Opportunity for Vertical Axis Wind Turbines in Floating Offshore Wind

Prepared on behalf of Scottish Enterprise

June 2021

The Consortia:

This publication and its contents have been produced for Scottish Enterprise by the Consortia to explore the opportunity for Vertical Axis Wind Turbines within the Floating Offshore Wind Market. The Consortia consist of four parties: NSRI, Subsea UK, University of Strathclyde and Wood; offering an informed, in–depth understanding of the offshore industry, research, the supply chain and wider industry bodies.

No party has direct interests with a turbine supplier meaning the study is considered impartial for the benefit of industry. The Consortia are industry agnostic, therefore, in a position to provide a learned experience across the marine and offshore industry.

The publication and its contents are provided on an 'as is' basis. All warranties as to the accuracy of the publication and all liability in connection with the use of the information or expressions of opinion contained in this publication are excluded.

This publication will inform on the status and potential to promote consideration of developing VAWT technology for industrial application. The report should not be considered as professional advice, nor acted upon without further review.

We hope you find this publication interesting and informative.

Acknowledgements:

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Executive Summary

NSRI, Subsea UK, the University of Strathclyde and Wood explore the reasons why Vertical Axis Wind Turbines (VAWT) are not being assessed for use in the Floating Offshore Wind sector. The Consortia bring an impartial and independent perspective, along with a strong legacy in offshore industries. There is an opportunity for Scotland to play a significant role in Floating Offshore Wind, particularly if an alternative turbine technology can be developed and industrialised capable of increasing the UK supply chain content beyond 60%.

This report explores the potential for disruptive Vertical Axis Wind Turbine technology to be utilised in the expanding floating wind market. In doing so, the potential to develop an industrial sector in Scotland, building on a strong legacy in engineering and offshore engineering and the large domestic market, with global reach. A recent study (1) indicated that the Scottish content in wind farm development is 18% of lifecycle expenditure and the UK content is 48%. VAWT technology would have the capability to push this beyond 60%.

Hitherto, the vast majority of onshore wind turbines and, all but a few offshore pilot projects, have been of the familiar 3-bladed Horizontal Axis Wind Turbines (HAWT) configuration. The technology is well understood, there is an established industrial supply chain and developers are comfortable in its application, particularly to offshore fixed bottom systems. Application further offshore in deeper water is still in its infancy with recent Hywind and Kincardine pilot projects. It is in this application that the report considers VAWT may offer some strategic advantages.

- Increased reliability through reduced mechanical complexity and increased with no requirement for turbine yaw and blade pitch mechanisms and potential to remove the drive train gearbox.
- Reduced host structure size, through the VAWT's lower Centre of Gravity (COG) and the reduction in transmitted thrust force.
- Improved assembly, installation and O&M, with the drive train and major electrical systems at lower levels rather than in the top of the tower nacelle.

The report takes the form of a techno-economic review to consider three key questions to determine the potential of the concept and whether any further supporting activity is merited.

Is the concept of VAWT in FOW application technically feasible?

Is the concept of VAWT in a FOW application commercially viable at scale?

Is there an economic case for industrial investment?

(1) BVGA, *UK and Scottish content baseline and roadmap*, April 2021

Is the concept of VAWT in a FOW application technically feasible?

VAWT is not an entirely new technology, systems do exist, primarily onshore, and by comparison to HAWT systems are notably smaller in capacity, size and number. HAWT systems are well proven and there are currently over 2000 units in Northern European waters ranging from 1-10MW. VAWT, by comparison, has only trialled a handful of demonstrator units offshore, and all are less than 1MW.

The commonly understood disadvantage of VAWT is its lower aerodynamic efficiency compared to HAWT (i.e. the ability to convert wind energy into mechanical (kinetic) energy in similar free stream conditions). However, this measure does not translate directly into a difference in Annual Energy Production (AEP) for a single turbine or a full wind farm which will be impacted by reliability, availability and uptime. In these areas, the study has identified that VAWT may offer significant advantages which more than balance the reduced aerodynamic efficiency. These areas require further investigation to fully understand the power generation capability and gains in mechanical reliability due to less complexity.

