Development of a multi rotor floating offshore system based on vertical axis wind turbines

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Abstract The upscaling of wind turbines results in fewer units per installed MW reducing infrastructure and maintenance costs of offshore wind farms. Multi rotor systems (MRS), comprising many wind turbine rotors on a single support structure, are potentially a means to maximize the upscaling benefit in achieving larger unit capacities than is feasible or economic with the conventional, 3-bladed horizontal axis wind turbine (HAWT). The MRS has an inherent upscaling advantage which, for a system with many rotors compared to a single rotor, reduces the total weight and cost of rotor-nacelle assemblies by a large factor. An innovative MRS design is presented based on vertical axis wind turbine (VAWT) rotors of the 2-bladed, H-type. Many disadvantages of VAWT design compared to HAWT in a single rotor system (reduced power performance and higher drive train torque, for example) are resolved in the MRS configuration. In addition, reduced component number and simpler components is advantageous for reliability and O&M cost. This MRS concept has many synergies arising from the choice of VAWT rotors. Results comprise a high-level evaluation of system characteristics and the first stage of more detailed investigation of aerodynamics of the high aspect ratio VAWT.

1. Introduction

Upscaling of the unit capacity of wind turbines has been an ongoing trend in commercial wind turbine development. This upscaling continues due to the benefit, in offshore projects especially, in reducing the total number of maintenance sites and costs of foundations and electrical interconnections within a wind farm of given total capacity [1].

Multi rotor systems (MRS), comprising a number of rotors on a common support structure, are increasingly being considered [2], [3], [4] as an alternative to upscaling the standard 3 bladed, HAWT. The MRS has an inherent upscaling advantage which, compared to a single rotor system, reduces the total weight and cost of rotor-nacelle assemblies (RNA) by a very large factor [3], [5]. Obvious concerns regarding the MRS concept are in the aerodynamics of closely spaced rotors, the engineering and cost of the support structure, yawing of the system as a whole and maintenance of a system with a very large component count. Analytical [6], and numerical analyses based both on vortex methods and on computational fluid dynamics (CFD) [3], wind tunnel experimental results [7], [8] and field testing [9] confirm no power performance loss and varying gains with close lateral spacing of rotors, associated with a blockage effect. Ongoing work by HAW Hamburg [10], [11], [12] has considered the impact of rotor number and system layout on structure costs and other aspects of MRS design [13].

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Diverse areas of MRS design have been addressed in PhD studies at the University of Strathclyde (UoS) including the overall system and loads [14], electrical systems [15], system yaw control using rotor thrust control [16]. In the Inwind.EU project, an availability and reliability analysis [3] highlighted the importance of having efficient methods to deal with minor faults. More detailed recent work on O&M highlights it as a critical area. Advantages of the MRS in avoiding the use of jack-up vessels through having in-built rotor handling systems, in redundancy of components reducing fault impact, in enhanced component reliability and the affordability of greater margins on fault critical components and in single machine faults affecting only a small fraction of system output are offset by the challenge of the larger total number of faults impacting on maintenance manpower demand and vessel logistics.

The distinctive aspect of the present work is in the development of an MRS system based on VAWTs rather than HAWTs. The idea is not entirely new, an MRS system based on spiral bladed VAWTs having been proposed by Coriolis Wind (no longer trading) [5]. The present system employs simple, 2-bladed H-type VAWTs aiming to show how limitations of such a design as a single rotor system maybe overcome with advantage in the MRS arrangement, exploring possible benefits in the avoidance of any additional engineering (as a floating system) for yawing in the sea and also likely benefits to O&M from reduced numbers of simpler components compared to an MRS based on HAWTs.

The overall aim is to develop a preliminary design of a floating VAWT based MRS and assess its potential to reduce cost of energy from offshore wind systems. The present work is the preliminary development of an outline design with a top-level assessment of some key design areas. The IEA 15 MW reference turbine [17], [18] is used as a baseline representative of a large offshore wind turbine design with public design information. This HAWT is compared with 48 MW MRS systems based on HAWT and VAWT rotors in the context of a large offshore wind farm. A multi-disciplinary team is assembled to address all relevant areas; fundamental aerodynamics, power performance and loads (TU Delft), structure and drive train (HAW Hamburg), floater (UoS) and O&M (UoS) using state of the art design tools. A detailed O&M model adapted for modelling MRS windfarms has been further developed in this project.

