60MW Multi-Rotor Vertical Axis Wind Turbine

Baseline report

Group 21

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Contents

1
Introduction

In the last 20 years, the demand for sustainable energy has been considerably increasing, especially due to the effects that climate change and global warming are having on the world. These potentially catastrophic events are mainly caused by the constant growth in the production of greenhouse gases resulting from the burning of fossil fuels. In light of this, a solution to this problem must be found to save humankind and ecosystems from being extinguished. This can be achieved in multiple ways, and one of these is finding alternative options to produce energy derived from fossil fuel combustion.

Wind power is one of the most sustainable ways of generating electricity, as no toxic emissions are produced. This recent energy source does not contribute to global warming and relies on a theoretically infinite source, which is air. In sufficiently windy areas (both onshore and offshore), wind turbines are one of the most economical methods of generating electricity. Consequently, this option appeals to many individuals, governments and organisations. However, one major problem with wind turbines, especially offshore ones, is that you need a larger turbine to produce more energy. Based on this, the upscaling of wind turbines diminishes the number of units per megawatt conveyed, resulting in a less complex infrastructure and cheaper maintenance cost. In addition, multi-rotor frameworks, which are made of multiple rotors working in parallel, may maximise the upscaling advantage in accomplishing more significant unit capacities than is doable or cost-effective with the conventional, 3-blade wind turbine (HAWT). Multi-Rotor frameworks with Vertical axes Wind Turbines (VAWT) permit advanced picks up at turbine and wind cultivate levels, increasing even more the performance. In light of this, this project aims to perform a ten weeks exercise consisting of a conceptual design of a multi-rotor VAWT. The objective is to design a wind turbine that would be more sustainable, cheaper and efficient than any other wind energy alternative. The wind turbine should aid in solving the eminent challenges of moving to a green economy.

This paper's scope is to set up the initial phases of the design process, defining requirements up to the subsystem level and the most feasible design options. As a consequence, the report is structured as follows. The first chapter of the report presents a sustainable development strategy. Being one of the main pivots around which the entire project orbits, the sustainability approach is a crucial element that needs to be adequately explored before proceeding to any phase in the design process. This section considers all the main aspects of it. The next chapter is a market analysis. To design something, it is always necessary to know what are the market needs and what design options already exist to tell if the project will be profitable or not. After that, a technical risk assessment is performed, presenting all possible risks and mitigation. Subsequently, Budget management and Resource allocation are presented. A functional flow diagram and its corresponding breakdown are then displayed. In this section of the paper, all the functions the turbine will need to perform are presented and broken down. This is done to help the formulation of the requirements that are listed in the following chapter.Finally, all the possible design options are also presented through means of a design options tree. This last is done for each subsystem of the final design of the turbine.

2
Sustainability

2.1. Materials and manufacturing

In terms of sustainability, the material selection plays the most important role [1]. Three crucial criteria are usually used for assessing how viable a material is for a specific task. First of all, there is the level of carbon emission emitted when producing a component. Secondly, the environment damage during extraction and mining and needs to be investigated and last but not least, the how much the material can be recycled and then used for either the same or other purpose.

Nowadays, the tendency of recycling materials used for wind turbines manufacturing has become a driving requirement in the design process. Nevertheless, the wind turbines can be on average 85% recyclable according to the Vestas Sustainability Report, the closed-loop recycling after the end-of-life is only able to supply between 3% and 12% of the total material demand of offshore wind energy. Three scenarios are considered for the future where more materials will be recycled. The best case scenario is when all materials from the outflow are 100% recyclable. The second one, which expresses the optimistic EoL rate, suggests that key materials together with rare Earth elements are recycled with high recycling rates. However, the bulk materials, such as the low-alloyed steel, concrete and polymers are assumed not be recycled. A more pessimistic strategy is the conservative EoL, where key materials with low recycling rates are considered recycled. Compared to the optimistic one, this time the rare ones are not assumed to be recyclable [2].

Impact of Material Choice

Typical wind turbines are mainly made of steel for the tower, concrete for the base, and fiber-reinforced composites for the blades [3]. Yang and Chen and Mendecka and Lombardi estimate that the raw materials used are responsible for 50%-70% of the $CO2_{eq}$ emissions of wind turbines [4] and [5]. To measure the sustainability of design options a procedure for calculating the environmental impact has to be established. This simplified method will be divided into two parts, one for foundations and structure and the second for the rotor and drive train. The distinction was made due to differences in the available literature.
For the foundations and the structure, a wide range of information is present, including a number of detailed life cycle analyses. A simplified LCA proposed by Mendecka and Lombardi has been deemed satisfactory for the peruses of the initial design. Despite the simple nature of the approach, the model has shown to be accurate to a reasonable degree so it will suffice for a preliminary design. The authors have calculated the life cycle environmental impact per kilogram of material used, that are prevalent in wind turbines. This included greenhouse gas emissions for global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). The equivalent emission for the use of these materials is shown in Table 2.1, along with the energy required to produce the material (CED). Additionally, the authors provide a method that enables the inclusion of the design wind speed into the calculation. It might not be crucial at the beginning, but the inclusion of that parameter could prove useful in the latter parts of the design. Table 2.1 shows the equivalent emissions associated with the use of three main materials commonly used in the construction of wind turbines.
These emissions can then be used in Equation 2.1 to calculate the environmental impact of a wind turbine. m_i is the mass of material i, and EI_i the environmental impact of that material. m_k is the mass of wasted material k, and EI_k the environmental impact of treatment of that waste material. e_j is the amount of

Table 2.1: *The equivalent emissions from the use of 1 kg of material [5]*

Material (1kg)	CO2eq GWP (kg)	SO2eq AP (kg)	PO4eq EP (kg)	Energy demand CED (MJ)
Chromium steel	0.184-0.196	0.550-0.621	0.191-0.196	1.045-1.226
Aluminium	7.259-9.379	75.990-81.000	11.943–20.888	76.162–81.572
Concrete	4.495–4.790	28.493–29.865	8.359–8.859	44.105–47.451

energy used, and EI_j is the environmental impact of the energy production of the energy carrier. r_{subs} is the mass of the direct emissions, and F_{subs} the environmental categorisation factor of those emissions.

$$EI_{LC} = \sum_i m_i EI_i + \sum_j e_j EI_j + \sum_k m_k EI_k + \sum_{subs} r_{\text{subs}} F_{\text{subs}} \tag{2.1}$$

Wind turbine rotors are typically made of fiber-reinforced composites, mainly glass-fiber reinforced composites [3]. The production of this GFRP has an $CO2_{eq}$ emission of 3.07 kg/kg [3].
The generators in wind turbines use permanent magnets that use rare-earth metals such as Neodymium (Nd), Dysprosium (Dy), Praseodymium (Pr) and Terbium (Tb) [2]. While the amount of material used for a single turbine is not that large, with the exponential increase of wind energy generation, the demand for these rare materials could be between 13-31 times the current demand towards 2040 according to Li et al..

2.2. Installation

The installation of piles and foundation of the wind turbine is another point which needs to be considered in the sustainability strategy. Since the procedures are almost the same and they cannot be changed significantly in terms of the energy consumed, the only aspect which is worth investigating is how these actions affect the environment. One problem that can arise is the noise pollution and how it affects the wildlife.

The noise pollution can be considered a problem especially when the system in installed. The magnitude of the sound produced when operating is not substantial, but it is a crucial problem since it generates a continuous noise. This has native impacts on marine life and birds. In order to decrease the noise generated during installation a few mitigation should be kept in mind. The first one is to select low-noise wind turbine design and noise-reducing foundations. Moreover, using bubble curtains can be a solution since they are mounted around the pile-driving area to reduce underwater noise. The principle on which these devices work is that they release a continuous stream of air bubbles that dampen the sound waves. Another measure would be to implement noise monitoring and management plans. Lastly, the installation of wind turbines should be scheduled during low-noise periods. For instance, the marine life is less active during summer.

Another addressed issue is the noise pollution by operating the wind turbines. Despite the fact that they do not produce as much disturbing sound as the ships or cruises, they do impact the marine life considerably. According to Stöber and Thomsen a 10 MW wind turbines yields a source level of 177 dB which can be considered relatively high. Moreover, especially seals and whales care perceive noise from a distance up to 10 km. There are two types of noises: mechanical noise sources and aerodynamic noise sources. The mechanical ones are produces mostly by the moving parts of the structure, such as gearboxes and generators, while the aerodynamic ones are created by the interaction of the flow with the blades and possibly walls of the structure. There are several techniques to reduce the noise which actively influences the design of the wind turbines. One option is to reduce the inflow turbulence noise by changing the leading edge shape. A few good examples of design are to have sinosoidal leading edge, serrrated airfoils or attaching leading edge slits. For the last two, the noise reduction is about 7 dB and 15 dB, respectively. They can be seen in fig. 2.1.
Another possibility of decreasing the disturbance sound aims to reduce the trailing edge influence. The solution comes by applying serractions or even better, brushes on the trailing edge since they minimise the sudden change in acoustic impedance at edges. The reduction is roughly between 3.2 dB and 5 dB.

Figure 2.1: *Leading edge design options for noise reduction [7]*

They are depicted in fig. 2.3 and fig. 2.2. One more solution for the high noise level is to have winglets, more precisely, shark or reference tips. It was proved that they do diminish the noise by 7%, but with a penalty in power of 3% [7].

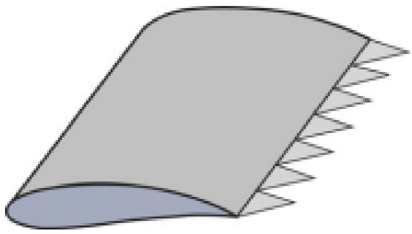


Figure 2.2: *Trailing edge serrations [8]*

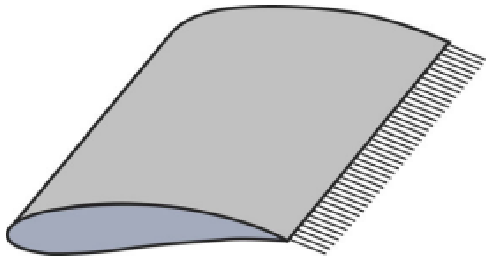


Figure 2.3: *Trailing edge brushes [8]*

2.3. Operations

Emissions

GHG (Green House Gas) emissions are a critical environmental issue. According to Wang and Sun [9], the lifetime emission intensity of current wind farms from design to end-of-life is 5.0/–8.2 g CO2/kWh electricity. Regarding O&M, GHG emissions will result from the diesel burning by the service vessels' engines and the cleaning, repair, and replacement of OWT components. The required materials and equipment are transported from shore to the assembly base and delivered to the wind farm, mainly by barges and tugboats. However, with the rapid expansion of offshore wind farms, attention must be paid to the issue of GHG emissions to maintain sustainable development.

Adopting more efficient maintenance arrangements can reduce GHG emissions produced by grid connection and maintenance activities. A significant reduction in the GHG produced during transport can be achieved using alternative shorter transport routes and utilization of warehouses closer to the farm with the replacement parts. A case study showed that CO2 emissions associated with the transport of OWTs and their components could be reduced by 33% with reasonably shorter transport routes; however, the operation only accounts for a very small portion of the emissions [10].

The use of steel and the replacement of OWTs make up a more significant proportion (3% planned, 47% unplanned) of the GHG emissions during operation compared to vessel transportation [11]. Of this amount, approximately 33% of the GHG emissions result from using specialized vessels to replace large components. At the same time, CTVs and helicopters account for only a minor part. Therefore, from a sustainability perspective, limiting the use of specialized vessels is beneficial.

A large percentage (46%) comes from producing and decommissioning lubricants and spare parts. Because failure rates determine the need for transportation and consequently affect fuel consumption, they are directly related to GHG emissions. Since the rotor and drivetrain rotate and the structures are exposed to corrosive seawater, the failure rates are frequently caused by wear and fatigue during operation. Some failures are considered to happen randomly without explicit trends and predictions. The major failures of these components and possible design requirements for sustainability are listed as follows[12]. By reducing the likelihood of these failures happening, the emissions can be reduced:

- Blade: deterioration, adjustment error, blades corrosion, crack, and severe aeroelastic deflections [[13][14][15]]; Therefore, it is beneficial to have the leading edge of the blade removable, thus reducing the need for complete replacement of the blades and the need for the vessels thereof.
- Shaft: shaft imbalance, shaft misalignment, shaft damage, and broken shaft [[16]]; Mitigations for this failure mode will be described later in the possible maintenance options.
- Gearbox: wearing, fatigue, pitting, gear tooth damage, braking in teeth, the eccentricity of toothed wheels, displacement, oil leakage, insufficient lubrication, high oil temperature, and poor lubrication [17]; Mitigations for this failure mode will be described later in the possible maintenance options.
- Generator: overspeed, overheating, wearing, excessive vibration, rotor asymmetries, bar break, electrical problems, insulation damage, slip rigs, winding damage, and abnormal noises [18]; Use of a central generator instead of smaller local generators for each turbine will make maintenance considerably more manageable.
- Bearings: overheating, spalling, wear, defect of bearing shells, and bearing damage [19]; Mitigations for this failure mode will be described later in the possible maintenance options.

Maintenance Techniques A practical and reliable maintenance strategy must be planned as it is crucial to OWTs' operations. Commonly utilised maintenance techniques are: reactive, preventative, and predictive. Reactive maintenance is carried out after the failure has already happened, is not desired since OWTs have high failure rates with low system reliability. Once a small failure is noticed late, it can evolve into a major failure resulting in unwanted downtime, and a possible need to replace the parts which will affect emissions negatively. Proactive maintenance is where scheduled inspection and replacement is carried out before failure to prevent minor faults from developing into major failure. Major failures (only 25% of all failures) contribute to 95% of downtime[12]. However, because the working environment of OWTs' is very chaotic and destructive, modelling for the decision of the maintenance intervals is not precise. Therefore, the visits need to be more frequent than required; this may generate more emissions than predictive maintenance because of the involvement of large crews and vessels. Predictive maintenance is where loads of data from the different subsystems of the OWT are collected to assess the situation of the structure. With this method, emissions can be pushed to the lowest, requiring maintenance only when indispensable. Therefore parts that are most prone to failure described above need to be equipped with onboard sensors such as ultrasonic, thermal, accelerometer, oil pressure, oil particulate, voltage, and temperature sensors.

Effects on marine wildlife The effects of offshore wind farm operations on marine wildlife (fish, , seabirds, etc.) cannot be neglected. Pile-driving impacts can be sensed by animals from large distances. Noise generated by regular turbine operation can't be heard at water depths below 20m [20]; however, leaked oil and other waste during component replacement operations are harmful to wildlife [21]. The effects on birds resulting from OWT O&M include flight-route changes, physical habitat changes, and collisions with the rotating blades or other superstructures [22]. Furthermore, transportation by boat or helicopter associated with maintenance may displace the activity space of birds.[12] Therefore, more environmentally friendly designs should be investigated, the farm's location should be studied, and the need for maintenance should be minimised.

Space efficiency While the north sea is a large area, there is more activity than there seems to be at first sight, and these operations such as fishing and shipping, along with ecological concerns and the suitability of certain areas for wind farm development do not leave much space for wind turbines. Recently plans to build wind farms at two sites in the north sea previously designated for offshore wind developments, were canceled as investigation showed they were less suitable due to potential effects on the ecosystem, fishing, and shipping [1] To be sustainable, the area efficiency of wind energy generation should be maximized, to minimize the required area for wind power generation.

2.4. End of Life

According to the EPA, the average life span of a conventional HAWT wind turbine accounted for 20 years in 2013 [23], given that the turbine is regularly inspected once every six months. This rather short life span for an electric production system is mostly due to the very high loads experienced during its lifetime. Conventional HAWT can operate in very high winds, up until a cut-out limit where the wind turbine is decelerated and parked to avoid structural failure. Nowadays, Vesta is commercialising their V236 15 MW HAWT, which has a cut-out speed of 31 m/s. Assuming a value of 6.5 for the wind tip speed ratio, common for best performance, this would equate with a tip speed of around 200 m/s. And yet, Vestas is guaranteeing a design lifetime of 25 years [24]. Thus, it is clear that the technological advances and opportunities, such as material advances and better simulation and modeling tools, have enabled the industry to design for longer lifetimes, which benefits both the customer which can receive green electricity for longer, and the wind turbine owner, which receives a longer utilisation phase and thus more revenue.