VAWT technology is considerably less mature than HAWT technology. While the latter has converged on the 3 bladed design with the mechanical and electrical machinery located in a nacelle at the top of a support tower, VAWT continues to explore a number of configurations. VAWT systems offshore have been limited to small pilot systems. There is no doubt to accelerate the development of VAWT technology to match HAWT systems does represent a considerable challenge, not least due to the lack of an established configuration.

A methodological approach was undertaken to assess the Technical Readiness Level (TRL) of the turbine and structure components in the integrated system from seabed to turbine tip. The review concluded that the application of VAWT technology was technically feasible. Much of the HAWT turbine equipment including generators, control systems and drive trains, could be adaptable and transferrable to VAWT; which would considerably shorten the timescale to deployment readiness. Components unique to VAWT such as bearings, brakes and power take-off do have industrial analogues so technology transfer will be possible although the development timescale will be longer. There is no discernible difference in the design options for floating structure systems (including mooring and anchoring) between HAWT and VAWT, with many technologies already field proven in the oil and gas industry. At field–level the support structures, array cables and operating methods will be broadly similar between VAWT and HAWT concepts.

To deliver a deployment ready VAWT alternative for floating wind will require technology acceleration. It will require a collaboration between academia, industry and government to establish the size of the prize, the preferred configurations, the transferrable technologies and incentivising technology developers. The study has identified ten key technical areas for further investigation to prime this activity grouped under the headings of Digital Simulation, Mechanical Design and Electrical Efficiency.

Is the VAWT concept in floating offshore wind application commercially viable at scale?

Offshore wind has grown significantly in the past decade and globally (fixed and floating) is projected to reach up to 1,000GW of installed capacity by 2050, currently UK has 10GW installed. Floating Offshore Wind is currently more expensive than offshore fixed bottom wind, but is projected to be similar by 2030 as outlined in ORE Catapult studies.

This review reviewed the economic differences between HAWT and VAWT concepts. Breakdown analysis showed that for a typical 500MW floating HAWT development 1/3 of capital cost is associated with the turbine, nacelle & blades, 1/3 with the structure and the remainder with cables, substations and development costs. Savings are likely achievable in the cost of structure as the tonnage reduces (analysis undertaken by Wood identified that the support structure tonnage for VAWTs could be reduced in sizeby 15% for semi-submersibles and 30% for SPAR designs). Cables and substations costs would be similar between the concepts, with some potential to reduce the cost of cable arrays with closer packing of the turbines. They key difference between the turbine costs is very difficult to establish given the difference in maturity of the concepts. It is considered, that the turbine costs are likely to be commensurate, fundamentally the components are broadly similar, removal of mechanical systems such as yaw and blade pitch are likely offset by braking and bearing equipment. The blades could be of a simpler design and have easier manufacture but require a support structure arrangement. The potential savings on IRM; mechanical simpler and easier access and installation and hook-up; smaller structures, lower centre of gravity were not considered to be sufficiently material to be included at this level of analysis.

At the level of detailed studied, the Consortia concluded the costs would be comparable between concepts, however a more detailed assessment is recommended. In addition to a more detailed review of particularly the turbine costs it is recommended that modelling of the economies of scale is conducted. HAWT having an established supply chain has already achieved many of these economies with which a putative VAWT industrial sector would need to compete.

Does the VAWT industrial potential provide an economic case for intervention and investment?

Reflecting on the above the table reflects on captures the major technical and commercial issues with VAWT in the context of floating offshore wind for 'current' (strengths and weaknesses) and 'future' (opportunities and threats) views. A similar analysis for HAWT is contained in the document.

VAWT in Floating Offshore Wind Context

Strengths

- Smaller structures potentially possible
- Easier personnel access to turbine (offshore)
- At field level majority of infrastructure is similar to HAWT (cables, moorings, etc)

Weaknesses

- Very few offshore prototypes
- Prototypes onshore or offshore at significantly lower power rating
- No existing (or very small) supply chain
- Poorer aerodynamic efficiency in steady-state conditions
- Low TRL for some key components
- Research legacy has not progressed concept, no real convergence on design choice

Opportunities

- Strong demand forecast, UK & global transposes to increased Scottish GVA
- Potential for increased reliability and in-field annual energy produced (AEP)
- Potential for higher power density
- Knowledge transfer from HAWT, O&G and other marine sectors
- First mover advantage for turbine manufacturer if concept successfully matured