2. The MRS VAWT concept

2.1. Design characteristics of single VAWT types

Table 1 comparing VAWT types shows that the spiral and high aspect ratio VAWTS each solve one problem with the classic H-type but have their own downside as single rotor systems. The proposed integration of VAWT units into an MRS has great synergies that largely defeat the limitations of single VAWT design shown in Table 1.

Table 1. Comparison of single rotor VAWT designs

			
	Low aspect ratio VAWT	**Spiral bladed VAWT**	**High aspect ratio VAWT**
Power performance	Cp 5-10% less than for HAWT	Cp 5-10% less than for HAWT	Gain in reduced end loss offset by increased cross arm drag
Torque rating	Typically 2 to 3 times that of HAWT	Typically 2 to 3 times that of HAWT	*Equal or less than HAWT*
Torque cycle	Approx. sinusoidal	*Smooth*	Approximately sinusoidal
Rotor structure	Demanding cross arm joints	Efficient at small scale too complex for large	Blade support issue (many cross arms)
Support structure	Challenging	Challenging	Challenging (long cantilever)

2.2. The 48MW VAWT MRS

The design proposed (Figure 1) comprises 96 high aspect ratio VAWTs, each of 500 kW rated power, mounted on a single floating structure and resulting in a total system of 48 MW. The VAWT turbines are 2 -bladed units of the H type with 4 units in vertical columns coupled together and connected to a single generator. Direct drive PMG generators are primarily considered although there is a wide choice of power conversion options for MRS [15]. Turbine control is effected by generator reaction torque and routine braking is done electrodynamically with failsafe mechanical shaft brakes on each turbine unit. Salient design characteristics of the proposed VAWT MRS system are now considered.

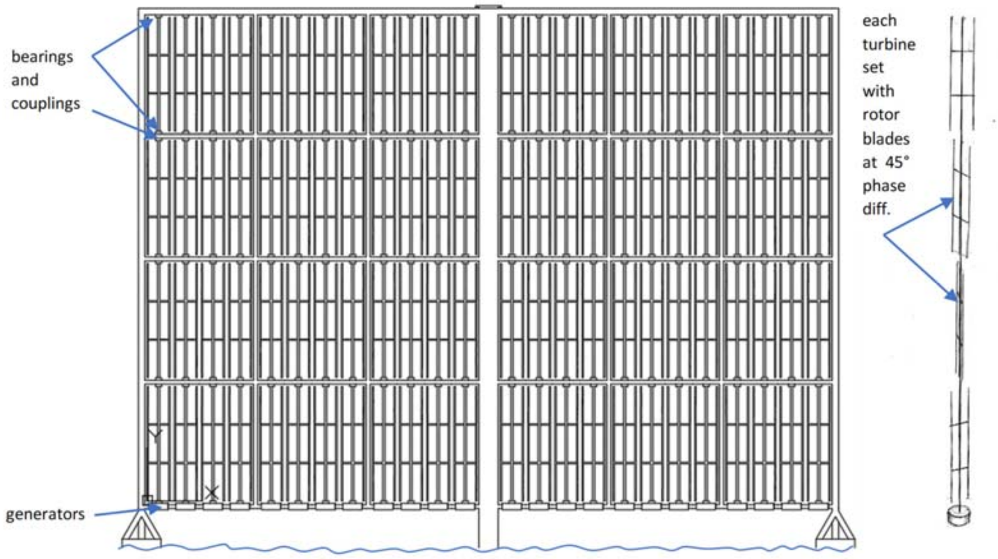

Figure 1. Multi rotor system of 48 MW based on high aspect ratio vertical axis wind turbines

Structure packing The limiting packing fraction of VAWTs of the H type is unity whereas for HAWTs it is minimum in triangular stacking at 0.907. This enables a reduction in the ratio of structure envelop area to total rotor swept area using VAWTs ~ 10%. The rectangular array is also much better suited for access and handling of components.

Power performance The high aspect ratio (5:1) minimises blade end losses. Blockage effects of close spaced rotors enhance power performance with added gain for counter rotating VAWTs.