Over the last decades, the life of the wind turbines has seen further extensions due to better asset management practices and improvements in technology and logistics. Several factors play a role in the decision making process, such as lifetime extension assessments, which investigates the condition of the turbine, the structural stability of the asset, the environmental conditions and the physical state of the equipment. If safety standards are met after an in-depth inspection of the structure, the turbine and all its subsystem, it is possible to repower the asset, usually by replacing the rotor and nacelle with more modern alternatives that can yield more electricity. This strategy is beneficial from both a financial and sustainability point of view, as additional electricity, and consequently additional revenue, can be produced at a limited and substantially lower monetary and material cost. Considering that majority of emissions associated with wind turbines come from the raw materials that go towards it, repowering the asset and prolonging its life for an additional period of 20-25 years would decrease the CO_{2eq} emissions per MW produced and increase the associated Energy Return on Investment (EROI).

Yet, as mentioned before, the repowering of an asset implies the removal of large parts and subsystems, the rotor and nacelle to name a few. Thus, there is a general requirement to use High Lifting Vehicles (HLV), in order to detach and transport these large subsystems, so that they can be dismantled and recycled or reused onshore. Apart from the high costs associated with renting such a vehicle, the emissions and the disturbance to the local marine life that these HLV produce is not negligible. The use of a multi-rotor system may heavily influence these operations, as a modular design with smaller dimensions and lower mass could circumvent the use of HLVs and improve the sustainability of turbine removal.

Once the used wind turbines are removed, they are sent onshore in order to be properly dismantled. Currently, Vestas assures its customers that up to 85% of the mass of their current turbines are recyclable [2]. Yet, the monopile of conventional HAWT, which is made mostly of fully recyclable materials such as steel

[1] URL: https://english.rvo.nl/information/offshore-wind-energy/offshore-wind-energy-plans-2030-2050#.[cited03May2023].

[2] URL: https://www.vestas.com/en/sustainability/environment/zero-waste [cited 02 May 2023]

and cast iron, accounts for most of the turbine's mass. Additionally, the rare-earth metals in the generators should be recycled if they can be extracted.

The main remaining problem is the other 15 % of the turbine mass which is mostly made up of the turbine blades. These are made of GFRP and other fiber-reinforced composites. As there is no large recycling industry for these composites, these are currently either landfilled or incinerated [25]. These materials are hard to recycle, but there are ongoing studies on various methods of recycling FRP turbine blades in the future [25]. By replacing these currently non-recyclable materials with recyclable options, such as steel or aluminum, the EoL recyclability of the system would be able to out-perform conventional HAWT designs. Yet, there is a number of hazardous materials that are currently indispensable, such as oil, lubricants and rubbers, mostly part of the drivetrain. Additional attention to the disposing and recycling of these materials needs to be taken into consideration, so that no sea water contamination occurs during removal of sub-systems.

Another tactic to approach the prolonging of the explotation phase of the project life is through life extension. Although similar to repowering, life extension differs in its degree of replacements and repairs. After the necessary structural, fatigue and environmental studies, decisive action is taken to perform minor to low-cost repairs and replacements so that the lifetime of the asset is prolonged another 5-10 years. This method presents itself as one of the most less emissive lifetime extension options for the asset, from the standpoint of the use of vessels and personnel, as it can be seen by the study performed by Offshore Renewable Energy Catapult, with results as presented in fig. 2.4

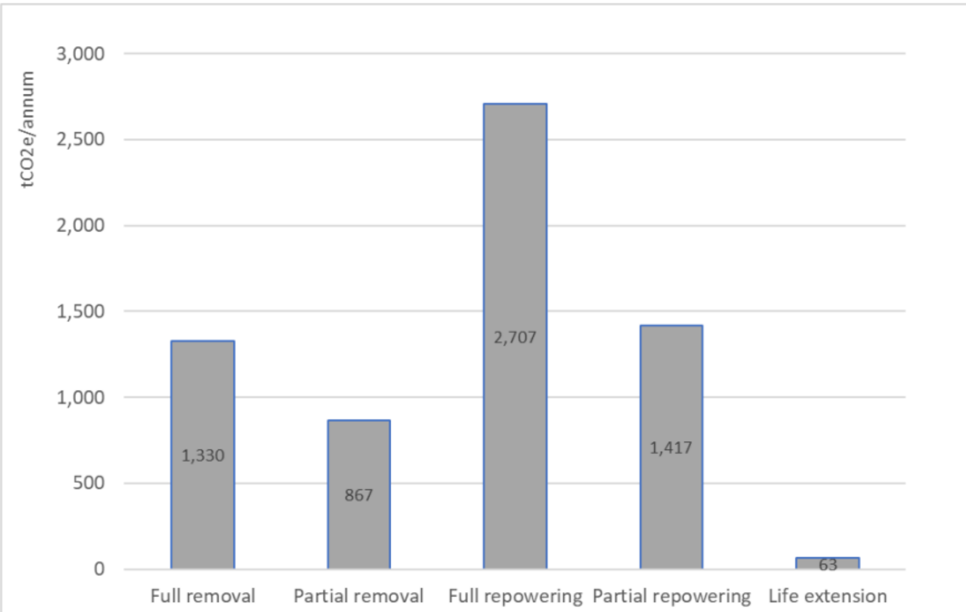


Figure 2.4: *" Comparison of marginal vessel carbon footprints for end-of-life scenarios at 25th year (excluding the first installation)" [26]*

Although life extension is a valuable tool for increasing the EROI of the asset and making the system more sustainable, it is only a prolonging of the inevitable decommissioning. According to decision 98/3 of the OSPAR convention, ratified by all Western European countries, all offshore structures above 4000 t are required to be disassembled by parts once they reach the end of their useful lives [3]. Thus, it is important to prepare for this event from the inception of the project. Otherwise, future generations of engineers will have to deal with the left behind structures and develop their own decommissioning plan, going against

[3]URL: `https://www.ospar.org/news/scm-21` [cited 02 May 2023]

the social sustainability strategy of this initiative. Moreover, planning and designing for the decommissioning phase would make the disposal of the asset go smoother and would mitigate the costs, emissions and impact on the environment.

An interesting removal tactic that has already proved useful in the offshore natural gas and oil extraction industry is piece small decommissioning. This practice revolves around the strategic cutting of the support structure in-situ into small and approachable chunks that can be more easily removed and transported back onshore. This approach is considered beneficial to the proposed system as it can manage the removal of tall structures by first attending to the topside subsystems before dismantling piece by piece the support structure. Moreover, by optimising the substructure removal plan from the design phase, it is possible to decrease the waiting times of the vessels, and thus the use of the highly polluting specialised vessels, during the most time consuming phase of decommissioning, the cutting. The overall plan of piece small decommissioning is presented in fig. 2.5

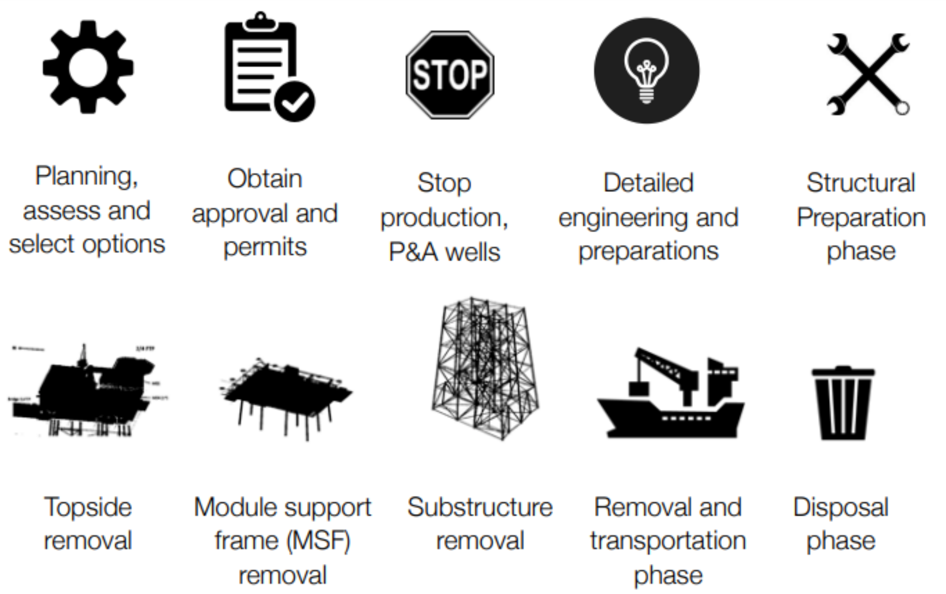


Figure 2.5: *Piece small removal plan [27]*

3 Market Analysis

The market analysis deals with the financial need of the product. If no one is willing to pay for it, it will not receive funding for development and production. It is important for the wind turbine system to be cost competitive and occupy a unique space of the market to justify funding it, but also to satisfy user requirement **US.REQ.03** The system shall have a 45 % lower levelized cost of energy than traditional horizontal axis offshore wind turbines.

3.1. Levelized cost of energy

The Levelized Cost of Energy (LCoE) is a metric to compare the costs of energy projects between each other. According to a study done by TNO [28] it is calculated as follows:

$$LCoE = \frac{\frac{CapEx}{a} + OpEx}{AEP} \tag{3.1}$$

Where CapEx is the capital expenditure, a is the annuity which divides the expenditure into yearly costs; OpEx is the yearly operational expenditure and the Annual Energy expenditure. Deciding a baseline for the LCoE is a crucial part of locating the niche that our product can inhabit and the beginning of detailing a budget for its cost as well.

According to Figure 3.1 [28], LCoEs of the range from 37 to 39 €/MWh are expected to be found with technological advancements in 2030., while LCoE-R - a metric that takes into account spatial planning risks in addition to other costs - is slightly higher and ranges from 38 to 40 €/MWh.

Table S2 Key features of the baseline and the three set with possible new locations

Set with possible new locations	Number of OWF	Surface (km$^{2)}$	Capacity (3.6 MW/km^2) (GW)	LCoE (€/MWh)	LCoE-R (€/MWh)
Baseline up to 2030	99	13,000	55*	-	-
Baseline planned after 2030	24	5,000	20**	39	40
LCOE-R based set	113	31,000	110	37	38
Visibility based set	130	34,000	120	37	38
Nature based set	87	21,000	77	38	38
OWF roll-out list after 2030 = Baseline planned after 2030 + LCOE-R based set	**137**	**36,000**	**130**	**37**	**38**

* The power density of these OWFs deviates from the power density of the reference farm which is 3.6 MW/km^2.

** This capacity is recalculated for a power density of 3.6 MW/km^2; see appendix I, table I.1.

Figure 3.1: *Key features of the baseline and the three set with possible new locations.[28]*

However, this is not the current competition but the extrapolation of current trends. National Renewable Energy Laboratory give a more recent estimate for the costs of energy for floating and standing wind turbines

National Renewable Energy Laboratory's lower estimate of LCoEs matches Catapult's and thus will be used in order to size the cost of the design. From now we will consider 50 €/MWh and 133 €/MWh to be a competitive price for sea bed fixed and floating platform wind turbines, respectively.

3.2. Market opportunity

The Dutch Government wants to produce 50 GW of offshore wind in 2040 and approximately 70 GW in 2050, providing ample need for more cost-effective wind energy solutions. [1] If this project were to be developed, there would be the need for at least 700 systems from the Dutch government alone. The global offshore energy production is projected to grow to 844 GW, providing an even bigger need for more efficient wind energy.[2]

In addition to this, the current trends in horizontal wind turbine design are trending towards larger and larger rotor areas, which lead to larger energy input per wind turbine e.g. General Electric's Haliade-X14 MW turbine with its 220m rotor size[3] and Vestas' V236-15.0 MW with 115.5 m blades[4]. However, this has various drawbacks: firstly, the larger size of the rotor and blades lead to much larger nacelles and structural elements being required due to a combination of the weight of the turbine as well as the torque and moments experienced by the entire structure. Secondly, the increase in the size of the rotors means that the distance between multiple wind turbines in a farm must increase, as the optimal distance between them is linked to the size of the rotors[29]. By developing alternate concepts to larger horizontal wind turbines, we have a niche in developing more energy dense and more robust designs, which in turn should snowball to better designs.

3.3. Costs

To determine what is a competitive cost for a turbine, the levelized cost of energy is multiplied by the amount of energy produced in the lifetime of the turbine. To determine a competitive price, the assumption of the lifetime of a wind turbine of 20 years is made [23]. A capacity factor of 60% [5] is also assumed. The capacity factor is the relation between the power the turbine produces on average and what it would have produced at maximum power. Table 3.1 describes a competitive cost of a wind turbine rated for various MW amounts. Depending on the achieved desired cost reduction, the lifetime cost of the turbine can be seen. The initial aim of the design is a Fixed platform 60MW wind turbine with a -45% cost reduction compared to other options. That would indicate the cost of the design should be less than 174 million euros. Although the design option for a floating wind turbine is still a possibility, the environment where it will most probably be deployed, i.e. the north sea currently houses both floating and Stationary wind turbines, so the cost must be competitive with the lower of the two.

[1] URL: https://english.rvo.nl/information/offshore-wind-energy/offshore-wind-energy-plans-2030-2050# [cited 01 May 2023]

[2] URL: https://www.dnv.com/research/download/oceans-future-thank-you.html [cited 01 May 2023]

[3] URL: https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine [cited 02 May 2023]

[4] URL: https://www.vestas.com/en/products/offshore/V236-15MW [cited 02 May 2023]

[5] URL: https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine [cited 01 March 2023]

Table 3.1: *Lifetime cost of the system in millions of euro, Fix:fixed base, Flo: floating base*

	Fixed45MW	Fix60MW	Fix100MW	Fix150MW	Flo45MW	Flo60MW	Flo100MW	Flo150MW
	10^6 EUR	10^6 EUR	10^6 EUR	10^6 EUR	10^6 EUR	10^6 EUR	10^6 EUR	10^6 EUR
-0%	237	316	526	789	630	839	1399	2099
-20%	189	252	421	631	504	672	1119	1679
-45%	130	**174**	289	434	346	462	769	1154
-60%	95	126	210	316	252	336	560	839

The cost breakdown will then be further investigated for 174 million wind turbine system. A percentage breakdown is taken from The Catapult Network[6] seen in Table 3.2. Aiming to reduce the lifetime cost by -45% is ambitious, but the main focus of the project is on the structure, turbine, and maintenance costs. Thus 3 options are presented for the 174 million turbines Table 3.2. The first two options are how the costs divide based on historical data for 174 million and for 316 million, which is what is expected of current competitors. The third option investigates how the costs should divide if cost reductions are only achieved in the focus categories of this project. In reality, the truth is somewhere in between.

Table 3.2: *Cost breakdown in millions of euro*

		$174 \cdot 10^6$ EURO	$316 \cdot 10^6$ EURO	$174/316 \cdot 10^6$ EURO
Development and project managment	3.5%	6.1	11.1	11.1
Nacelle	11.7%	20.4	37.0	8.2
Rotor	5.6%	9.7	17.7	4.0
Tower	1.9%	3.3	6.0	1.3
Other turbine	10.3%	17.9	32.5	7.3
Total	29.5%	51.3	93.2	20.8
turbine foundation	8.2%	14.3	25.9	25.9
Cables	5.0%	8.7	15.8	15.8
Offshore substation	3.5%	6.1	11.1	11.1
other balance of plant	1.0%	1.7	3.2	3.2
Total	18.0%	30.8	55.9	55.9
Offshore cable installation	6.4%	11.1	20.2	20.2
Foundation installation	3.2%	5.6	10.1	10.1
Turbine installation	1.4%	2.4	4.4	4.4
Other installation	8.2%	14.3	25.9	25.9
Total	19.2%	33.4	60.7	60.7
Maintenance and service	18.9%	32.9	59.7	13.3
Operations	9.3%	16.2	29.4	6.6
total	28.2%	49.1	89.1	19.9
Decommissioning	1.8%	3.1	5.7	5.7
Total	99.9%	173.8	315.7	174.0

3.4. Beneficial features and possible niches

Various possible features were identified as niches that can be specialized into. These will be made part of the design tree to test for their feasibility as well as their equivalent requirements

Firstly, on site, production of energy-intensive products such as hydrogen and helium may be a method

[6]URL: https://guidetoanoffshorewindfarm.com/wind-farm-costs [cited 01 May 2023]

of immediately utilizing part of the energy gathered. By increasing the size of the platform at the base of the turbine, a production site can be envisioned. As described by a report by TNO[28], This could be an advantageous way to immediately use the energy without requiring any major changes to the electrical grid to which the wind farms are connected to.