Threats

- Needs considerable investment to mature concept
- Considerable technical & business risk on ability to mature concept to commerciality
- Needs to displace or work alongside incumbent HAWT market providers
- Technical show-stoppers not yet identified
- Cost base to be fully developed

The Scottish and UK governments have strong growth targets for offshore wind. The low, medium and high growth scenarios developed by the Offshore Renewable Energy Catapult (OREC) have been used in the study to estimate the Gross Value Add (GVA) of citing a VAWT system manufacturing and assembly cluster in Scotland. The basis for the scenarios is that VAWT technology could be applied to 25% of the projected cumulative capacity, ostensibly the three main suppliers (Siemens Gamesa, GE and Vestas) get 75% leaving 25% for a fourth (VAWT) manufacturer. The low and high scenarios are sensitivities around the medium growth scenario.

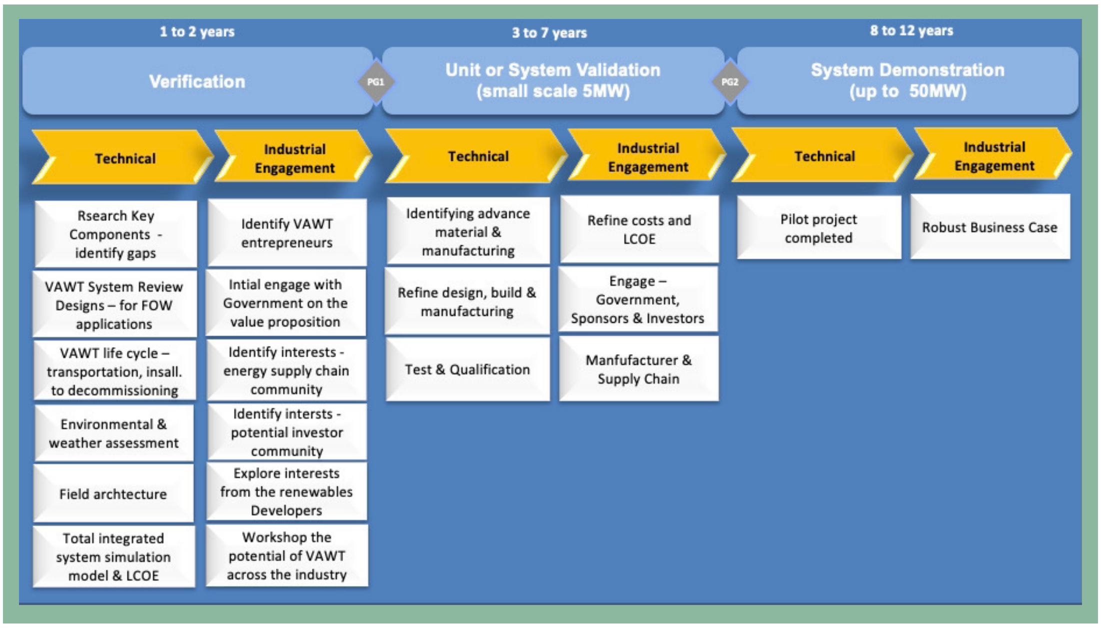
	Low Growth	Medium Growth	High Growth
Cumulative VAWT development by 2050	6GW	10GW	27GW
No. of VAWT turbines (assume 15MW)	400 Units	667 Units	1800 Units
Gross Value Add (£bn present value)	£2.11bn	£3.75bn	£8.35bn

The economic assessment clearly highlights that the opportunity for a fourth turbine system (including electrical and mechanical systems) supplier is significant, both within the UK and international market. Securing a manufacturer significantly increases local economic growth. Whether that capacity focuses on HAWT, given it is the proven accepted design in onshore and shallow water applications, or selects VAWTs which may be more suited for deep water application is open to debate but there is a clear economic incentive to pursue floating offshore wind. VAWT may be considered a higher investment risk than HAWT, however if successful the return would be considerably higher with first mover advantage consolidating market-share and opening up significant export opportunities.