Rotor support Structural support of a single high aspect ratio VAWT is challenging. Each MRS VAWT unit is integrated with top and bottom bearings avoiding cantilevering a long structure.

Torque cycle The 4 turbines in each column are rigidly connected with blade azimuth positions set differing in phase by 45° (Figure 1, right) giving a smooth, 8 phase torque input to the generator. This preserves simplicity and uniformity of rotor design.

O&M impacts Reliability is much enhanced avoiding pitch systems and yaw systems. In the VAWT MRS with rotors connected in sets of 4, electrical and control components are reduced by a factor of 4. O&M cost reduction also arises from the large unit capacity which is 3 times that of the largest commercial HAWT (Ming Yang MySE 16.0-242). The design intention is to avoid any need to return the complete system to shore base in the event of any RNA fault.

Yawing The design avoids the costs and complexity of a mechanical yaw system mounted on the floater or a turret with swivel bearing for yawing the floater in the sea. Instead, with the VAWT rotors being tolerant to varying wind directions, excepting ones closely aligned to the plane of the structure frame, the system can drift slowly downwind on conventional catenary moorings.

Floater Torque reaction With a large single floating VAWT, there is substantial additional demand on the moorings which must react the full generator torque. In the proposed MRS system, adjacent columns will counter-rotate. The net torque reaction on the floater will be very small.

3. Aerodynamics of high aspect ratio, H-type VAWTs in close spacing

3.1. Aspect ratio and blade end loss effects

VAWTs can in specific circumstances achieve high power performance [19] but gains are often limited due to support structure drag and tip loss. The rotor power performance coefficient, $C_p = 0.49$, of the IEA 15 MW reference wind turbine would rise by~ 8% to about 0.53 if the tip loss were eliminated. This suggests that there could be substantial benefit in a VAWT design that could much reduce tip loss (blade end) effects. In uniform flow, the C_p of a typical single H-type VAWT is a function of the aspect ratio and load distribution in the actuator cylinder's upwind and downwind portions. The multi rotor arrangement is based on a VAWT units with a 5:1 aspect ratio. From calculations based on a 3D actuator cylinder, [20], [21]. the influence of rotor aspect ratio on the maximum C_p (as a fraction of the C_p for infinite aspect ratio) for a VAWT primarily loaded upwind is illustrated in Figure 2. In this case the rotor has ¾ loading in the upwind half and C_p is expressed as a fraction of the value of C_p for infinite rotor aspect ratio. At the 5:1 aspect ratio selected for the VAWT MRS units, there is almost no loss associated with rotor aspect ratio effects.

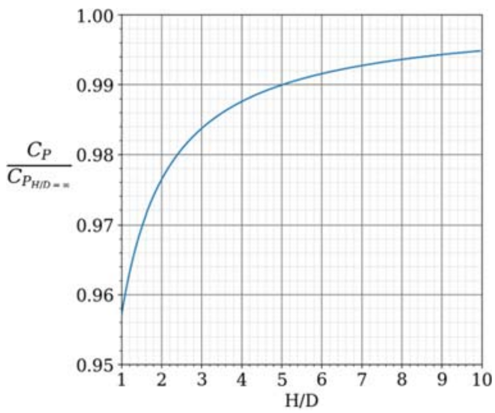

Figure 2. -Power coefficient of as function of aspect ratio, H/D.

3.2. Blockage effects at close spacing with co-rotation and counter-rotation

The Betz actuator disc limit applies when the flow has free expansion around the turbine. When this is not the case, more flow is forced through the turbine and more power may be extracted. Such blockage effects apply to tidal turbines confined in a narrow channel or in wind tunnels where the walls confine the total flow. A related effect termed 'local blockage' [22] obtains with rotors closely spaced in a plane where the flow expansion is inhibited by adjacent rotors. At optimal packing for HAWTs [22], the ideal maximum coefficient of power can be increased from the Betz limit 59.3% to the 79.8%. In the Innwind.EU project [3], a power performance gain of 8% of the 45 rotor MRS relative to a single HAWT rotor of the same total swept area was predicted. Similar effects of blockage apply to VAWTs [23]. Pairing VAWTs [24] side by side results in a power increase compared to two isolated VAWTs, and the clockwise-anticlockwise pair (also referred to as an 'inner-upwind' pair) provides the greatest increase in power; 13% -16% power gain was predicted [24] for a rotor spacing with swept areas 30% of diameter apart. In de Tavernier et al [25], it was shown that the proximity of the actuators leads to an increased thrust and power conversion, with gains of approximately 4% in power for thrust coefficients around 0.8. There is also evidence [26] that the inner-upwind combination produces a beneficial C_p characteristic with a flatter peak.

