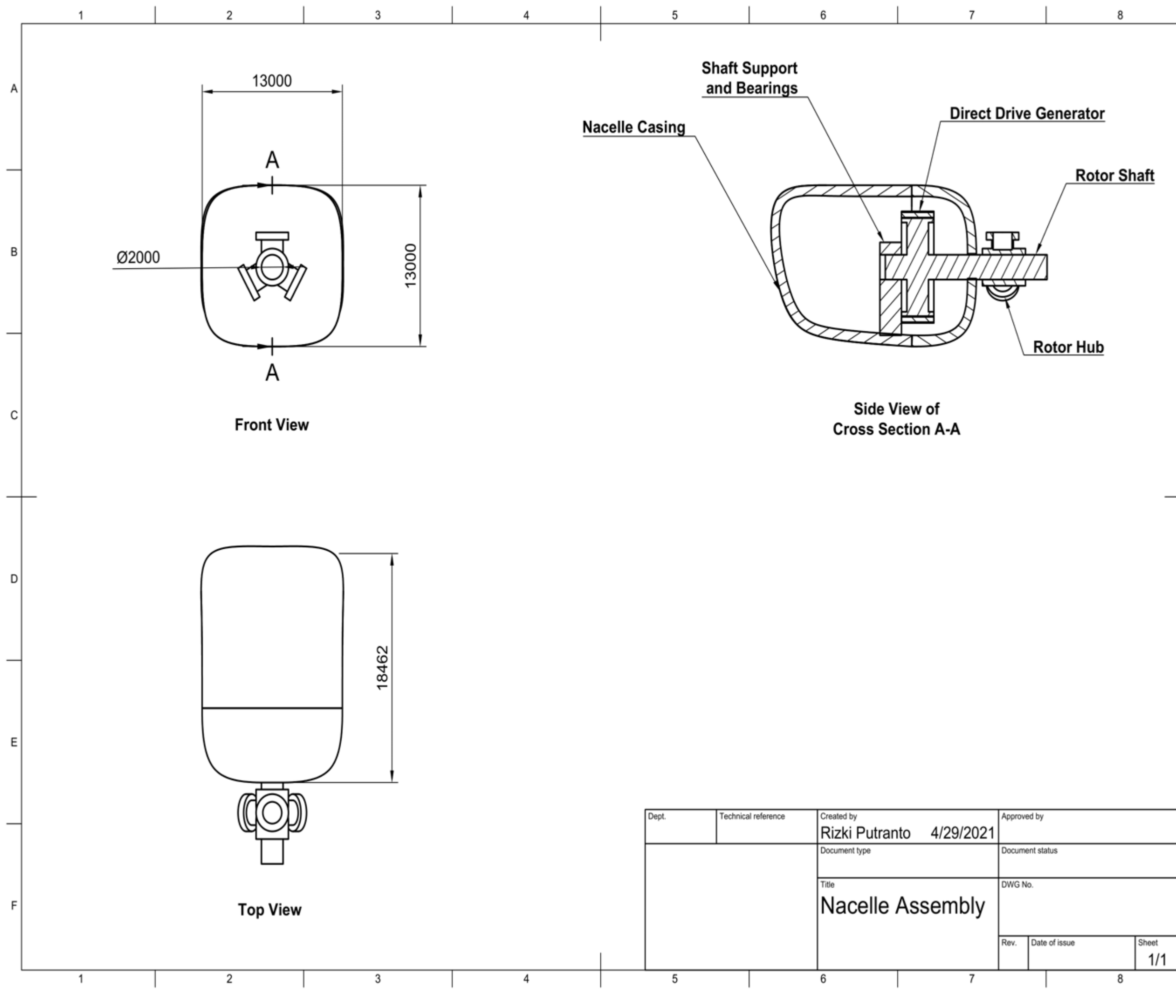

FIGURE 6.3 – ENLARGED 2D CAD TECHNICAL DRAWING

FIGURE 6.4 – 3D CAD RENDER