	Influencers	Blockers
Political	• Increase local content • Increase export opportunity • Build upon industrial strategy – high value manufacturing and employment • Potentially Scotland being an industrial leader • Flagship green investment	• Low territorial position no in-country FOW manufacturing / assembly • Other countries exploring VAWT for FOW • Declining manufacturing sector
Economic	• FOW demand exists & growing • LCOE comparable once proven • Scottish / UK prize if first movers • O & G entrants – Operator & Supply Chain • Investor community highly focused on green energy	• Incumbent turbine manufacturers low incentive to change • High development investment • Investment outcome uncertainty • Clear prize for wind developers
Social	• O & G transition skills & offshore experience • If VAWT successful significant high value jobs and manufacturing base • Safety and environmental benefits	• Limited expertise to champion VAWT • Requires a change to adopt new technology • Societal adoption of new technology
Technical	• Engaged international research & development • Build on analogues and O&G success • Reduced size / cost of structures	• Key components at very low TRL • No single adopted VAWT design • History of not getting beyond demonstrator stage • Disruptive technology being adopted

Scotland has the opportunity to be a market leader in floating offshore wind hosting a Centre of Excellence, which would not be a single physical facility, but more of a 'hub and spoke' model bringing together key aspects spread across Scotland from ports, research, advanced simulation, manufacturing, assembly and testing. This strategic vision will deliver high-value green jobs, however there are many considerations to be addressed as discussed in the report, to that end the following actions offer a structured plan.

The proposed way forward takes a three phased systematic approach that offers phase gates to make informed decisions both with respect to technology and industrial engagement, thereby de-risking any investment. The three phases of 'Verification', 'Unit and System Validation' and 'System Demonstration' enables a logical technical and commercial readiness level to be continuously assessed. It is important that both the Technical Readiness Level (TRL) and Commercial Readiness Level (CRL) run in parallel, thereby enabling and facilitating the opportunity; this approach will assist not only in accelerating the opportunity, but also provide appropriate investment decisions.



The outcome of this study suggests there is an opportunity for a fourth turbine manufacturer in Scotland and for VAWT to be explored further, developing robustness to the key areas with engagement from industry and investors. This study has highlighted the potential for VAWT and for Scotland to create a paradigm shift for floating offshore wind, both in the UK and internationally. The timeline for achieving commercialisation by 2035 will require focus both technically and within industry, therefore it should be considered critical to progress the next phase.

1 Introduction

1.1 Background

Study Participants

NSRI, over the last 2 years, have been exploring reasons why Vertical Axis Wind Turbines (VAWT) could be assessed for use in the floating wind sector and whether this presents an opportunity for a disruptive new turbine design to enter this emerging market. The development of VAWT's may offer an opportunity for the Scottish supply chain to be a supplier of turbines. NSRI, working for the benefit of industry, are truly impartial and have been working with the University of Strathclyde and Wood to assess the opportunity. NSRI brings a balance of in–depth technical and commercialisation knowledge, and as the technology arm of Subsea UK, works closely with industry.

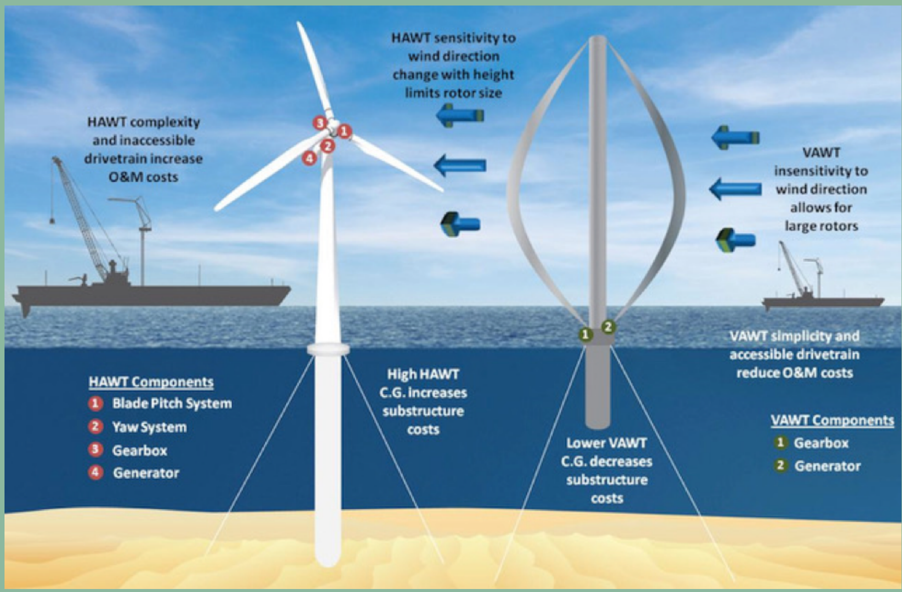
The University of Strathclyde have been engaged in research, studies and tests, exploring the various types of VAWT and their potential for Floating Offshore Wind. This work, some of which was completed ten years previously, was notably ahead of the market and struggled to gain traction. Wood, as specialist engineers, with extensive experience in industrial dynamic modelling with floating structures and their mooring, bring an integrated systems approach from seabed to the turbine tip.