3.3. Rotor aerodynamic design

The VAWT proposed for the VAWT MRS is 2 bladed H-type using blade sections of the DU17DBD25/DU17W25 aerofoil [27] of length 88.7 m, diameter 17.73m and chord width 0.63 m. The performance is calculated using the actuator cylinder model originally proposed by Madsen [21] and implemented by Leblanc and Ferreira [28]. Rotor solidity, σ based on the definition $\sigma = Bc/R$ where B is blade number, c is chord width and R is rotor radius is approximately 14%.

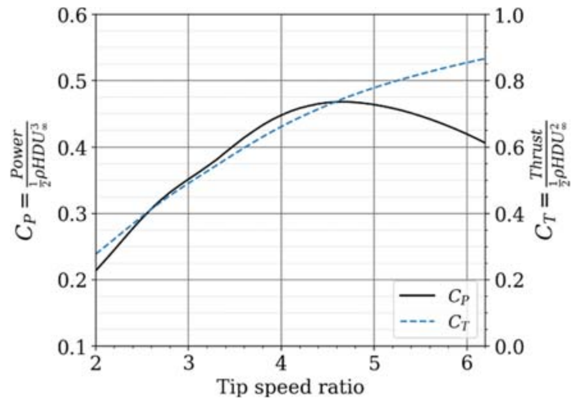

Figure 3. Power coefficient C_p and thrust coefficient C_t as a function of tip speed ratio.

Power and thrust coefficients as a function of tip speed ratio are presented in Figure 3. The predicted performance allows for cross arm drag but does not account for blockage benefit.

4. Rotor support structure frame design

4.1. Simplified space frame design

A simplified method for dimensioning of HAWT MRS space frames [29], [10] has been developed to design and compare different space frame topologies considering variations of geometric design parameters such as the space frame depth, space frame tower connection and the location of bearings.

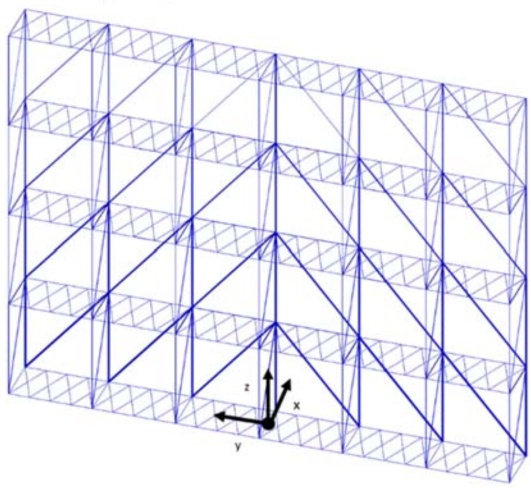

Figure 4. Space frame of the 48 MW VAWT MRS

The VAWT MRS space frame structure (Figure 4) has 4 rows and 6 columns with each structure cell holding 4 VAWT units, resulting in 96 VAWT units in total. A horizontal spacing between blade tips of 5% of the rotor diameter is used. The same spacing is used for the vertical distance between the rotors in each column. This leads to overall dimensions of 446 m width and 358 m height. The depth of the space frame (x-direction in Figure 4) can be varied in the concept analysis and is defined by a depth ratio: ratio of space frame depth to space frame width (dimension in y-direction in Figure 4). A truss structure with diagonal stiffening elements is used to allow a good load distribution.