In addition to this, as shown by the Table 3.2, maintenance is a major part of the costs of a wind turbine, and by minimizing the need for this and/or increasing the ease of maintenance, lower costs and more favourable design can be achieved. Options for this are varied but may include: an On-site maintenance robot/crane to minimize the amount of human maintenance needed, or an on-site way of assembling the structure and replacing parts can be added, eliminating the need for large specialized ships.

Another possible niche to research is the re-purposing of decommissioned oil platforms. Given that the platforms already have a foundation built, this could be a way of decreasing the installation costs by reinforcing existing foundations instead of building entirely new ones, however, the reliability of the constructions would need to be confirmed on a case-by-case basis if the structure is strong enough to withstand the wind loads to begin with.

Additionally, as mentioned in Section 3.2, the increase in power density has various benefits that can be used to corner the market. The increase in power density allows for wind farms to be more compact, thus leading to more sustainable and environmentally friendly farms. This also potentially decreases price estimates if having fewer turbines (and fewer foundations to build) with larger structures leads to lower overall costs for energy requirements despite their individual higher costs.
[30]

4

Technical risk assessment

In this chapter the technical risk assessment of the project mission is performed. This consists of identifying the technical risks that affect the success of the project mission. The risks are quantified according to their perceived probability of occurrence and seriousness of impact. Next, a mitigation plan is devised for the risks that pose the highest impact on the project mission to bring them down to an acceptable level.

4.1. Risk identification

Risk categorisation

To identify the technical risks affecting the designed system, risk categories were first identified in order to break down the aspects of the project where risks might arise. This is broken down into:

Technical performance risks These are risks that affect the system during operation causing it to perform to a level lower than required. This can result from not accounting for certain criteria in the design of the system.

Cost risks These are risks which can increase the costs of the project beyond the allocated budget.

Scheduling risks These are risks which can cause a delay in the scheduling of the project mission. This includes the design, production, transportation, operation and decommissioning of the system.

Sustainability risks Since sustainability is a driving factor in the design of this mission, risks related to not meeting the sustainability goals of the system or inadvertently becoming unsustainable are included in this category

Programmatic risks These are risks which result from events out of control of the project management. This can include events that arise due to higher management or international or national directives. This can also include natural disasters and other events which pose a risk on the success of the mission.

Next, the risks in each category are identified and quantified based on their probability of occurrence and consequence on the success of the mission. In order to have a less subjective categorisation of likelihood and consequence. They are categorised according to the tables below. The consequences are categorised according to the INCOSE definitions [1] :

[1]URL: https://brightspace.tudelft.nl/d2l/le/content/498709/viewContent/2937470/View [cited 04 May 2023]

Likelihood categories:	Likelihood of occurrence
Very unlikely	<5%
unlikely	<25%
plausible	<50%
likely	<95%
very likely	>95%

(a) *Likelihood categories*

CATEGORY	PERFORMANCE CONSEQUENCES	RATING
CATASTROPHIC	Failure to meet the requirement would result in mission failure. Significant degradation/non-achievement of technical performance.	0.9
CRITICAL	Failure to meet the requirement would degrade system performance to a point where mission success is questionable. Some reduction in technical performance.	0.7
MARGINAL	Failure to meet the requirement would result in degradation of the secondary mission. Minimal to small reduction in technical performance.	0.5
NEGLIGIBLE	Failure to meet the requirement would create inconvenience or non-operational impact. No reduction in technical performance.	0.1

(b) *Consequence categories [INCOSE]*

Figure 4.1: *Categorisation of likelihood and consequence of risks*

4.1.1. Identified risks

The identified risks in each category are laid out below:

Technical Performance Risks

TP.01 System is unable to meet power requirement
TP.02 An element of the structure fails due to operational loads
TP.03 The whole structure fails due to operational loads
TP.04 An individual subsystem fails
TP.05 System fails to stay above water
TP.06 Losing communication with control station
TP.07 Logistics of accessing wind farm are too difficult
TP.08 Problems connecting to grid
TP.09 Too much standby time
TP.10 Implementing an undetected error in design
TP.11 Errors in manufacturing lead to additional loads
TP.12 Control system receives incorrect parameters

Cost Risks

CO.01 Maintenance costs are too high
CO.02 Operational costs are too high
CO.03 Critical component is too expensive
CO.04 Material cost is too high
CO.05 Production process is too expensive
CO.06 Delayed break-even time
CO.07 EOL disposal cost is too high

Scheduling Risks

SC.01 Delays in construction
SC.02 Delays in design process
SC.03 Delays in transportation
SC.04 Low availability of required material
SC.05 Certification delays

SC.06 Operator training
SC.07 Testing shows limitations that lead to design delays

Sustainability Risks

SU.01 Unexpected harm to surrounding ecosystems
SU.02 EOL procedure becomes unsustainable
SU.03 Material used turns out to be dangerous for environment or operators
SU.04 Too high transportation emissions
SU.05 Production methods are unsustainable

Programmatic Risks

PR.01 Collisions with ships
PR.02 Natural disasters
PR.03 Unexpected weather forecast
PR.04 Killer new regulations after design stage
PR.05 Climate change during life
PR.06 Military intervention in windfarm site
PR.07 Unsafe maintenance conditions
PR.08 Reduced funding for the project
PR.09 Failure to certify system

For each of these risks the likelihood and consequence are predicted and added to Figure 4.2. It is important to note that as the project progresses the perceived likelihood and consequence of the risks can change. This is therefore a preliminary assessment of risk that is subject to change as further analysis is performed and further levels of design detail are reached.

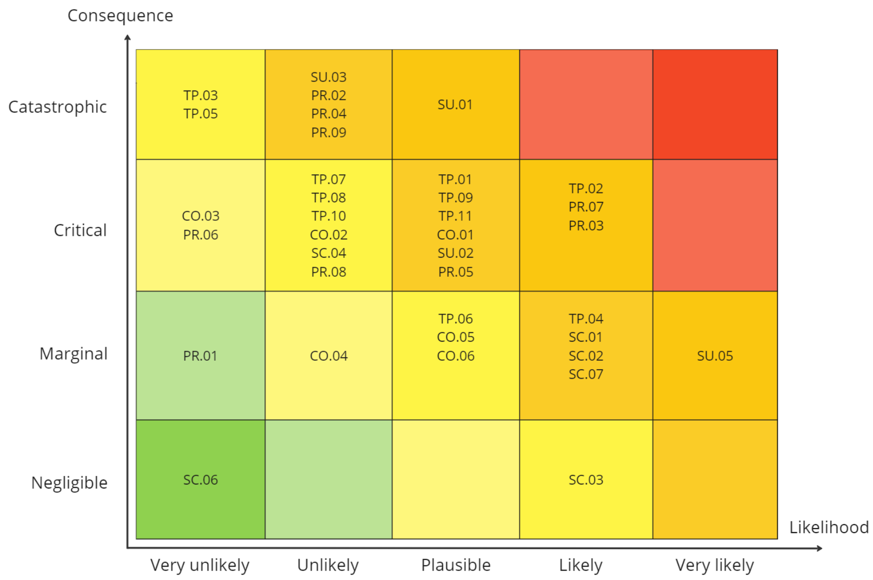


Figure 4.2: *Pre-mitigation risk matrix*

4.2. Risk mitigation

Next, risk mitigation measures are determined for the risks with the highest combination of likelihood and consequence (risks coloured orange in Figure 4.2). The reasoning for assessing this risk as a high risk is also given in Figure 4.3.

Risk	Reason for risk	Risk Mitigation	New position
TP.01 - Unable to meet power requirement	If the system is unable to meet the power requirement, this is critical as it reduces technical performance significantly. This is plausible as rated power output is limited by many factors such as optimal wind speed and structural integrity of rotors.	1. Perform predictive maintenance 2. Perform feasibility analysis when designing 3. Perform a power budget 4. Increase efficiency of wind turbine 5. Improve design	Unlikely, critical
TP.02 - An element of structure fails due to operational loads	This is a critical risk as the failure of a structural element could induce additional loads on other parts of the structure and damage it. This is also likely to happen in the lifetime of the system due to fatigue, corrosion, etc.	1. Adding a safety margin to allow for additional loads 2. Add redundancy in structural members 3. Avoid interconnection between systems (if one element fails it will not affect other components) 4. Add reinforcing elements (stringers) 5. Perform preventive maintenance	unlikely, marginal
TP.04 - Individual subsystem fails	It is likely that an individual subsystem will fail during the lifetime of the system. This can be due to multiple factors depending on the subsystem. This is marginal as it leads to the failure of a single subsystem only, not affecting the entire architecture. This however depends on the failed element.	1. Add redundancy 2. Perform predictive maintenance 3. Implement a monitoring program for each subsystem	plausible, marginal
TP.09 - Too much standby time	This is a critical risk as it directly lowers the power output and efficiency of the farm. Too much standby time could also lead to issues such as rust. It is a plausible risk as it could be caused by high complexity or fragility leading to frequent maintenance stops, or due to a small operational wind speed margin.	1. Reduce complexity of system 2. Add safety margins to reduce maintenance frequency 3. Maximise wind speed margins of the turbine to increase operation time	unlikely, critical
TP.11 - Errors in manufacturing lead to additional loads	This is a critical risk that can cause a component or element to be loaded unfavourably. There is a plausible chance that this happens especially if there is a high component count.	1. Reduce manufacturing tolerances	unlikely, marginal
CO.01 - Maintenance costs are too high	This is a plausible risk arising from failure of subsystems and components. It could be that accessing the wind farm could be costly, but also the maintenance could require specialised equipment or personnel, which would increase cost. This is critical to the success of the system as maintenance is an ongoing task and therefore reduces the profit from the system significantly.	1. Optimize maintenance schedule 2. Perform maintenance only when it is really needed 3. Automate maintenance 4. Implement predictive maintenance 5. Use more reliable components	unlikely, marginal
SC.01 - Delays in construction	Delays in construction are likely to occur due to poor planning, limited resources, etc. This can affect the success of the project if delays are large, however they are less relevant once operation begins.	1. Increase workforce 2. Invest in high quality equipment	plausible, marginal
SC.02 - Delays in design process	Delays in design process are likely due to limited resources, errors in design and insufficient time planning. This can delay the operation phase but does not constitute a critical risk to the success of the project unless the delays are large.	1. Make sure to follow the schedule 2. Work the necessary amount of hours every day (8h) 3. Be present during sessions 4. Do not waste time	unlikely, marginal

SC.07 - Testing shows limitations that lead to design delays	The testing phase oftentimes leads to the discovery of problems with the design that need to be fixed. This can cause a delay, however this is a normal part of design and should not lead to significant risks to the success of the project.	1. Perform only necessary tests 2. Rely more on use of numerical models	Plausible, marginal
SU.01 - Unexpected harm to surrounding ecosystems	The wind farm will be built in an offshore area that may be populated by other living organisms. Therefore, the wind farm may have a serious impact on the surrounding ecosystems. This would have catastrophic consequences leading to mission failure since institutions will never allow the building of the farm.	1. Study site ecology 2. Avoid fragile areas 3. Minimise system size 4. Minimise noise emissions	critical, unlikely
SU.02 - EOL procedure becomes unsustainable	This risk is related to the fact that the end of life procedure of the turbines may result being unsustainable. This is a pretty critical risk since one of the main objective of the project is to have sustainable operations and end of life.	1. Maximise material reusability and/or recyclability 2. Compose detailed EOL procedure plan	unlikely, marginal
SU.03 - Material used turns out to be dangerous for environment or operators	It is not possible at all to use construction materials that are dangerous for people health. This would result in legal problems and in a catastrophic failure of the project. Therefore needs to be absolutely avoided.	1. Use materials that have been tested to be safe 2. Perform weathering/submersion tests on component materials 3. Apply a strict safety procedure for operators 4. Provide high quality safety equipment 5. Implement precoutionary safety procedure for environment	very unlikely, critical
SU.05 - Production methods are unsustainable	Production methods will always have at least a small amount of emissions produced. Therefore production methods will never be 100% green. As a consequence this it is very likely to be present but at the same time marginal.	1. Optimise logistics 2. Use manufacturing methods that minimise waste 3. Employ lean production 4. Recycle waste	likely, marginal
PR.02 - Natural disasters	With natural disasters it is meant all the natural phenomena that the farm may be subjected to during its lifetime. This includes storms, earthquakes, tsunamis ... These are events that may represent a risk for the farm and would result in catastrophic failures, although theyare pretty unlikely.	1. Implement predicting models 2. Design against most likely natural events	very unlikely, critical
PR.03 - Unexpected weather forecast	Sometimes it may happen that the weather conditions predicted by the control station in order to operate the turbines are not fully correct. This may result in some turbines not operating at the maximum efficiency. This can be considered as a marginal consequence.	1. Implement emergency procedures to prevent damage 2. Design for unexpected weather conditions	likely, marginal
PR.04 - Killer new regulations after design stage	Once the design is completed, it will not be possible to change or readapt it to external factors anymore. This includes the eventuality of new regulations being published at later stages.	1. Strictly follow and keep track of all the regulations until the wind farm is built	very unlikely, catastrophic
PR.05 - Climate change during life	Climate change is an important issue that in the following years will increasingly be more relevant. It is possible that climate change will affect the operation and efficiency of the wind farm, therefore it is a potential risk. It is not possible however to know what will be its effects in the future.	1. Design for worse climate conditions	plausible, marginal
PR.07 - Unsafe maintenance conditions	Maintenance is a crucial element of a wind turbine design. It is a critical risk therefore to not have safe maintenance procedures.	1. Apply a strict safety procedure for operators 2. Design for facilitated maintenance 3. Automate maintenance as much as possible 4. Minimise maintenance	plausible, marginal
PR.09 - Failure to certify system	It may happen that some aspects of the wind farm need to be certified by the government or institutions. This means that a legal procedure needs to be followed and approved in order to proceed in the project. The fact that this procedure does not end well can be seen as a risk and its consequence may be catastrophic as well as causing delays in the schedule.	1. Add certification killer requirements 2. Design to comply with certifications	Very unlikely, catastrophic

Figure 4.3: *Risk mitigation actions for highest risks*

This leads to the updated post-mitigation matrix as seen in Figure 4.4:

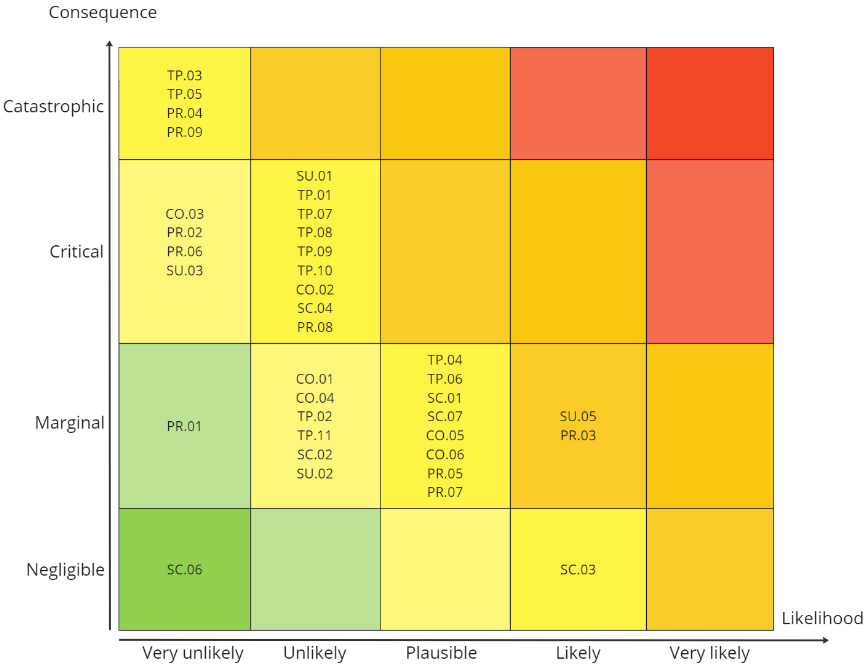


Figure 4.4: *Post-mitigation risk matrix*

Although **SU.05** and **PR.03** still appear in the orange part of the post-mitigation risk matrix, some risks have to be accepted due to limited ability to mitigate them. For **SU.05**, reduction methods are oftentimes by nature unsustainable due to their energy requirements and emissions and so it is difficult to mitigate this to a point where it becomes negligible. **PR.03** relates to unexpected weather conditions that can damage the systems. It is impossible to reduce the likelihood of this as weather conditions are out of control, but the consequences of this depend on the magnitude of the event. An event with a larger magnitude than has historically occured can still cause damage despite designing against it. Therefore the risk cannot be considered negligible even after mitigation. Therefore those two risks must be accepted post-mitigation.