The relationship between the parties, bringing together a supply chain trade body, industry engineering expertise and academic research as a single collaborative entity creates something that is well placed to consider VAWT from an integrated technology, business and economic standpoint. Building upon previous work NSRI, as the Consortia leader, approached Scottish Enterprise to perform a high level screening study as a first stage to explore the application of VAWT. The proposed outcome would be to establish feasibility and to identify the key areas of focus, both technically and commercially, for any further work. The participants believe that the development of VAWTs may offer an opportunity for the Scottish supply chain to be a supplier of turbines and increase the UK supply chain content beyond 60%.

Offshore Wind

Wind turbines generate electricity by converting kinetic energy from wind motion. Two alternative configurations are possible and have been utilised: vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT) - see Figure 1. Both have their advantages and disadvantages, with HAWT dominating the onshore and offshore fixed wind applications. In offshore fixed wind applications the HAWT generators are located at the top of the towers one hundred metres plus above the sea, introducing difficulties to install, operate and maintain. The support structure for a wind turbine must not only support the weight of the topside assembly but the thrust motions associated with the turbine. In the concept of Floating Offshore Wind (FOW) the large overturning (capsize) forces demands substantial hull structures. Certain VAWT configurations can reduce overturning potentially realising significant optimisation in the hull form.

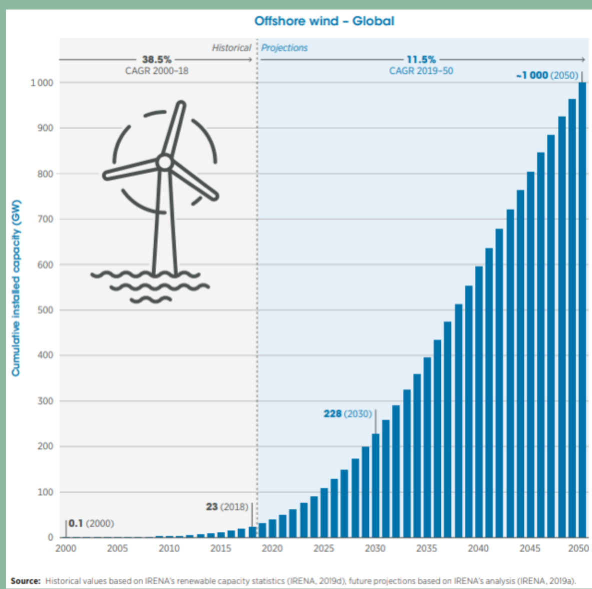
Figure 1 - Differences between HAWT& VAWT



As Figure 2 shows, offshore wind has grown rapidly in the last decade and is projected to achieve a global deployment of nearly 1000GW of installed capacity by 2050. This figure includes both shallow water and deep water, however, it is generally recognised that deeper water will maximise the opportunity in harvesting offshore wind. Deeper than 50m will economically require the wind turbines to be installed on floating structures which will be exposed to harsher environments.

Floating Offshore Wind is still in its infancy, although over the last 5 years it has gained significant momentum as pilot demonstrator projects are being trialled. These pilot projects have all used HAWT technology and marine structures based on those used for oil and gas. This is in somewhat akin to the initial oil and gas developments in the North Sea where fixed platforms based on Gulf of Mexico designs were deployed to be later supplanted by floating platforms and subsea wells which were better technically, economically and environmentally suited to the local conditions. The offshore marine sector offers a significant amount of hard experience from other industries such as oil and gas, where increased focus on technology, process and learning contributed to enhancing safe and profitable operations. With the advent of net zero, the oil and gas industry is focused on diversifying its business activities into renewable energies and during the course of this study a number of companies have approached NSRI.