4.2. Dimensioning process

The masses (10.76 t per RNA) of the 500 kW VAWT rotors are scaled from the 444 kW HAWT MRS rotors of the Innwind.EU 20 MW HAWT MRS [3]. Rated thrust force (85 kN per RNA) are similarly scaled. Each space frame member is dimensioned against yield strength and stability (Euler buckling) with applied safety factors. A thickness to diameter ratio of 1/120 is used. The space frame comprises 863 elements. There are around 220 distinct tube diameters after the initial dimensioning. The largest diameter is around 1.75 m, at the bottom row of the structure. A minimum diameter of 200 mm is set. To reduce the number of tube sizes, a classification into a set number of 20 bins is used. This increases the mass slightly but will benefit in having more standardised elements including joints and welds.

4.3. Space frame results

A space frame depth (Figure 5) of around 12% of the overall width (approximately 50 m) minimises space frame mass. The two points shown define a lower limit of possible depth ratio where the rotor swept area would touch the rear structural elements. To compensate for the simplified approach in the space frame dimensioning process, the space frame mass is doubled based on comparison with the more detailed evaluation in the Innwind project [3]. The resulting overall mass of space frame (5462.7 t) and RNA (1032.5 t) in combination with the centre of gravity is used in preliminary design of the floater.

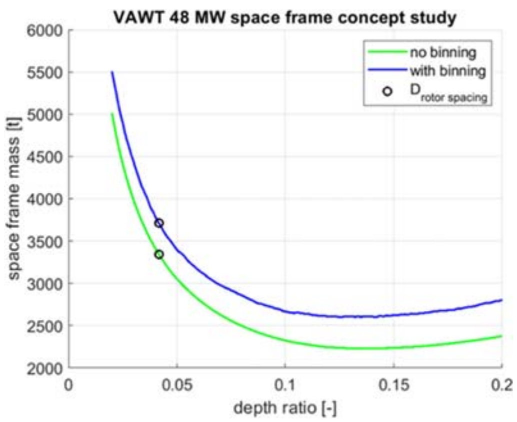

Figure 5. Space frame mass in relation to the space frame depth ratio

5. Drive train design

5.1. Drive Train Design

The shaft bearings and complete rotor assembly of each VAWT unit are supported in the space frame (Figure 1). The upper bearing is chosen to be the fixed bearing, (taking radial and axial forces) the lower bearing being the floating bearing (taking only radial forces). This leads to shaft tension by rotor gravity loads and avoids shaft buckling problems. In the proposed VAWT MRS design four VAWT units with aspect ratio 5 are connected via shaft couplings to a single generator at structure base The generator at base level allows for easiest maintenance access but involves the torsional wind-up of 4 shafts and puts a factor of 4 on shaft torque rating requiring a larger shaft in comparison to a solution with one generator per rotor. A generator at mid-level could preserve the torque smoothing and involve the wind-up of only two shafts. The most natural solution of one generator per rotor would lead to lightest shafts and additional control possibilities but negate the important O&M advantage of fewer electrical components.

5.2. Torque shaft design and drive train vibrations

Connecting 4 long shafts may lead to drive train torsional vibrations since each torque shaft in itself is an elastic torsion spring and each rotor comes with a substantial mass moment of inertia. The shaft is designed for static strength with a global safety factor of 2 and a static shear strength of 300 MPa. Only the lowest shaft must transmit the torque of all four rotors, but manufacturing is standardised using a common design for all VAWTs. At a fixed wall thickness ratio of $d_s/t_s = 60$ ($d_s$shaft diameter, t_s wall thickness) estimated diameters and wall thicknesses (Table 2) are relatively small in consequence of applying torsion-only loading. Comparing the shaft masses to HAWT of the same rated power, the VAWT shafts are heavier due to much greater length. The masses in Table 2 for HAWT MRS have been scaled from a 2.1 MW HAWT with a shaft mass of 8 tons in forged steel with a diameter of 700 mm at main bearing position [30].

Table 2. Dimensioning of shafts

Shaft property		IEA 15 MW	V 15 MW AR 1	V 15 MW AR 5	VMRS 2 MW	VMRS 0.5 MW	HAWT MRS
diameter	d_s [m]		2.1	1.6	0.47	0.3	
wall thickness	t_s [mm]		35.5	27.1	7.88	5.0	
weight	m_s [t]	153	409	535	7.9	3.1	0.9
Eigenfrequency 1st	ω [Hz]		0.0164	0.0214	0.0367	0.134	

After shafts being dimensioned, a torsional vibration analysis is performed. A mass moment of rotor inertia has been crudely estimated by assuming that 70% of the RNA mass is rotating in the rotor radius R.