5 Budget management and Resource allocation

5.1. Monetary budget

The current monetary budget can be extrapolated from the cost breakdown created from the market analysis in Chapter 3. Given that this is an initial budget based on a HAWT instead of a VAWT this is only accurate up to a point, especially given the potential differences in structural design as will be discussed in the design option tree. Thus the main take away from the cost analysis is the upper limit for the cost. In this case given that the cost is calculated assuming multiple smaller HAWT as opposed to a larger VAWT an increase in cost from the decided 174 million euro will be applied. This is due to the non linear nature of increasing structural needs due to increases of size (given that the loading of forces and moments that determine the structural characteristics do not increase linearly with size, and cause a larger increase in price than shown). Thus by increasing the total structural costs to those without the % decrease a more reasonable budget is achieved. Thus the initial budget is set at 93.2 + 55.9+ 33.4+ 49.1 = 231.6 million Euro. This is only a preliminary budget and its % will vary largely depending on the exact design option chosen, especially between floating and standing configurations which each have separate foundation costs. This in combination with the cost risks detailed in Chapter 4 lead to a very high initial contingency being optimal. Thus the contingency for the budget is set at 25%. It is important to note that if there are any changes in the requirements of the project, these will have a change in the proposed budget as well, especially energy requirements.

5.2. Mass budget

The mass budget is one of the most important aspect for this project. Together with the monetary one, they are considered to run such a complex project. Since this is only the preliminary phase, it was required to only find the a few initial estimations in terms of the weight of the wind turbines. Since the design has not been established, it is difficult to estimate the mass of the entire body. However, a few useful algorithms have been found that offered a guideline for the initial calculations. They seems to be reasonably reliable and thus, some of them will be used in the late stage of the mass calculations. The total mass of the wind turbine is dependent on the existing elements and hence, the following components have been identified: rotors, nacelles, foundation, vertical structure, computer system, control surfaces, drivetrains, high lift devices, sensors and cabling.

The total mass of the assembly was estimated to be around 4366.8 t. The tower weights 1192.7 t, the turbine weights 1380 t, while the coating applied for the outer surface weights 800 t and the inner-array cable weights 14.5 t. The kg/m was assumed to be 0.6612 kg/m [1]. The weight-to-length ratios for different components were found in literature [31].
[2]

5.3. Human resources allocation

Human resource allocation is one more aspect that needs to be taken in to account when developing the project of an offshore wind turbine. The following sections include a brief description of the life stages of

[1] URL: https://www.fms.pt/en/copper/cables/copper_cable.html [cited 04 May 2023]
[2] URL: https://www.fms.pt/en/copper/cables/copper_cable.html [cited 04 May 2023]

the wind turbine, starting with the manufacturing of it and finishing with the end of life procedures, along with the concerns for efficient and effective allocation of human resources.

5.3.1. Manufacturing

The impact of different materials and manufacturing methods on the human resources required for them depend greatly on the exact techniques used during the manufacturing processes, as well as the transportation taken for getting raw materials to manufacturing sites. Information on the exact manpower can be generally gleaned, but as the manufacturers and suppliers are separate entities to the wind turbine designers, operators and maintainers, the ability to influence this value lies only in the choice of manufacturing method, quantity and urgency of the part necessity.

What is possible to affect, is the choice of manufacturers. There are a a variety of drivers for different manufacturer choice; including sustainability concerns, where the manufacturers with minimal negative environmental effects should be chosen (be that due to minimal transport or more sustainable building practices); cost of parts, where the cheapest possible option is the preferred; quality of items where the best quality is preferred.

In this respect care must be taken from a human resources perspective to align the goals of the project with the characteristics of the manufacturers in order to maintain an economically and socially sustainable practice as well as an environmentally sustainable one. As a baseline only companies certified with the relevant ISO standards, mainly of the 9000, 14000, 45000, and 29400[3] series.

5.3.2. Transport and Installation

Transport and installation have been grouped together as they influence each other heavily, since for any on site installation, only the tools brought during transport are available. Transport is divided in two main sectors: on land and by sea. Although smaller components may be transported by air instead of by land, the major components of the wind turbines are transported by land to docks where they are then placed on specialized ships that act both as a transportation methods and as installation platforms.

For the portion on land, the transport is usually done either by trucks or by trains. Due to the size of the components this is a lengthy and costly process that may cost upwards of 100,000 euro[4] and involve multiple parties including and not limited to the transport companies, traffic officials and route engineers to ensure the transport can be done effectively.

Once the transportation reaches the allotted docks, the components are moved onto ships to transport them to the installation locations. At that point Jack-up ships, floating vessels and various cranes are used in order to place arrange and place the components in the correct locations[32]. Jack-up ships are equipped with legs that can be deployed to raise the ship above the waterline, in order to provide a more stable base to operate from. Where the water is too deep for the leg length, floating vessels are instead used in conjunction with floating cranes. The only alternative exists for floating wind turbines where it is possible to assemble them near shore before towing it out to its preferred location. This is also the method by which floating wind turbines are relocated to different projects.Finally the cabling and undersea connections are installed with the use of specialized cabling ships.

All of this work is done by specialized contractors, and are chosen by location and availability of ships in addition to the sustainability, efficiency and cost metrics. The Netherlands has multiple companies that specialize in the various steps of transportation and installation, as outlined by the Dutch offshore Wind manual [32] including Biglift, Boskalis and Jack-up barge to name a few.

As described in a project sheet from Boskalis for a project in Wikinger [33] involving the installation of 70 wind turbines foundations, each wind turbine installation takes little under a week to install onsite thus

[3] URL: `https://www.iso.org/news/ref2527.html` [cited 04 May 2023]
[4] URL: `https://www.veritread.com/how-to-transport-a-wind-turbine/` [cited 04 May 2023]

leading to the length of the operation being largely dependent on the amount of wind turbines in the wind farm to install as well as the travel times to reach the installation location.

In this portion of the life cycle the main allocation of human resources from perspective of the designer lies with supervision of the installation, inspection of the site and assembly as well as initial testing before regular operation commences. Apart from this, interfacing with the relevant electrical grid connection officials and overseeing the relevant connection is required.

5.3.3. Operation

The operation stage of the wind turbine deals with the properly functioning of the system. Depending on weather conditions, wind speed or the required power to be produced, it is assumed that the wind turbine will not work all the time. However, when operating, it will be self-operating and it will be turned on/off by different control surfaces. These actuators will be administrated by the personnel from an onshore station. The estimated number of people needed for such tasks is about three people since someone should be present at the location all the time. The reason behind this amount of people comes form the fact the they will work in 8-hour shifts.

5.3.4. Maintenance

The maintenance is more complex life stage of the a wind turbine. According to Wozniakowski-Zehenter, a wind farm of common size might have a maintenance staff of about 50 to 100 people. [5] This is due to the fact of needing specialised and trained people, such as engineering, technicians, support staff or even safety officers, managers when this is the case. Nevertheless the size of the design wind turbine is not comparable with the one of a wind farm, a large group of people might be required because of the complexity of the developed system. Moreover, the management of logistics will need to be considered since usually the maintenance work demands tooling, spare parts, ships, vessels and so on. There are several maintenance strategies that can be be adopted. They will be presented in the following breakdown figure:

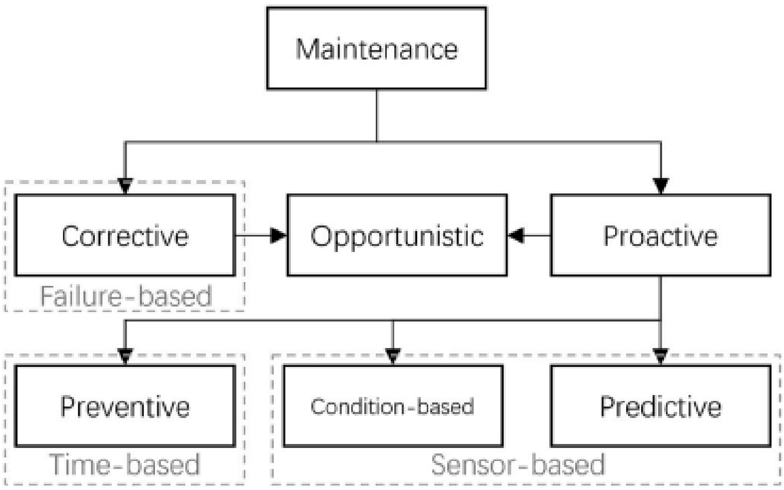


Figure 5.1: *Classification of maintenance strategies [34].*

As depicted in fig. 5.1, the first maintenance strategy is the corrective one. In this case, the maintenance is done after the failure already occurred and it can be very complicated. Considering that if any issue appears and compromises the entire operation of the system, it means that the mitigation is crucial and

[5] URL: https://www.identecsolutions.com/news/hse-offshore-wind-communication [cited 04 May 2023]

should be done in the lowest time possible. Such mission could take multiple days depending on the severity of the issues and availability of the piece that needs to be replaced. A problem that jeopardises the entire turbine should require many people because of the effectiveness desired. For this reason, it is estimated that between five to ten people will be needed.
The second strategy is the preventive one which refers to the scheduled maintenance based on the predefined period or given level of power generation. They are routine checks that will not require a great amount of staff. It is estimated that around three people will be enough for this task.

The third maintenance strategy is condition based maintenance (CBM), which requires various sensors in order to signal the need of inspection/maintenance when a certain threshold for these sensor's output is reached. Additionally, using the great number of data from sensors, it is possible to create models so that maintenance action can be planned in advance. This activity generally requires more time as a result of its complexity. It is not urgent, but the measure which needs to be taken could be extensive. Consequently, a group of three to seven employees will be needed. The approximation of people is dependent of the seriousness of the issue. Multiple sensors will be placed in order to identify the problem before it becomes more serious [34].

A comparison among the presented maintenance strategies will be displayed in the next table:

	Corrective maintenance	**Preventive maintenance**	**CBM**
Trigger	Failure	Planned date	Real-time
Initial cost	Low	Medium	High
Operating cost	High	Medium	Medium
Number of failures	High	Low	Medium
Unnecessary visits	High	Medium	Low
Unplanned maintenance	Low	Low	High
Maintenance regarding failures	After	Before or after	Shortly after
Downtime	High	Medium	Medium
Level of automation	Low	Low to medium	Medium to high

Table 5.1: *Comparison among different maintenance strategies [34].*

5.3.5. End of life

The end of life processes of a wind turbine are mainly divided in 3 territories: removal of the wind turbine as a whole; recycling and reuse of components; and the re-powering of the turbine. Given that, as mentioned in Section 2.4 eventually all wind turbines must be decommissioned and disassembled, part of the work that goes into recycling plans must be continuously updated and refined throughout the years, as it is probable that over the course of the lifespan of the wind turbine new methods of recycle the materials are made possible. In addition to this, the re-powering of a wind turbine is another task that must be analyzed before placed into effect in order to ensure that turbine system does not have more wear or suffer higher fatigued than planned. Finally the actual decommissioning event and processes will once more require the usage of specialized firms, similar or same as for installation to take down and correctly transport the various components to their final destination.

5.4. Sustainable budgets

As many of our requirements involve sustainability, it is useful to begin thinking about the budgets for various, less sustainable decisions. Mainly in the usage of rare earth metals and non-recyclable composites.

5.4.1. Rare earth metals

The usage of rare earth metals in wind turbines is mostly found in the generators in the form of permanent magnets [35]. This has recently become more prominent as a result of the trend of increasing the size of

HAWT's and with that their increase high torques from the loads of their rotors thus requiring higher spec generators. However none of the requirements for this project explicitly require the usage of such high end generators. The choice of using VAWT's leads to many possibilities including the usage of multiple low end generators to equate the power of a larger generator. Thus no specification can be made at this moment. Only during the trade off will this become more apparent.

5.4.2. Non-recyclable composites

The current technology uses a lot non-recyclable composite materials. They are highly preferred over conventional raw ones due to their superior mechanical properties. They are mostly used for essential parts of the wind turbines, such as blades or nacelles. However, a large amount of energy is required to produce them which is further reflected in a high level of emissions. Nowadays, there is a tendency of using more recyclable composites as a result of a better resource management and increased sustainability awareness. Two solutions can be identified regarding the CO_2 emissions and footprint: to try to reduce the use of such energy consuming materials or even better, replace them by alternative fibres.

The industry of offshore wind energy uses composites that have almost 80% of their matrix made of thermoset, which cannot be recycled. The material is called glass fiber and it is one of the best available products on the market. An option to reduce the usage of glass fiber is to opt for fhybrid composites, such as S-Glass (i.e. magnesium alumina-silicate glass) or R-Glass (i.e. calcium alumina silicate glass) [36]. Other alternative is to use carbon fibers that display an excellent toughness and a lower density which results in thinner, tougher and lighter rotor blades. Moreover, an impressive alternative for the current trend is the aramid and basalt fibers since they show a proper mechanical strength [37].

Lastly, a promising choice for using renewable resources are the natural fibres like flax, coir and bamboo. Apart from having manufacturing processes that are not extremely energy consuming, the costs are also fairly low. Two more advantages of natural fibres over the synthetic ones is that they have a low density and are biodegradable. At their end of life, they can be grinded and then reused. In contrast, they have a variable quality, poor mechanical properties or water absorption tendency and a limited thermal stability. What was concluded after multiple research stages is that a few natural materials can satisfy the 20 year design life criteria. In addition, they are not affected by fungi or microbial agents which is encouraging for the offshore wind energy industry [38].

6

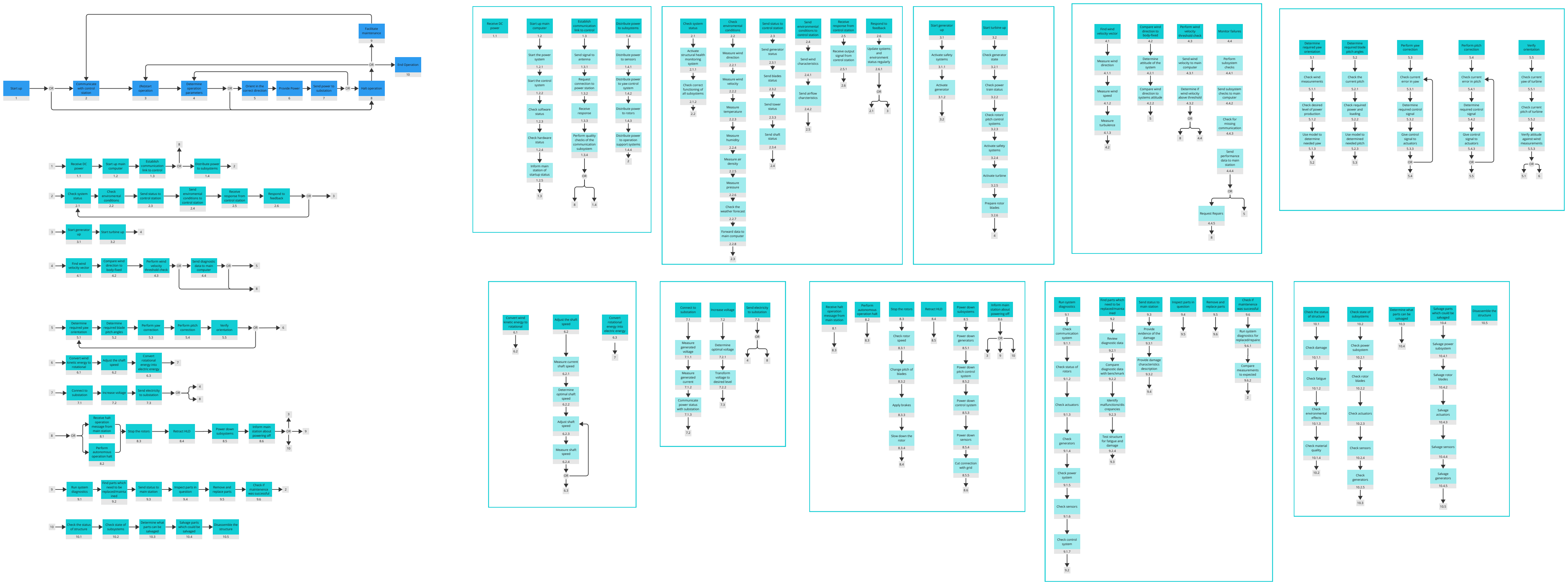
Functional flow diagram and functional breakdown diagram

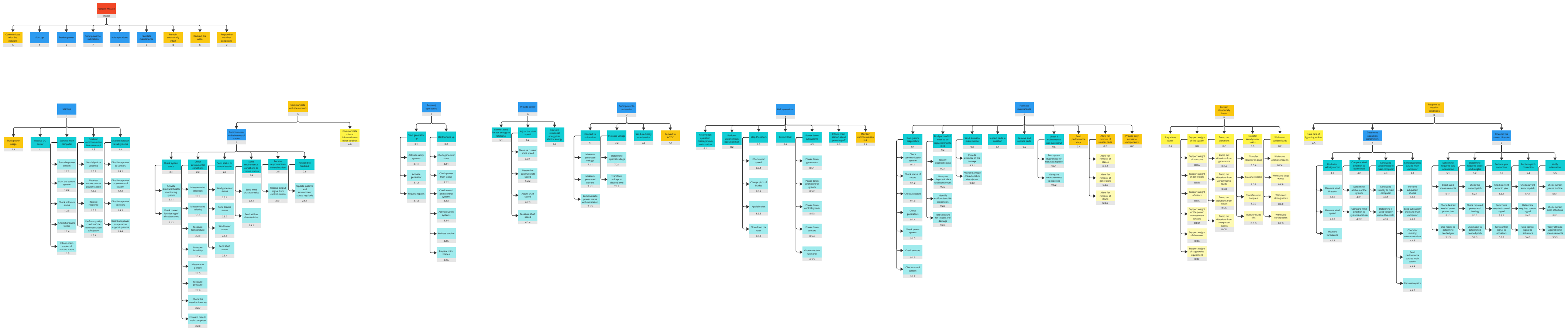
To identify functions that are required to be performed by the system in a systematic way, functional flow, and breakdown were made. For the functional flow diagram, the functions that the system has to perform were laid out in the order in which they have to be performed. The high-level tasks were broken down into lower levels, twice in a row. This gave several low level functions, which the system has to perform.