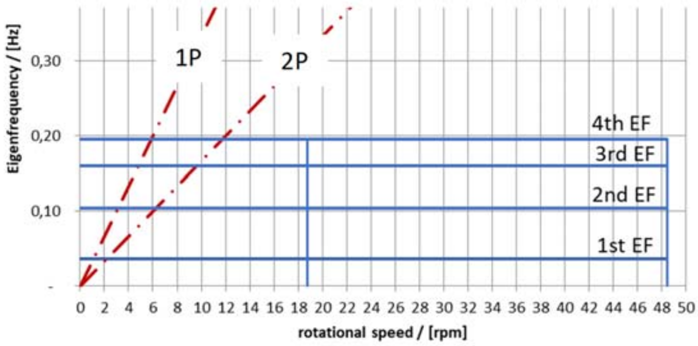

Figure 6. Drive train torsional vibration Campbell diagram for VAWT 4 rotor column

Eigenfrequencies for a drive train of n masses and n springs with the last spring end being fixed can be calculated as [31]. Results indicate a soft design with operation below 1P. The large cyclic torque variation of a single two bladed H-type rotor will in the 4-rotor column be averaged out at connection to the generator.

6. Floater design

Floating substructure types can be classified in A) ballast-stabilised, i.e. spar as in Hywind Scotland Pilot park B) waterplane area-stabilised i.e. barges and semisubmersibles (e.g. Windfloat by Principle Power), and C) mooring-stabilised, i.e. TLP, [32]. This initial assessment adopts a spar configuration for the simplest comparison to single rotor floaters although a semi-submersible is the probable future solution to avoid excessively deep draft. A parametric analysis of th VAWT MRS floating substructure based on scaling from [3], takes as input a mass above substructure of 14472.7 te, the centre of gravity vertical position at 156 m, the maximum aerodynamic thrust force as 8.164 MN and the height of 214.5 m for its point of application. The objective is the definition of the approx. geometric dimensions of the floating substructure and the amount of structural material required.

Key performance indicators are the static tilt inclination angle, θ, (calculated as in [32]) due to the aerodynamic inclining moment M_I of the VAWT MRS, and, as a cost indicator, the approximate mass of structural offshore steel necessary for the substructure. The spar, as represented by a simple cylinder with a constant radius R and a total draft T, has the vertical coordinate of the centre of buoyancy at $z_{CB} = -T/2$. The total substructure mass is the sum of its structural mass and ballast mass. The substructure structural (steel) mass is assumed to be 13% of the mass of displaced water [33], with a centre of gravity at $-T/2$, and the ballast mass can be calculated as the difference between the buoyancy force and the sum of the weight of the topside and the substructure structural mass, while its centre of gravity is calculated assuming a ballast tank at the bottom of the spar, with a ballast density equal to 1907 kg/m^3 [34]. Floatability is imposed by ensuring a ballast mass higher than zero.

The 5MW OC3 spar substructure steel mass [35] is considered as a benchmark for the steel mass. Feasible designs are in the coloured regions; white ones represent non-physical solutions (not floating or not statically stable). Reducing max θ which is usually in a range between 5° and 10° [36], requires a larger draft for a given radius, or a larger radius for a given draft and more costly substructure (Figure 7, right). This range allows for added dynamic response, due to wave oscillatory loads. Using the rated power divided by the substructure structural steel as a performance indicator, to be more efficient than the OC3 requires values (Figure 7, right) lower than 48MW/5MW = 9.6.

Considering a max θ of 10°, we can find floating substructure for the 48MW VAWT MRS with a better MW/tonnes ratio (i.e. lower than 9.6 in the graph) for deep draft (higher than 120m) and radii between 10 and 12.5m. The deep draft may be a limitation for this spar option, and a waterplane-area stabilised option will be investigated in future studies.

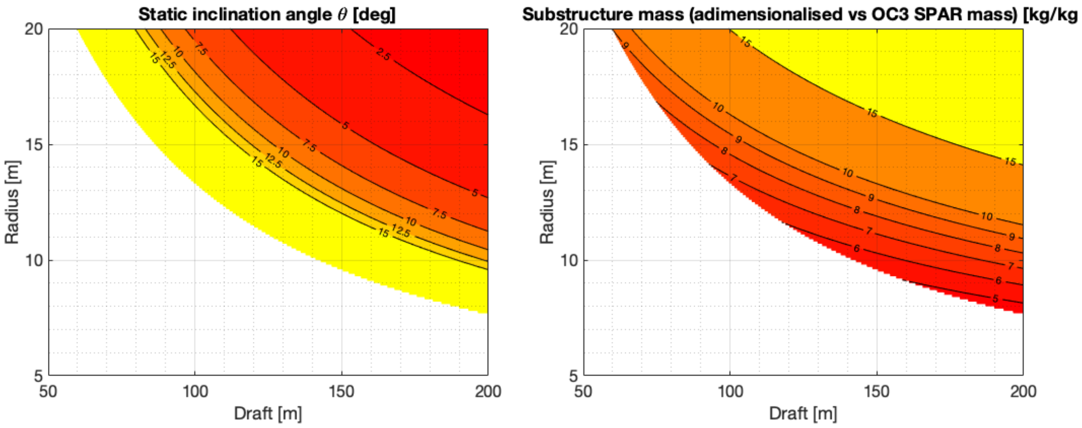

Figure 7. floating substructure parametric design: static inclination angle (left); dimensionless steel mass as a function of spar radius and draft (right)

The VAWT MRS, due to counter rotation of many rotor sets, imposes little torque reaction on the floater and its moorings, a significant advantage compared to large single turbine floating VAWT systems [37],[38].

7. O&M comparisons

7.1. Modelling of O&M

The O&M model is based on one originally developed by UoS [39] developed into the Trios OPEX model of Trios Renewables and extensively validated against the ECN (both analytic & time series versions) and MAINSYS (Shoreline) off-the-shelf OPEX tools [40], [41]. Iterations of this model have been used to support project decisions relating to, for example, the Beatrice Offshore Wind Farm (2016) and the SeaGreen project (2019). Trios produces a time series simulation representing wind farm operation on an hourly or half hourly time step, accounting failure and repair processes, allocating people and vessel resources as in actual operational practice over the operational life of a site. Met ocean and wind speed data are used in the model to constrain access and lifting operations.

7.2. Failure data

Table 3. Failure data groups

	HAWT		HAWT MRS		VAWT MRS		SH	MH	MV
	major	minor	major	minor	major	minor		number	
ELECTRICAL GROUP	0.623	2.472	0.063	0.303	0.034	0.259	3	83	22
MECH&STRUCTURE	0.431	3.302	0.011	0.177	0.004	0.121	3	59	23
YAW SYSTEM	0.007	0.182	0.014	0.364	0.000	0.000	3	1	0
PITCH SYSTEM	0.180	0.896	0.036	0.179	0.000	0.000	3	96	0
CONVERTERS	0.086	0.094	0.043	0.047	0.043	0.047	3	14	14

Without relevant failure data for VAWTs, failure rate data based on Carroll [42] reduced to the groups of Table 3 was used in evaluation of O&M comparisons. The absence of pitch and yaw systems in the VAWT MRS, the improved reliability of blades considering reduced surface erosion susceptibility of VAWTs at around half the tip speed of HAWTs, the improved reliability of generators and converters with uprating margins, and reductions in the number of components in various grouped categories is reflected in the data of Table 3.

7.3. O&M of Floating Wind Turbines

There is limited industry experience of floating offshore wind (FOW) technology with only 73 MW operational [43] but with much market growth expected. Crown Estate Scotland in January 2022 leased seabed options for approximately 16 GW of FOW. Inwater depth > 50m, the use of conventional major component replacement vessels will not be viable [44]. New solutions include floating-to-floating transfer, floating cranes, self-hoisting equipment and tow-to-shore [45]. The tow-to-shore strategy is the most favoured primarily using readily available, inexpensive tugboats and anchor handling vessels. However, longer weather windows of several days may be required for the disconnection and transit phases of the operation. The disconnection process of the mooring and electrical system considered sound in theory has yet to be tried in practice and allocated time and cost. There are also concerns regarding the availability of ports which could support such operations. In the VAWT MRS concept proposed, the system would never be returned to shore for any RNA failure. This reduces the requirement for long periods of access, which may be especially problematic with exploitation of sites further from shore with more challenging environmental conditions. For new 16 MW plus single turbines, the tow-to-shore strategy will be a lengthy process resulting in significantly large downtime.