The functional flow breakdown included the functions that were added in the functional flow diagram in addition to some functions which need to be performed by the system in perpetuity (not chronological). This includes supporting functions which are needed to support the functions in the functional flow diagram. The blue color used for the functions in the functional flow was kept in the functional breakdown and the added functions are displayed in yellow.

The functions from the functional breakdown diagram were later used in Chapter 8. The functions were used to determine the functional requirements of the system, not yet present due to user, mission, or standard requirements. Some of these were applicable to the whole system, while others were subsystem specific.

Functional Flow Block Diagram





Perform Mission
Master
Communicate with the network
A
Start up
1
Provide power
6
Send power to substation
7
Halt operations
8
Facilitate maintanance
9
Remain structurally intact
B
Redirect the wake
C
Respond to weather conditions
D

7 Design options

The goal of a design options tree is to present an exhaustive list of every feasible and infeasible option. Then to discard infeasible and otherwise discountable options and to arrive at truly feasible options. Initially all possible options are generated in a team brainstorming session and subsequently formalized. All the options are then put on the design tree and can be seen below. The obviously infeasible and trivially discountable are eliminated. The reason for their dismissal is noted down next to them. After the initial elimination a new tree of "maybes" is made summarizing the designs left.
From the decision tree of "maybes" design concepts are made to illustrate the main design branches and options available. The design options are presented below the two design trees.
Some of the design trees are linked to other more than others Figure 7.1 allowing for elimination of some of the combinations.

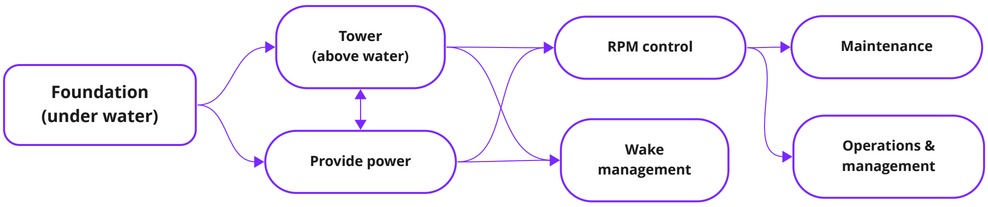


Figure 7.1: *Design option dependence*

Looking at the design options HAWT and VAWT, with a generator for each rotor, the number of generations required is higher than for the the combined VAWT design. To investigate, an example is set up. A truss structure of size AxA needs to be covered with generators. It is assumed we have a given mass budget for the generators M. The calculation uses the following nomenclature. Mass of one generator: M_g, total power: P_{tot}, free stream velocity: V_{inf}, ratio between tip speed and free stream velocity: λ, diameter: d, and the number of generators in a row: n.
The number generator rows for VHWT grouped generators is 1 and for the other two options it is n

$$M_g \propto T[39] \tag{7.1}$$

$$P \propto d^2 \tag{7.2}$$

$$P = T/\omega \tag{7.3}$$

For VHWT grouped rotors

$$M = nM_g \propto nT = n * d * a/\omega = n * d * a/(2v_{inf}\lambda/d) = n * d^2 * a/2v_{inf}/\lambda \propto 1/n \tag{7.4}$$

For other options

$$M = n * n * M_g \propto n * n * T = n * nd * d/\omega = n^2 * d^2 * a/(2v_{inf}\lambda/d) = n^2 * d^3 * a/2v_{inf}/\lambda \propto 1/n \tag{7.5}$$

This means that for the VH grouped rotors design, the number of generators in a row is the same for all options, while the number of generators in a column is 1. For the other options, the number of generators in a column is n. VAWT with grouped rotors will have N generators in total, while non-grouped VAWT and HAWT will have N^2 generators. This means that the VAWT grouped rotors design will require the least maintenance. We can take another conclusion from this derivation. If all design options are to have the same amount of generators, the VAWT grouped rotors design will have the lowest cost.
The two main decisions still to be made are, what foundation type is appropriate, is the use of additional flowers advantageous, and what is the structure of the tower. In the next week, simple models will be developed and based on them the trade-off for the structure and foundations type will be chosen.

7.1. Subsystem definition

Based on functions and geometry, the system was divided into subsystems. These have a more clear set of responsibilities and requirements, which allows them to be designed in a smaller design space. To a large degree, these align with the design options tree. The list and the brief summary of the requirements are:

Foundation (FND): Part of the turbine which attaches it to the sea floor. It fixes the turbine in place, and for some designs, it may transfer loads from the rest of the structure to the ocean floor.

Tower (TWR): The part of the structure which is above the water surface and is responsible for the transfer of loads between all other subsystems.

Yaw Control (YCS): Responsible for changing the yaw angle of the system as instructed by the control inputs provided by OCT.

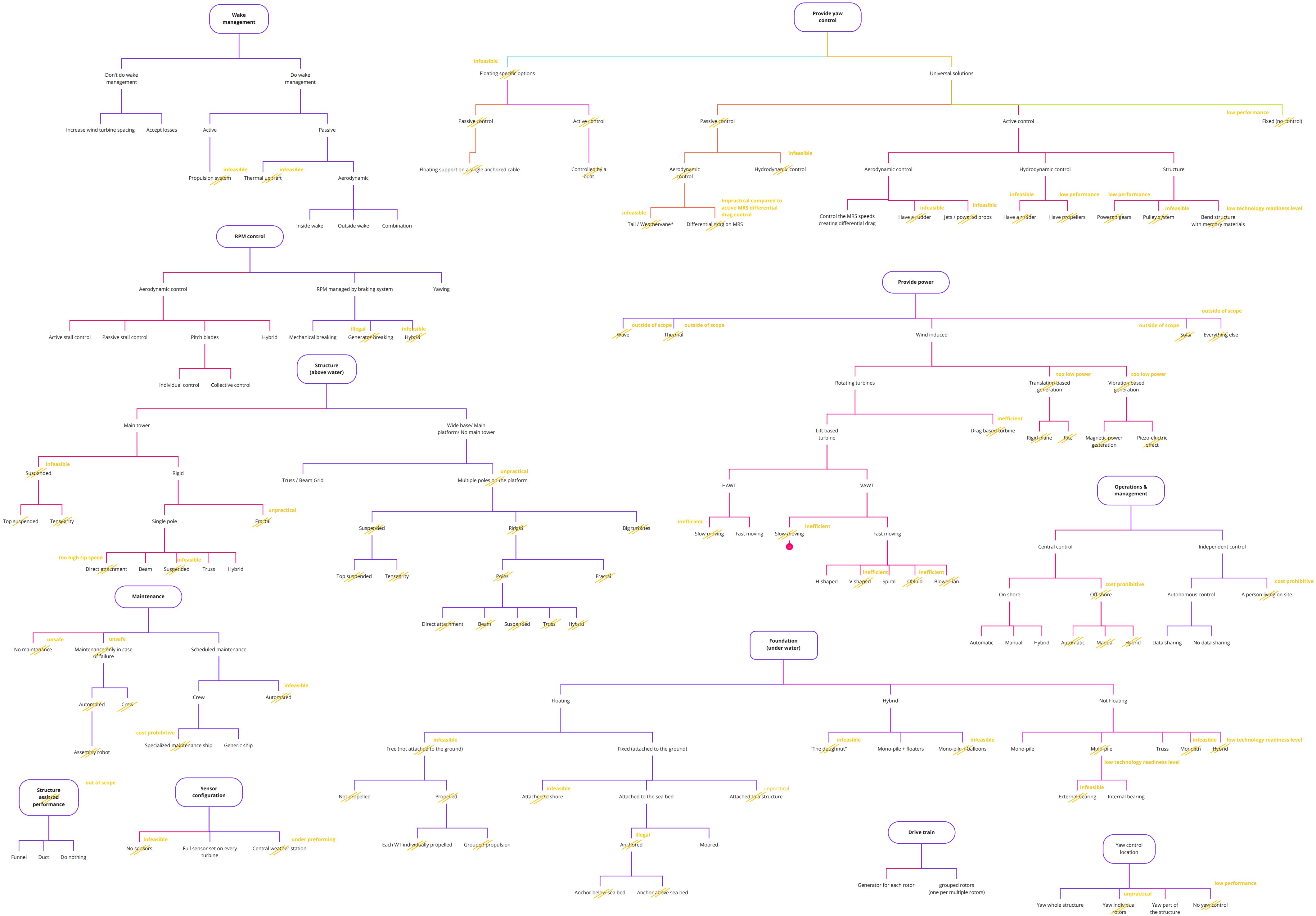
Power Control (PCT): Responsible for the control of power production by managing the rotation of the rotor.

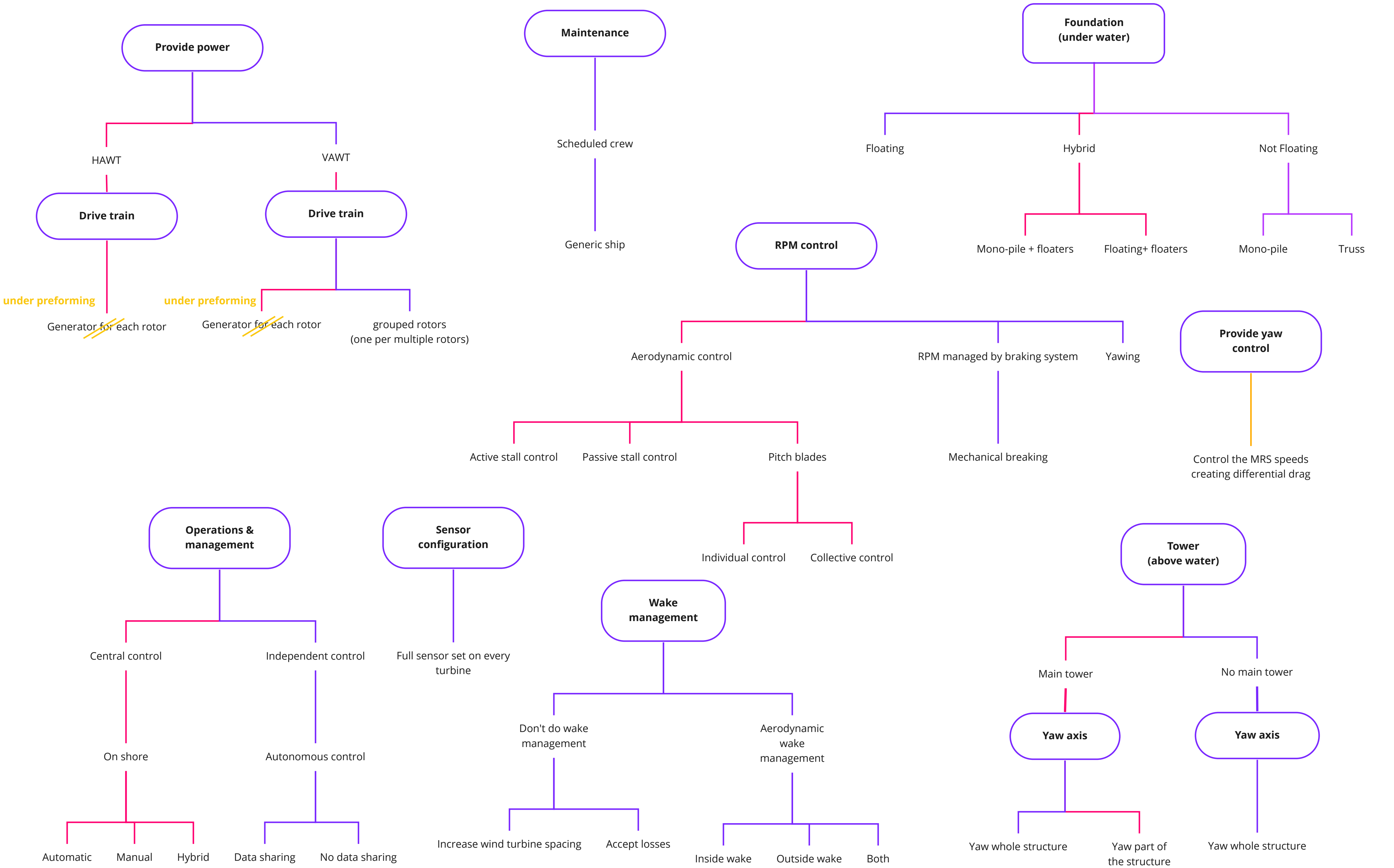
Wake Control (WCT): The purpose of WCT is to control the wake behind the turbine in order to increase the performance of the system.

Drive Train (DRT): Contains the equipment responsible for the production of electrical power frthe om rotational energy of the RTR.

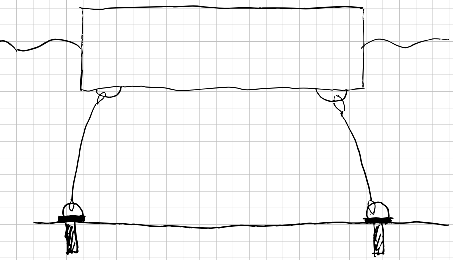
Rotor (RTR): Rotor includes the turbine blades and the hubs that connect the blade to the drive train, and its function is to transfer the wind energy into rotational energy.

Operation Control (OCT): This includes the electronic, sensors, and other equipment which support the nominal operations of the turbine and maintenance.