7.4. Results

Wind farms ~ 1GW total rating single are compared as composed of 16 MW single turbines (represented by upscaling the IEA 15 MW wind turbine) and as composed of HAWT and VAWT MRS of 48MW rating.. Maintenance activities were conducted by a fleet of SOV (Service Operation Vessel) and/or SWATH (Small Waterplane Area Twin Hull) vessels.

Table 4. TRIOS OPEX Model simulation results

		VMRS	HAWT	HMRS
Annual Average	Energy Generated (MWh)	**4.91E+06**	4.71E+06	4.37E+06
	Energy Lost (MWh)	**2.01E+05**	3.00E+05	1.02E+06
	Revenue Generated (£)	**£196,463,006**	£188,279,283	£174,604,371
	Lost Revenue (£)	**£8,036,340**	£12,001,453	£40,780,819
	Capacity factor (%)	**58%**	56%	52%

Due to the small rotor size and built-in redundancy an MRS with many rotors, the criticality of immediate repair is eliminated. Single rotor faults compromise only a few percent of total output and none whatever if in some cases, redundant components can automatically take over to restore functionality. This has allowed a failure threshold to be introduced where transfer is only required when a predetermined number of failures has occurred. Accounting for the differing unit capacities of single turbine (16 MW), HAWT MRS (0.5 MW) and VAWT MRS (2MW, considering 4 0.5 MW units have a common generator) the modelling considered failures before visit of, 1, 10 and 2 for single HAWT, HAWT MRS and VAWT MRS respectively. The VAWT MRS (Table 4) is the best performing technology with respect to all metrics.

Despite the smaller rotor size and ability to implement a threshold, the HMRS experiences resource utilisation issues. With 96 rotors the HAWT MRS requires an impracticably large sized team and fleet to operate. The VMRS overcomes these issues due to its smaller number of rotors (24) and therefore reduced components requiring repair. This proved to be much more manageable with a fleet of only 3 vessels being required to maintain high availability for the site.

The VMRS is able to make use of the small rotors and batched failures, without becoming overwhelmed by the need for high resources for operation. Simulations show an impressive availability of 97%, which is very competitive against current turbines. It is recommended that the group/batch maintenance approach is taken for this concept as, while it takes a small hit in availability, this is outweighed by the reduction of the strain on staff and vessels, while also saving on vessel expenses such as fuel consumption.

8. Discussion and conclusions

It seems likely that in the MRS configuration, if not otherwise, the H type VAWT may match the power performance of large HAWTs. Outline structure design based on previous design experience of MRS structures does not flag any particularly problematic areas. Standardisation of RNA systems, and structure cells offers benefits in overall production cost and reliability beyond those associated with scaling. The drive train (shaft, bearings, brakes generators) are low torque aggregating to less than 20% that of competing large HAWTs leading to large savings in first cost, characteristic of MRS systems. However, coupling long shafts together leads to a torsionally-soft system and may leave concern about control response as yet unexplored although the torsional wind-up can be halved by having generators at mid-level. A check on floater design suggests the system should not be disadvantaged in mass and cost relative to its power rating. Recent studies have suggested that MRS with very many rotors can become problematic for O&M manpower and vessel resources and that O&M may be the most critical area for viability of the MRS concept, at least in systems with very many rotors (> 40). The present analysis highlights the likely benefits to O&M of the VAWT MRS concept in eliminating some reliability critical components and having generally simpler and fewer components than HAWTs.

The MRS is well suited to hydrogen production [46] on site providing a large platform for the electrolyser, compressors and other necessary equipment. For electricity production, a low rated wind speed and low power density (332 W/m^2 for the IEA 15 MW design) minimises cost of energy considering the high electrical costs between each turbine output terminals and the land based grid. If production for hydrogen is on site and de-coupled from short term electricity demand, then the same total energy can be produced with a higher rated power but smaller turbines reducing the overall frontal area of an array such as in Figure 1 by ~40% and thereby much reducing system cost.

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