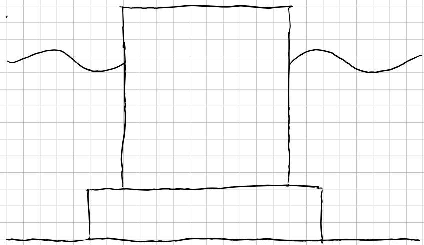

Wake management
Don't do wake management
Increase wind turbine spacing
Accept losses
Do wake management
Active
Propulsion system
infeasible
Passive
Thermal updraft
infeasible
Aerodynamic
Inside wake
Outside wake
Combination
RPM control
Aerodynamic control
Active stall control
Passive stall control
Pitch blades
Individual control
Collective control
Hybrid
RPM managed by braking system
Mechanical breaking
Generator breaking
illegal
Hybrid
infeasible
Yawing
Provide yaw control
Floating specific options
infeasible
Passive control
Floating support on a single anchored cable
Active control
Controlled by a boat
Universal solutions
Passive control
Aerodynamic control
Tail / Weathervane*
infeasible
Differential drag on MRS
Impractical compared to active MRS differential drag control
Hydrodynamic control
infeasible
Active control
Aerodynamic control
Control the MRS speeds creating differential drag
Have a rudder
infeasible
Jets / powered props
infeasible
Hydrodynamic control
Have a rudder
infeasible
Have propellers
low pefromance
Structure
Powered gears
low perfomance
Pulley system
infeasible
Bend structure with memory materials
low technology readiness level
Fixed (no control)
low performance
Provide power
Wave
outside of scope
Thermal
outside of scope
Wind induced
Rotating turbines
Lift based turbine
HAWT
Slow moving
inefficient
Fast moving
VAWT
Slow moving
inefficient
Fast moving
H-shaped
V-shaped
inefficient
Spiral
Obloid
inefficient
Blower fan
Drag based turbine
inefficient
Translation based generation
too low power
Rigid plane
Kite
Vibration based generation
too low power
Magnetic power generation
Piezo-electric effect
Solar
outside of scope
Everything else
outside of scope
Structure (above water)
Main tower
Suspended
infeasible
Top suspended
Tensegrity
Rigid
Single pole
Direct attachment
too high tip speed
Beam
Suspended
infeasible
Truss
Hybrid
Fractal
unpractical
Wide base/ Main platform/ No main tower
Truss / Beam Grid
Multiple poles on the platform
unpractical
Suspended
Top suspended
Tensegrity
Rigid
Poles
Direct attachment
Beam
Suspended
Truss
Hybrid
Fractal
Big turbines
Operations & management
Central control
On shore
Automatic
Manual
Hybrid
Off shore
cost prohibitive
Automatic
Manual
Hybrid
Independent control
Autonomous control
Data sharing
No data sharing
A person living on site
cost prohibitive
Maintenance
No maintenance
unsafe
Maintenance only in case of failure
unsafe
Automated
Assembly robot
Crew
Scheduled maintenance
Crew
Specialized maintenance ship
cost prohibitive
Generic ship
Automated
infeasible
Foundation (under water)
Floating
Free (not attached to the ground)
infeasible
Not propelled
Propelled
Each WT individually propelled
Grouped propulsion
Fixed (attached to the ground)
Attached to shore
infeasible
Attached to the sea bed
Anchored
illegal
Anchor below sea bed
Anchor above sea bed
Moored
Attached to a structure
unpractical
Hybrid
"The doughnut"
infeasible
Mono-pile + floaters
Mono-pile + balloons
infeasible
Not Floating
Mono-pile
Multi-pile
low technology readiness level
External bearing
infeasible
Internal bearing
Truss
Monolith
infeasible
Hybrid
low technology readiness level
Structure assisted performance
out of scope
Funnel
Duct
Do nothing
Sensor configuration
No sensors
infeasible
Full sensor set on every turbine
Central weather station
under preforming
Drive train
Generator for each rotor
grouped rotors (one per multiple rotors)
Yaw control location
Yaw whole structure
Yaw individual rotors
unpractical
Yaw part of the structure
No yaw control
low performance


Provide power
HAWT
VAWT
Drive train
Drive train
under preforming
under preforming
Generator for each rotor
Generator for each rotor
grouped rotors
(one per multiple rotors)
Maintenance
Scheduled crew
Generic ship
Foundation
(under water)
Floating
Hybrid
Not Floating
Mono-pile + floaters
Floating+ floaters
Mono-pile
Truss
RPM control
Aerodynamic control
RPM managed by braking system
Yawing
Active stall control
Passive stall control
Pitch blades
Mechanical breaking
Individual control
Collective control
Provide yaw
control
Control the MRS speeds
creating differential drag
Operations &
management
Central control
Independent control
On shore
Autonomous control
Automatic
Manual
Hybrid
Data sharing
No data sharing
Sensor
configuration
Full sensor set on every
turbine
Wake
management
Don't do wake
management
Aerodynamic
wake
management
Increase wind turbine spacing
Accept losses
Inside wake
Outside wake
Both
Tower
(above water)
Main tower
No main tower
Yaw axis
Yaw axis
Yaw whole structure
Yaw part of
the structure
Yaw whole structure

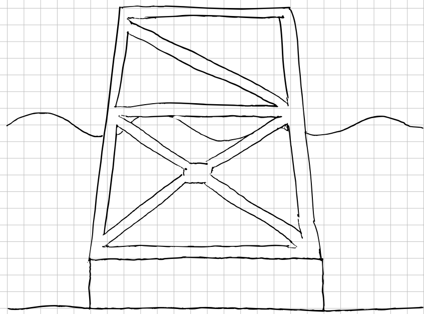
Floating Foundation



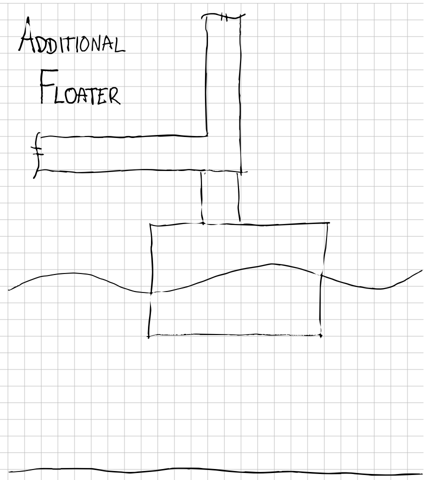
Mono-pile Foundation



Truss Foundation

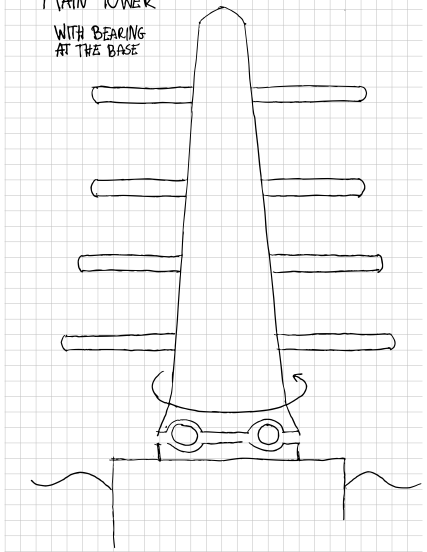


Additional Floater



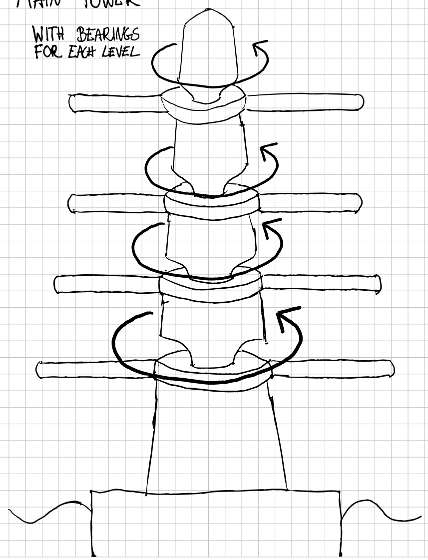
Main Tower

With bearing at the base



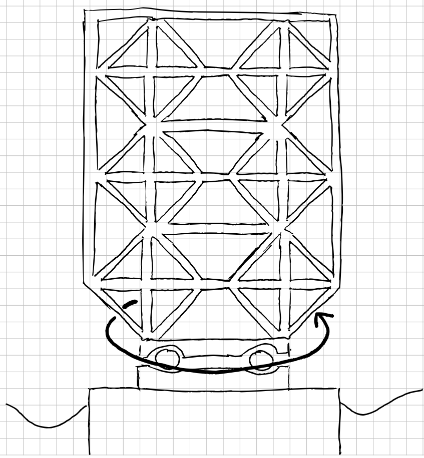
Main Tower

With bearings for each level



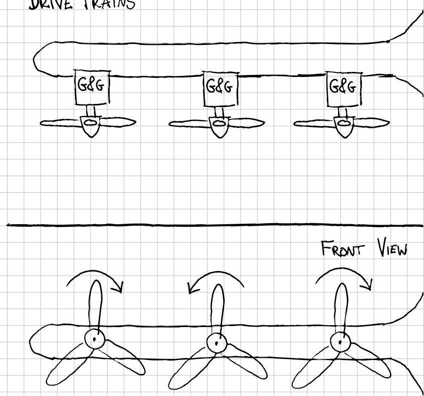
No Main Tower

With bearing at the base



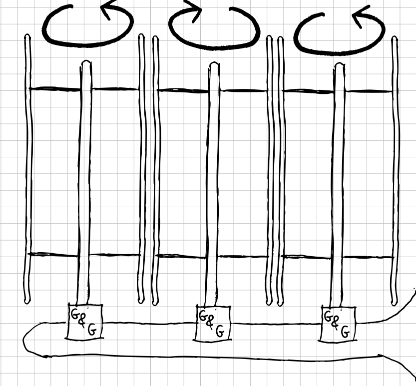
HAWT

With individual drive trains



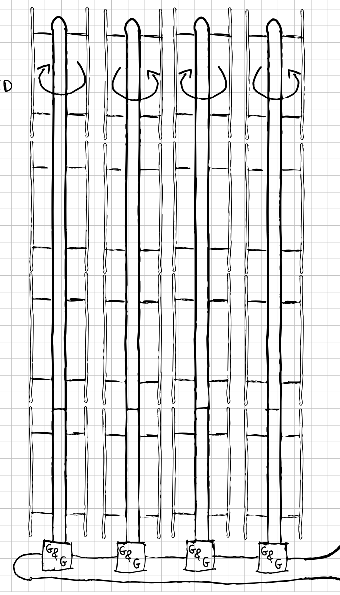
VAWT

With individual drive trains



VAWT

With grouped drive trains



8 Requirements

In order to create a suitable design, a necessary number of requirements must be formulated. This help limit the design space so that only feasible designs are considered. They also ensure that the final product performs the specified function in an appropriate way. Since changes in requirements cause greater and greater costs further down in the design process, it is important to define them in a clear and effective way. They should be Specific, Measurable, Attainable, Realistic, and Testable (or Traceable).

To determine top-level requirements, three different tasks were performed: requirement discovery tree with regard to electricity production (the main task of the system), applicable regulation standard, and the previously mentioned function flow diagram Chapter 6.

Each of these produced a set of requirements, which were broken down whenever possible to formulate three sets of requirements. There was some overlap between the different requirements. The three main sets of requirements are thus grouped into four categories: technical user requirements (marked as UR-X), mission requirements (marked as MR-X), standard compliance requirements (marked as SR-X), and lastly, functional requirements (marked as FR-X).

The mission requirements are presented below. The overview of where they originate in the mission requirement discovery tree can be seen below.

From these top-level requirements, subsystem requirements for every subsystem listed and code convention 'MR-XX-STR-XX' is used The considered subsystems are the foundation (FND), the tower (TWR), the yaw control subsystem (YCT), the power control subsystem (PCT), the drive train (DRT), the rotor (RTR), and the operations control subsystem (OCT). These subsystem requirements can be seen below in Section 8.5.

8.1. User requirements

UR-01: The system shall deliver at least 60 MW of power

UR-02: The system shall have an energy density of at least 16 $\mathrm{MW\,km^{-2}}$

UR-03: The system shall have a 45 % lower levelized cost of energy compared to traditional horizontal axis offshore wind turbines

UR-04: The system shall have multiple rotors

UR-05: The system shall have lower lifetime emissions than traditional horizontal axis offshore wind turbines

UR-06: The system shall have increased material recyclability than traditional horizontal axis wind turbines

UR-07: The system shall have decreased rare metal use compared to traditional horizontal axis wind turbine

UR-08: The system shall have a wake re-energizing management system

UR-09: The system shall be installable offshore

UR-10: The system shall have less impact on marine life than traditional horizontal axis offshore wind farms

8.2. Mission requirements

MR-01: The system shall be able to be produced by small Original Equipment Manufacturer(s)

MR-02: The metal components of the system shall be produced from common, easily sourced metals, limited to **<TBD>**

MR-03: The system shall have lifetime of at least **<TBD>** years.

MR-04: The system shall have RoF (Rate of Failure) lower than **<TBD>**

MR-05: The system shall be maintainable by replacement of critical components

MR-06: Average time to repair shall be lower than **<TBD>**

MR-07: The system shall allow predictive (condition-based) maintenance

MR-08: The system shall be maintained without total operation halt

MR-09: The system shall be accessible by service barges

MR-10: The system shall have a power rating of 60 MW

MR-11: The system shall have an Annual Energy Production of **<TBD>**

MR-12: The system shall have an energy export limit of **<TBD>**

MR-13: The system shall have an energy density of at least 16 $\mathrm{MW\,km^{-2}}$

MR-14: The system shall have a ramp up limit of **<TBD>**

MR-15: The system shall have a ramp down limit of **<TBD>**

MR-16: The system shall produce electricity at a cost of no more than **<TBD>** € $\mathrm{kWh}^{-}1$

MR-17: The emissions produced by the system to produce 1 kWh shall be less than **<TBD>** of CO2

MR-18 The system shall produce electrical current with frequency of **<TBD>** Hz

MR-19: The system shall have a total production cost of less than **<TBD>** €

MR-20: The system shall have a cost of transport of less than **<TBD>** €

MR-21: The average annual costs for maintenance shall be less than **<TBD>** € over its lifetime

MR-22: The costs of decommissioning of the system shall not exceed **<TBD>** €

MR-23: The technologies used by the system shall be at least lab tested to be considered technologically mature enough

MR-24: The system shall be ready for deployment by **<TBD>**

MR-25: The system shall be able to be dismantled by **<TBD>**

MR-26: The system shall comply with the Offshore Wind Energy Act

MR-27: The system shall comply with the Flora and Fauna Act

MR-28: The system shall not exceed the height of 310 m

MR-29: The system shall be profitable without the intervention of governmental subsidies

MR-30: The system shall use less than **<TBD>** % of total mass as composites

MR-31: The composites used for the system shall be **<TBD>** % percentage of its mass recycleable by the end of life

MR-32: The system shall use at least **<TBD>** % of recyclable metals

MR-33: The system shall operate with mean wind speed of **<TBD>** $\mathrm{m\,s^{-1}}$

MR-34: The system shall operate with maximum wind speed of at least **<TBD>** $\mathrm{m\,s^{-1}}$

MR-35: The system shall have a cut-out speed of at least **<TBD>** $\mathrm{m\,s^{-1}}$

MR-36: The system shall be able to allign to the wind

MR-37: The system shall be able to allign to a specified direction

MR-38: The system shall incorporate a wake energizing subsystem

8.3. Functional requirements

FR-01 System shall track the power it uses for operation.

FR-02 System shall check the status of its software on startup.

FR-03 System shall check the status of its hardware on startup.

FR-04 System shall be able to communicate to the main control station

FR-05 The system shall be capable of distributing power to its subsystems

FR-06 System shall be able to check status and functioning of its subsystems.
FR-07 The system shall be able to check environmental conditions.
FR-08 The system shall be able to have access to the weather forecast
FR-09 The system shall be able to adjust the speed of the rotor
FR-10 The system shall be able to adjust the amount of power it produces
FR-11 The system shall be connected to the power substation
FR-12 The system shall be able to measure the voltage it generates within <TBD> margins
FR-13 The system shall be able to convert AC current into DC current
FR-14 The system shall be capable of informing the main station about powering off
FR-15 The system shall be able to maintain its communication link while its operation is halted
FR-16 The system shall be able to detect failures
FR-17 The system shall be able to locate failures
FR-18 The system shall be able to alert the maintenance department if failure occurs
FR-20 The system shall remain structurally functional for its entire time of operation
FR-21 The system shall stay above water
FR-22 The system shall support its own weight of <TBD>
FR-23 The system shall damp out any vibrations experienced during normal and extreme conditions
FR-24 The system shall withstand impacts up to <TBD> levels
FR-25 The system shall be able to determine its attitude
FR-26 The system shall be able to gather data needed to verify its communications are working
FR-27 The system shall be able to change the pitch of the turbine blades.
FR-28 The system shall be able to yaw

8.4. Standard requirements

SR-01: The system shall withstand the normal wind conditions for its installation location
SR-02: The system shall withstand the extreme wind conditions, occurring every 50 years for its installation location
SR-03: The system shall withstand the extreme wind conditions, occurring every year for its installation location
SR-04: The system shall withstand the normal marine conditions for its installation location
SR-05: The system shall withstand the extreme marine conditions, occurring every 50 years for its installation location
SR-06: The system shall withstand the extreme marine conditions, occurring every year for its installation location
SR-07: The system shall withstand fatigue due to normal marine and wind conditions at its location
SR-08: The system shall withstand the ultimate load case: extreme sea state in combination with extreme wind conditions
SR-09: The system operator shall not be hindered by the effects of sea currents at the installation location
SR-10: The system shall be able to operate between extreme air temperatures of -20°C to 50°C
SR-11: The system shall be able to operate between extreme water temperatures of 0°C to 35°C.
SR-12: The system shall incorporate provisions for safe access for inspection and maintenance
SR-13: The normal operation of the system shall be possible at the platform level
SR-14: The system shall have safeguards to prevent personnel from falling
SR-15: The system shall have safeguards to protect personnel from moving components in a way that may cause harm
SR-16: The personnel platform shall be placed outside of the splash zone
SR-17: The system shall have a safety margin between rotors and any access platform
SR-18: The system shall protect all mechanical systems against the marine environment
SR-19: The system shall allow for parking of the wind turbine

SR-20: The system shall comply with ISO-61400-3 (2009)

8.5. Subsystem requirements

8.5.1. Foundation (FDN)

Mission requirements

MR-02-FND-01: The tower shall be produced from common, easily sourced metals, limited to **<TBD>**
MR-03-FND-01: The foundation subsystem shall have a lifetime of at least
MR-07-FND-01: The foundation shall be maintained by [**<TBD>** METHOD]
MR-08-FND-01: The foundation shall be maintainable without halting operations.
MR-09-FND-01: The foundation shall not interfere with service barge access
MR-20-FND-01: The foundation shall be transportable to the installation location at a cost of less than €**<TBD>**
MR-21-FND-01: The average annual cost of maintenance for the foundation shall not exceed **<TBD>** over its lifetime
MR-22-FND-01: The cost of decommissioning the foundation shall not exceed €**<TBD>**
MR-23-FND-01: The foundation technology used shall be lab tested
MR-24-FND-01: The foundation shall be ready for deployment by **<TBD>**
MR-25-FND-01: The foundation shall be able to be dismantled by **<TBD>** in accordance with REF-LAW
MR-26-FND-01: The foundation design shall comply with the Offshore Wind Energy Act
MR-27-FND-01: The foundation design shall comply with the Flora and Fauna Act

Functional requirements

FR-21-FND-01: The foundation shall keep all other subsystems above water
FR-22-FND-01: The foundation shall support a weight of **<TBD>**

Standard requirements

SR-02-FND-01: The foundation shall withstand the maximum bending load of **<TBD>** caused by extreme wind conditions
SR-05-FND-01: The foundation shall withstand the maximum bending load of **<TBD>** caused by extreme marine conditions
SR-06-FND-01: The foundation shall withstand the fatigue load of **<TBD>** under normal wind conditions for at least **<TBD>** years
SR-06-FND-02: The foundation shall withstand the current induced fatigue load of **<TBD>** under normal marine conditions for at least **<TBD>** years
SR-07-FND-01: The foundation shall withstand the ultimate bending load of **<TBD>** caused by a combination of extreme wind and marine conditions
SR-20-FND-01: The foundation shall withstand the additional loads of **<TBD>** during piledriving
SR-20-FND-02: The foundation shall be protected against corrosion

8.5.2. Tower (TWR)

Mission requirements

MR-01-TWR-01: The tower shall be able to be produced by samll Original Equipment Manufacturer(s)
MR-02-TWR-01: The tower shall be produced from common, easily sourced metals, limited to **<TBD>**
MR-03-TWR-01: The tower shall have a lifetime of at least **<TBD>** years
MR-04-TWR-01: The tower shall have a RoF lower than **<TBD>**
MR-05-TWR-01: The tower shall be maintainable by replacement of its components
MR-06-TWR-01: The tower's meantime to repair of **<TBD>**
MR-07-TWR-01: The tower shall allow for inspection of structurally critical segments
MR-07-TWR-02: The tower shall facilitate inspection of parts with non-destructive testing methods

MR-07-TWR-03: The tower shall allow for operation with **<TBD>** damage for the duration of time between two repair intervals
MR-07-TWR-04: The tower shall report data about strain of parts central to structural integrity
MR-09-TWR-01: The tower shall be accessible by service barges
MR-09-TWR-02: The tower shall be accessible for maintenance without external mobility equipment
MR-19-TWR-01: The tower shall have a total production cost of less than **<TBD>** €
MR-19-TWR-02: The tower shall have an assembly cost less than **<TBD>** €
MR-20-TWR-01: The tower shall have a total transport cost of less than **<TBD>** €
MR-21-TWR-01: The tower shall have an average annual maintenance cost of less than **<TBD>** € over the its lifetime
MR-22-TWR-01: The cost of tower decommissioning shall be lower than **<TBD>** €
MR-23-TWR-01: The technologies used for the construction of the tower shall be at least lab-tested to be considered technologically mature enough.
MR-24-TWR-01: The tower shall be ready for deployment by **<TBD>**
MR-25-TWR-01: The tower shall be dismantled by **<TBD>**
MR-28-TWR-01: The tower shall not exceed the height of 310 m above sea level.
MR-30-TWR-01: The composites used by the tower shall not exceed **<TBD>** tonnes
MR-31-TWR-01: The composites used for the system shall be **<TBD>** % of its mass recycleable by the end of life
MR-32-TWR-01: The tower shall consist of at least **<TBD>** % of recyclable metals by mass
MR-34-TWR-01: The tower shall withstand loads due to maximum wind speed of at least **<TBD>** $\mathrm{m\,s^{-1}}$

Functional requirements
FR-01-TWR-01: The tower shall track the power it uses for operation
FR-01-TWR-02: The tower shall communicate the power it uses for operation to the control system
FR-03-TWR-01: The tower shall report its status on system startup
FR-05-TWR-01: The tower shall be able to receive power from the rest of the system
FR-16-TWR-01: The tower shall be able to detect structural failures of size **<TBD>** and failures of its supporting equipment
FR-17-TWR-01: The tower shall be able to locate faults larger than **<TBD>**
FR-20-TWR-01: The tower stay above water
FR-20-TWR-02: The tower shall transfer all loads to the foundation
FR-21-TWR-01: The tower shall support its weight of **<TBD>**
FR-21-TWR-02: The tower shall support loads of YCS of **<TBD>**
FR-21-TWR-03: The tower shall support loads of PCT of **<TBD>**
FR-21-TWR-04: The tower shall support loads of WCT of **<TBD>**
FR-21-TWR-05: The tower shall support loads of DRT of **<TBD>**
FR-21-TWR-06: The tower shall support loads of RTR of **<TBD>**
FR-21-TWR-07: The tower shall support loads of OCT of **<TBD>**
FR-22-TWR-01: The tower shall damp out vibrations caused by aerodynamic loads
FR-22-TWR-02: The tower shall damp out vibrations caused by YCT subsystem
FR-22-TWR-03: The tower shall damp out vibrations caused by PCT subsystem
FR-22-TWR-04: The tower shall damp out vibrations caused by WCT subsystem
FR-22-TWR-05: The tower shall damp out vibrations caused by DRT subsystem
FR-22-TWR-06: The tower shall damp out vibrations caused by RTR subsystem
FR-22-TWR-07: The tower shall damp out vibrations caused by OCT subsystem
FR-23-TWR-01: The tower shall withstand sudden loads due to impacts of up to **<TBD>**
FR-27-TWR-01: The tower shall be able to be yawed

Standard requirements
SR-01-TWR-01: The tower shall withstand normal wind conditions for its installed location

SR-02-TWR-01: The tower shall withstand extreme wind conditions for its installed location, occurring every 50 years for its installed location

SR-03-TWR-01: The tower shall withstand extreme wind conditions for its installed location, occurring every year for its installed location

SR-03-TWR-02: The tower shall withstand fatigue caused by extreme wind conditions for its installed location, occurring every year for its installed location

SR-04-TWR-01: The tower shall withstand normal marine conditions for its installed location

SR-05-TWR-01: The tower shall withstand extreme marine conditions for its installed location, occurring every 50 years for its installed location

SR-06-TWR-01: The tower shall withstand extreme marine conditions for its installed location, occurring every year for its installed location

SR-06-TWR-02: The tower shall withstand fatigue caused by extreme marine conditions for its installed location, occurring every year for its installed location

SR-08-TWR-01: The tower shall withstand fatigue due to normal wind and sea condition loading

SR-09-TWR-01: The tower shall withstand ultimate loading case: extreme sea state in combination with extreme wind conditions

SR-10-TWR-01: The tower shall operate in the air temperature range between -20°C and +50°C

SR-10-TWR-02: The tower shall operate with maximum temperature differential of **<TBD>** between top and bottom of structure

SR-11-TWR-01: The tower shall operate between extreme wind temperatures of 0°C and +35°C

SR-12-TWR-01: The tower shall include safety guards and railing to facilitate maintenance

SR-12-TWR-02: The tower shall include secure storage of safety equipment needed to perform inspections and maintenance

SR-13-TWR-01: The tower shall facilitate option of platform access to the control point(s) of the system

SR-14-TWR-01: The tower shall include safeguards to prevent personnel from falling

SR-15-TWR-01: The tower shall include safeguards to protect personnel from moving parts

SR-16-TWR-01: The tower shall have its platform outside of the splash zone

SR-17-TWR-01: The tower shall have a safety margin between rotors and any access platform

SR-18-TWR-01: The tower shall protect all mechanical systems against the marine environment

SR-19-TWR-01: The tower shall support loads imposed by parking of the wind turbine

SR-20-TWR-01: The tower shall tolerate damage caused by solar radiation of intensity of $1000\,\mathrm{W\,m^{-2}}$

SR-20-TWR-02: The tower shall tolerate loads and damage caused by hail, rain, and snow at the installed location

SR-20-TWR-03: The tower shall tolerate impacts by mechanically active particles of impulse of **<TBD>**

SR-20-TWR-04: The tower shall withstand effects of salinity caused corrosion

SR-20-TWR-05: The tower shall withstand lighting strikes over the course of its lifetime, based on the location of its installation

SR-20-TWR-06: The tower shall withstand damage caused by impact of traffic vessels of mass of less than **<TBD>**

SR-20-TWR-07: The tower shall tolerate load case caused by rotor failure

SR-20-TWR-08: The tower shall withstand loads for the case of parked turbines

8.5.3. Yaw control (YCT)

Mission requirements

MR-02-YCT-01: The yaw control subsystem shall be produced from common, easily sourced metals, limited to <TBD>

MR-03-YCT-01: The yaw control subsystem shall have a lifetime of at least <TBD> years

MR-04-YCT-01: The yaw control subsystem shall have a rate of failure limited to <TBD>

MR-06-YCT-01: The yaw control subsystem shall have an average MTTR of at least <TBD> hrs

MR-07-YCT-01: The yaw control subsystem shall house sensors allow predictive (condition-based) maintenance

MR-08-YCT-01: The yaw control subsystem shall allow for individual turbine yaw locking

MR-19-YCT-01: The yaw control subsystem shall have a cost of less than <TBD> €

MR-21-YCT-01: The yaw control subsystem shall have an annual of less than <TBD> eur

MR-23-YCT-01: The yaw control subsystem shall have a Technology Readiness Level (TLR) of at least 9

MR-32-YCT-01: The yaw control subsystem shall use recyclable metals for at least <TBD> % of its mass

MR-34-YCT-01: The yaw control subsystem shall be able to operate at maximum wind speeds of <TBD> m/s

Functional requirements

FR-04-YCT-01: The yaw control subsystem shall communicate yaw errors to the operation control subsystem

FR-28-YCT-01: The yaw control subsystem shall be able to yaw at a rate of <TBD> m/s

FR-28-YCT-02: The yaw control subsystem shall incorporate a breaking system

FR-28-YCT-03: The yaw control subsystem shall withstand a breaking load of <TBD> kN

FR-28-YCT-04: The yaw control subsystem shall communicate with the central command center

FR-28-YCT-05: The yaw control subsystem shall be able to have a pointing accuracy of <TBD> rad

Standard requirements

SR-06-YCT-01: The yaw control subsystem shall be able to withstand fatigue due to normal wind conditions

SR-07-YCT-02: The yaw control subsystem shall withstand extreme wind conditions

SR-12-YCT-01: The yaw control subsystem shall be accessible to inspection and/or maintenance

8.5.4. Power control (PCT)

Mission requirements

MR-02-PCT-01: The metal components of the PCS (Power Control Subsystem) shall be produced from common, easily sourced metals, limited to **<TBD>**

MR-03-PCT-01: Parts of the PCS shall have a lifetime of at least **<TBD>** years.

MR-04-PCT-01: The PCS shall have RoF (Rate of Failure) lower than **<TBD>**

MR-05-PCT-01: The PCS shall be maintainable by replacement of critical components

MR-06-PCT-01: Average time to repair shall be lower than **<TBD>**

MR-07-PCT-01: The PCS shall allow predictive (condition-based) maintenance

MR-08-PCT-01: The PCS shall be maintained without total operation halt

MR-21-PCT-01: The average annual costs for maintenance shall be less than **<TBD>** € over its lifetime

MR-23-PCT-01: The technologies used by the PCS shall be at least lab tested to be considered technologically mature enough

MR-33-PCT-01: The PCS shall operate with mean wind speed of **<TBD>** $\mathrm{m\,s^{-1}}$

MR-34-PCT-01: The PCS shall operate with maximum wind speed of at least **<TBD>** $\mathrm{m\,s^{-1}}$

MR-35-PCT-01: The PCS shall have a cut-out speed of at least **<TBD>** $\mathrm{m\,s^{-1}}$

Function requirements

FR-27-PCT-01 The PCS shall be able to change the pitch of the turbine blades.

FR-27-PCT-01-01 The pitch control shall have a pitch rate of <TBD> rad/s

FR-27-PCT-01-02 The control pitch subsystem shall be able to adjust the rotor pitch according to the wind speeds automatically

FR-27-PCT-01-03 The pitch system break shall withstand a torque load of <TBD> kN

FR-10-PCT-01 The system shall be able to adjust the amount of power it produces

FR-10-PCT-01-01 The Control subsystem shall be a to activate specific wind turbines automatically if operational conditions are met

FR-10-PCT-01-02 The PCS shall be able to power down autonomously and upon requests from the main station

Standard requirements

SR-01-PCT-01: The PCS shall withstand the normal wind conditions for its installation location

SR-02-PCT-01: The PCS shall withstand the extreme wind conditions occurring every 50 years for its installation location

SR-03-PCT-01: The PCS shall withstand the extreme wind conditions occurring every year for its installation location

SR-05-PCT-01: The PCS shall withstand the extreme marine conditions occurring every 50 years for its installation location

SR-06-PCT-01: The PCS shall withstand the extreme marine conditions occurring every year for its installation location

SR-08-PCT-01: The PCS shall withstand the ultimate load case: extreme sea state in combination with extreme wind conditions

SR-10-PCT-01: The PCS shall be able to operate between extreme air temperatures of -20°C to 50°C

SR-11-PCT-01: The PCS shall be able to operate between extreme water temperatures of 0°C to 35°C.

SR-12-PCT-01: The PCS shall incorporate provisions for safe access for inspection and maintenance

SR-13-PCT-01: The normal operation of the PCS shall be possible at the platform level

SR-17-PCT-01: The PCS shall have a safety margin between rotors and any access platform

8.5.5. Wake control (WCT)

Mission requirements

MR-03-WCT-04: The wake control system shall be entirely reliable for the entire design lifetime of the system

MR-38-WCT-01: The wake control system shall have a wet surface of <TBD> m^2

MR-38-WCT-02: The wake control system shall have a lift coefficient of at least <TBD>

Standard requirements

SR-01-WCT-01: The wake control system shall successfully transfer aerodynamic loads during normal wind conditions to the tower subsystem

SR-03-WCT-01: The wake control subsystem shall successfully transfer aerodynamic loads during extreme wind conditions to the tower substructure

8.5.6. Drive train (DRT)

Mission requirement

MR-01-DRT-01: The drive train shall be producible by small Original Equipment Manufacturer(s)

MR-02-DRT-01: The drive train shall be produced from common easily sourced metals, limited to **<TBD>**

MR-03-DRT-01: The drive train shall have a lifetime of at least **<TBD>** years

MR-04-DRT-01: The drive train shall have a RoF (Rate of Failure lower than **<TBD>**

MR-05-DRT-01: The drive train shall be replaceable

MR-06-DRT-01: The average repair time of the shaft shall be lower than **<TBD>**

MR-06-DRT-02: The average repair time of the gearbox shall be lower than **<TBD>**

MR-06-DRT-03: The average repair time of the generators shall be lower than **<TBD>**

MR-06-DRT-04: The average repair time of the bearings shall be lower than **<TBD>**

MR-06-DRT-05: The average repair time of the couplings shall be lower than **<TBD>**

MR-07-DRT-01: The shaft shall be maintainable by predictive maintenance

MR-07-DRT-02: The gearbox shall be maintainable by predictive maintenance
MR-07-DRT-03: The generators shall be maintainable by predictive maintenance
MR-07-DRT-04: The bearings shall be maintainable by predictive maintenance
MR-07-DRT-05: The couplings shall be maintainable by predictive maintenance
MR-08-DRT-01: A part of the drive train shall be maintainable without halting operations of the entire system
MR-10-DRT-01: The drive train shall have a power rating of 60 MW
MR-11-DRT-01: The drive train shall transmit an annual amount of energy of **<TBD>**
MR-14-DRT-01: The drive train shall withstand the ramp-up limit of **<TBD>**
MR-18-DRT-01: The generators shall produce electrical current with a frequency of **<TBD>** Hz
MR-19-DRT-01: The drive train shall have a production cost of less than €**<TBD>**
MR-20-DRT-01: The drive train shall be transportable to the installation site for a transport cost less than €**<TBD>**
MR-21-DRT-01: The average annual costs for the drive train shall be less than €**<TBD>** over the lifetime of the system
MR-22-DRT-01: The cost of decommissioning the drive train shall not exceed €**<TBD>**
MR-23-DRT-01: The drive train technology shall be lab tested
MR-24-DRT-01: The drive train system shall be ready for deployment by **<TBD>**
MR-25-DRT-01: The system shall be able to be dismantled by **<TBD>**
MR-26-DRT-01: The drive train shall comply with the Offshore Wind Energy Act
MR-27-DRT-01: The drive train shall comply with the Flora and Fauna Act
MR-33-DRT-01: The drive train shall operate with mean wind speeds of at least **<TBD>**
MR-34-DRT-01: The drive train shall operate with maximum wind speeds of **<TBD>**

Functional requirements
FR-11-DRT-01: The generator shall be connected to the power substation

Standard requirements
SR-01-DRT-01: The drive train shall withstand the torsion fatigue loads of **<TBD>** under normal wind conditions for at least **<TBD>** years
SR-02-DRT-01: The drive train shall withstand the maximum torsion load of **<TBD>** due to extreme wind conditions
SR-10-DRT-01: The drive train shall be able to operate in extreme air temperatures of $-20\,°C$ to $50\,°C$
SR-12-DRT-01: The drive train shall be safely inspectable and maintainable
SR-19-DRT-01: The drive train shall have a mechanical brake to allow for parking the wind turbine
SR-20-DRT-01: The drive train shall allow for rotor idling to prevent gear wearing

8.5.7. Rotor (RTR)

Mission requirements
MR-02-RTR-01: The rotor shall be produced from common, easily sourced materials, limited to **<TBD>**
MR-03-RTR-01: The rotor shall have a rate of failure lower than **<TBD>**
MR-04-RTR-01: The rotor shall have a lifetime of at least **<TBD>** years
MR-05-RTR-01: The rotor shall be replaceable
MR-08-RTR-01: The rotor shall be able to be halted on its own
MR-10-RTR-01: The rotor shall produce a nominal torque of **<TBD>**
MR-14-RTR-01: The rotor shall have a ramp up speed of **<TBD>**
MR-15-RTR-01: The rotor shall have a ramp down speed of **<TBD>**
MR-19-RTR-01: The cost of rotor production shall be less than **<TBD>**
MR-19-RTR-02: The cost of rotor replacement shall be less than **<TBD>**
MR-33-RTR-01 The rotor shall withstand fatigue caused by aerodynamic loads experienced by normal

MR-34-RTR-01: The rotor shall withstand loading caused by extreme wind conditions at the installed location

Functional requirements

FR-17-RTR-01: The rotor shall be able to locate large failures of the blades and hubs

FR-23-RTR-01: The rotor shall be able to withstand any vibrations experienced during installation, operation, and decommissioning

FR-24-RTR-01: The rotor shall withstand impacts by particles with an impulse of up to **<TBD>**

Standard requirements

SR-09-RTR-01: The rotor operation shall not be hindered by the effects of the sea the location of its installation

SR-19-RTR-01: The rotor shall be able to stop and be parked

8.5.8. Operations Control (OCT)

Mission requirements

MR-04-OCT-01: The operations control system shall have a RoF lower than **<TBD>**

MR-07-OCT-01: The operation control subsystem shall monitor the vibration of the tower subsystem

MR-07-OCT-02: The operation control subsystem shall monitor the vibration of the drive train subsystem

MR-07-OCT-03: The operation control subsystem shall monitor the vibration of the rotor subsystem

MR-07-OCT-04: The operation control subsystem shall monitor the strains of the tower subsystem

MR-07-OCT-05: The operation control subsystem shall monitor the strains of the drive train subsystem

MR-07-OCT-06: The operation control subsystem shall monitor the strains of the rotor subsystem

MR-07-OCT-07: The operation control subsystem shall monitor the lubricant levels of the drive train subsystem

MR-07-OCT-08: The operation control subsystem shall monitor the particulate number of the oil of the drive train subsystem

MR-07-OCT-09: The operation control subsystem shall monitor the temperatures of the drive train subsystem

MR-14-OCT-01: The operations control system shall have a ramp-up limit of **<TBD>**

MR-15-OCT-01: The operations control system shall have a ramp-down limit of **<TBD>**

MR-18-OCT-01: The operations control system shall maintain an electrical current frequency of **<TBD>** Hz

MR-35-OCT-01: The operations control system shall engage emergency brakes if the cut-out speed of **<TBD>** is reached.

MR-36-OCT-01: The operations control system shall calculate required yaw adjustments for the YCT

Functional requirements

FR-01-OCT-01 OCT shall track the power it uses for operation.

FR-02-OCT-01 OCT shall check the status of its software on startup.

FR-03-OCT-01 OCT shall check the status of its hardware (sensors and electronics) on startup.

FR-04-OCT-01 OCT shall be able to communicate to the main control station

FR-05-OCT-01 The OCT shall be capable of distributing power to its subsystems

FR-06-OCT-01 The OCT shall be able to check status and functioning of its subsystems.

FR-07-OCT-01 The OCT shall be able to check environmental conditions.

FR-07-OCT-01-01 The OCT shall be able to check the wind direction.

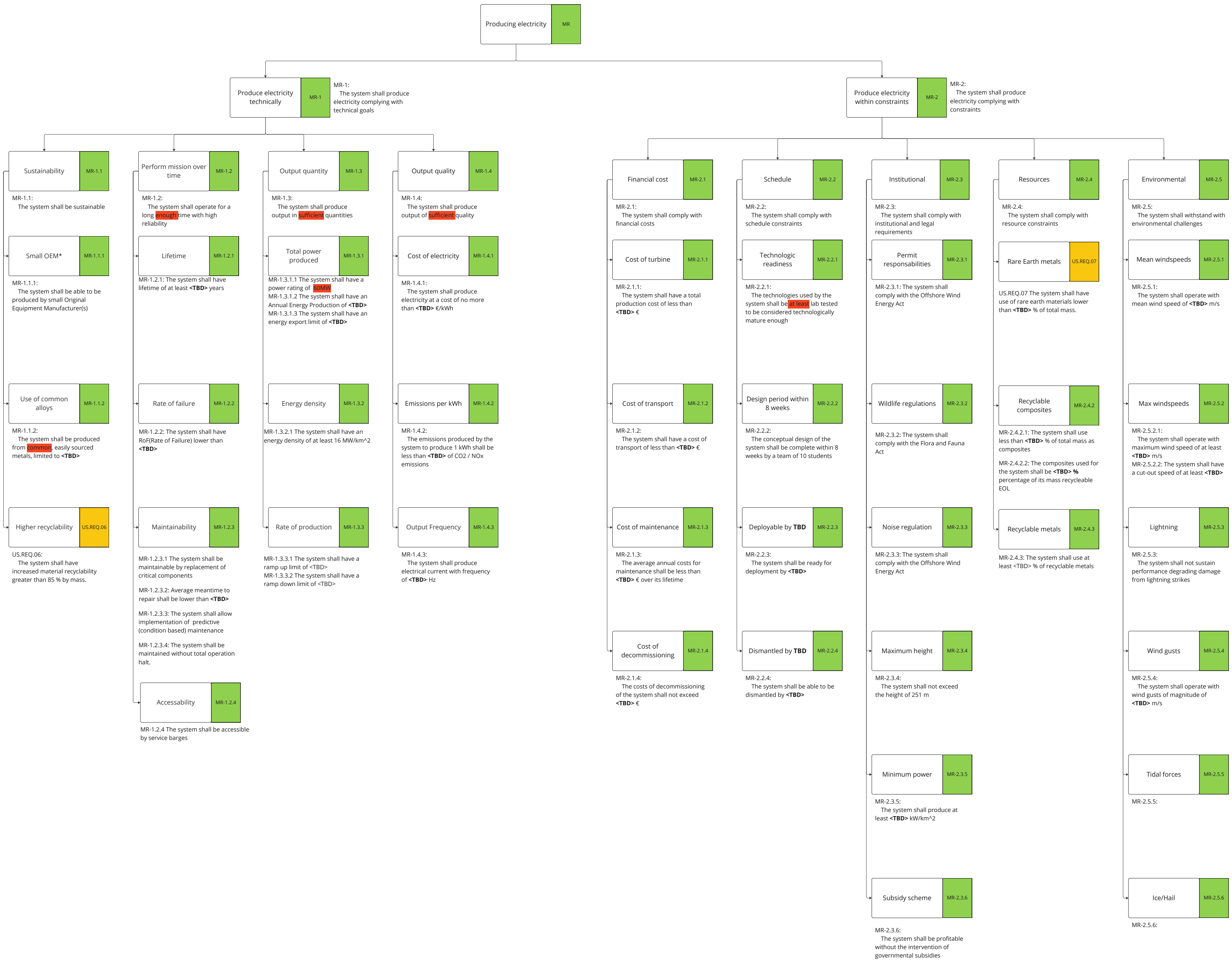
FR-07-OCT-01-02 The OCT shall be able to check wind velocity.

FR-07-OCT-01-03 The OCT shall be able to check air temperature.

FR-07-OCT-01-04 The OCT shall be able to check the water temperature.

FR-07-OCT-01-05 The OCT shall be able to check the air humidity.

FR-07-OCT-01-06 The OCT shall be able to check the air density.
FR-07-OCT-01-07 The OCT shall be able to check the air pressure.
FR-08-OCT-01 The OCT shall be able to have access to the weather forecast
FR-11-OCT-01 The OCT shall be connected to the power substation
FR-14-OCT-01 The OCT shall be capable of informing the main station about powering off
FR-15-OCT-01 The OCT shall be able to maintain its communication link while its operation is halted
FR-16-OCT-01 The OCT shall be able to detect failures
FR-17-OCT-01 The OCT shall be able to locate failures
FR-18-OCT-01 The OCT shall be able to alert the maintenance department if a failure occurs
FR-21-OCT-01 The OCT shall stay above water
FR-23-OCT-01 The OCT shall damp out any vibrations experienced during normal and extreme conditions
FR-25-OCT-01 The OCT shall be able to determine its attitude
FR-26-OCT-01 The OCT shall be able to gather data needed to verify its communications are working


Producing electricity
MR
Produce electricity technically
MR-1
MR-1:
The system shall produce electricity complying with technical goals
Produce electricity within constraints
MR-2
MR-2:
The system shall produce electricity complying with constraints
Sustainability
MR-1.1
MR-1.1:
The system shall be sustainable
Small OEM*
MR-1.1.1
MR-1.1.1:
The system shall be able to be produced by small Original Equipment Manufacturer(s)
Use of common alloys
MR-1.1.2
MR-1.1.2:
The system shall be produced from common, easily sourced metals, limited to **<TBD>**
Higher recyclability
US.REQ.06
US.REQ.06:
The system shall have increased material recyclability greater than 85 % by mass.
Perform mission over time
MR-1.2
MR-1.2:
The system shall operate for a long enough time with high reliability
Lifetime
MR-1.2.1
MR-1.2.1: The system shall have lifetime of at least **<TBD>** years
Rate of failure
MR-1.2.2
MR-1.2.2: The system shall have RoF(Rate of Failure) lower than **<TBD>**
Maintainability
MR-1.2.3
MR-1.2.3.1 The system shall be maintainable by replacement of critical components
MR-1.2.3.2: Average meantime to repair shall be lower than **<TBD>**
MR-1.2.3.3: The system shall allow implementation of predictive (condition based) maintenance
MR-1.2.3.4: The system shall be maintained without total operation halt.
Accessability
MR-1.2.4
MR-1.2.4 The system shall be accessible by service barges
Output quantity
MR-1.3
MR-1.3:
The system shall produce output in sufficient quantities
Total power produced
MR-1.3.1
MR-1.3.1.1 The system shall have a power rating of 60MW
MR-1.3.1.2 The system shall have an Annual Energy Production of **<TBD>**
MR-1.3.1.3 The system shall have an energy export limit of **<TBD>**
Energy density
MR-1.3.2
MR-1.3.2.1 The system shall have an energy density of at least 16 MW/km^2
Rate of production
MR-1.3.3
MR-1.3.3.1 The system shall have a ramp up limit of <TBD>
MR-1.3.3.2 The system shall have a ramp down limit of <TBD>
Output quality
MR-1.4
MR-1.4:
The system shall produce output of sufficient quality
Cost of electricity
MR-1.4.1
MR-1.4.1:
The system shall produce electricity at a cost of no more than **<TBD>** €/kWh
Emissions per kWh
MR-1.4.2
MR-1.4.2:
The emissions produced by the system to produce 1 kWh shall be less than **<TBD>** of CO2 / NOx emissions
Output Frequency
MR-1.4.3
MR-1.4.3:
The system shall produce electrical current with frequency of **<TBD>** Hz
Financial cost
MR-2.1
MR-2.1:
The system shall comply with financial costs
Cost of turbine
MR-2.1.1
MR-2.1.1:
The system shall have a total production cost of less than **<TBD>** €
Cost of transport
MR-2.1.2
MR-2.1.2:
The system shall have a cost of transport of less than **<TBD>** €
Cost of maintenance
MR-2.1.3
MR-2.1.3:
The average annual costs for maintenance shall be less than **<TBD>** € over its lifetime
Cost of decommissioning
MR-2.1.4
MR-2.1.4:
The costs of decommissioning of the system shall not exceed **<TBD>** €
Schedule
MR-2.2
MR-2.2:
The system shall comply with schedule constraints
Technologic readiness
MR-2.2.1
MR-2.2.1:
The technologies used by the system shall be at least lab tested to be considered technologically mature enough
Design period within 8 weeks
MR-2.2.2
MR-2.2.2:
The conceptual design of the system shall be complete within 8 weeks by a team of 10 students
Deployable by **TBD**
MR-2.2.3
MR-2.2.3:
The system shall be ready for deployment by **<TBD>**
Dismantled by **TBD**
MR-2.2.4
MR-2.2.4:
The system shall be able to be dismantled by **<TBD>**
Institutional
MR-2.3
MR-2.3:
The system shall comply with institutional and legal requirements
Permit responsabilities
MR-2.3.1
MR-2.3.1: The system shall comply with the Offshore Wind Energy Act
Wildlife regulations
MR-2.3.2
MR-2.3.2: The system shall comply with the Flora and Fauna Act
Noise regulation
MR-2.3.3
MR-2.3.3: The system shall comply with the Offshore Wind Energy Act
Maximum height
MR-2.3.4
MR-2.3.4:
The system shall not exceed the height of 251 m
Minimum power
MR-2.3.5
MR-2.3.5:
The system shall produce at least **<TBD>** kW/km^2
Subsidy scheme
MR-2.3.6
MR-2.3.6:
The system shall be profitable without the intervention of governmental subsidies
Resources
MR-2.4
MR-2.4:
The system shall comply with resource constraints
Rare Earth metals
US.REQ.07
US.REQ.07 The system shall have use of rare earth materials lower than **<TBD>** % of total mass.
Recyclable composites
MR-2.4.2
MR-2.4.2.1: The system shall use less than **<TBD>** % of total mass as composites
MR-2.4.2.2: The composites used for the system shall be **<TBD> %** percentage of its mass recyclable EOL
Recyclable metals
MR-2.4.3
MR-2.4.3: The system shall use at least <TBD> % of recyclable metals
Environmental
MR-2.5
MR-2.5:
The system shall withstand with environmental challenges
Mean windspeeds
MR-2.5.1
MR-2.5.1:
The system shall operate with mean wind speed of **<TBD>** m/s
Max windspeeds
MR-2.5.2
MR-2.5.2.1:
The system shall operate with maximum wind speed of at least **<TBD>** m/s
MR-2.5.2.2: The system shall have a cut-out speed of at least **<TBD>**
Lightning
MR-2.5.3
MR-2.5.3:
The system shall not sustain performance degrading damage from lightning strikes
Wind gusts
MR-2.5.4
MR-2.5.4:
The system shall operate with wind gusts of magnitude of **<TBD>** m/s
Tidal forces
MR-2.5.5
MR-2.5.5:
Ice/Hail
MR-2.5.6
MR-2.5.6:

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