Figure 2 - Offshore Wind Global Growth Prediction



With a strong legacy in offshore industries, there is an opportunity for Scotland to play a significant role in floating offshore wind, particularly if an alternative turbine technology can be developed and industrialised. Disruptive technologies may carry a high risk, however equally so they offer potential higher valued returns with respect to increased jobs in high-value manufacturing and high-tech innovation.

1.2 Turbine opportunity

In the 1980s the two fundamental wind turbine technologies HAWT and VAWT co-existed, with both offering turbines capable of generating around 1MW power. Incentivised by visionary policies and pricing structures, the Danish government targeted wind energy as a key source of renewable energy, this lead to the Danish inventor Henrick Stiedal pioneering designs based on 3 bladed HAWT designs, which were subsequently licensed to Vesta Wind Systems A/S and Bonus Energy (later acquired by Siemens). 3 bladed HAWT designs were deployed in the first offshore wind farm (Vindeby in 1991) and since then turbine manufacturers have developed and up-scaled their designs. To date, offshore wind developments have been predominately in shallow water where water depths are less than 50m with structures fixed to the seabed and relatively near to shore. Over three decades there have been significant learnings particularly around offshore installation, operational uptime and reliability, inspection, and access.

Many of the learnings are still to be applied, as the full life cycle of development, operation and decommissioning continues to mature and find a balance of cost efficiency and sustainability.

Progressing HAWT in a floating offshore wind context will introduce additional challenges due to the increase in support structure size and weight, in addition to accessing to the drive train nacelle high above the sea level. This will be further magnified as HAWT turbines further increase in size.

Developing VAWT technology may offer significant advantages for floating offshore wind. The drive system is located closer to the support structure base and could lead to smaller support structures being required. Further to this, VAWT may have a broader wind envelope to be operational and consideration should be given to power performance within the wind farm application beyond pure efficiency of the turbine aerodynamics.

Despite the dominance of HAWT and its established supply chain, VAWT technology continues to be pursued for both onshore and offshore applications, with manufacturers serving onshore VAWT markets in USA, Canada, Europe and Asia. There have been a number of offshore demonstrator VAWT projects performed at lower power ratings including Deepwind, Vertiwind, Skwid (tank test) and SeaTwirl, with the latter planning a 2MW pilot to be installed in 2022, as part of an Interreg programme (European Funded). Additionally, interest is growing in America with the US Department of Energy commissioning research programmes via Sandia Laboratories.

1.3 The study

Floating offshore wind presents a unique opportunity for VAWT concepts to be re-considered. The economic benefits are considerable if a Scottish technology developer could commercialise VAWT for floating offshore wind applications on a large scale. As part of Scotland's focus on maximising the economic opportunity of a transition to net zero emissions, Scottish Enterprise has commissioned the Consortia to perform an objective, high-level techno-economic review of the VAWT opportunity in floating offshore wind applications. The Consortia members bring together a strong cross-section of experience: University of Strathclyde's previous research, Wood's offshore marine engineering expertise and Subsea UK and NSRI's strong network across the Blue Economy, along with business assessment. With no allegiances to the turbine manufacturing community nor the developers, the Consortia is uniquely positioned to provide an informed, impartial and independent opportunity assessment.

The question is, can a 'disruptive' Vertical Axis Wind Turbine offer an alternative to Floating Offshore Wind Horizontal Axis Wind Turbines?

The objective of the techno-economic review is to respond to the following three key questions to determine whether a further, more detailed investigation is merited. The study will draw from publicly available resources and the experience of the Consortia members. By addressing these three questions, the Consortia will provide evidence to Scottish Enterprise to enable an informed decision on a potential second phase.

Is the concept of VAWT in a floating offshore wind application technically feasible?

Is the concept of VAWT in a floating offshore wind application commercially viable at scale?

Is there an economic case for industrial investment?

1.4 Methodology

TECHNICAL	COST	ECONOMIC	INDUSTRIAL
• Literature review of previous research and current technology • Comparison of HAWT and VAWT	• Data gathering of public domain information • Cost comparisons for HAWT and VAWT	• Floating offshore wind market review • GVA projections for Scotland	• Outline industrial engagement opportunities • High level review of potential supply chain organisations

Technical Feasibility

Turbines – An assessment of the technical challenges facing both VAWT and HAWT design concepts to generate power effectively indicates where further work is required to mature the VAWT concept and provides an indicative timeline.

Structures – A review of the technology is provided and indicative sizing analysis performed to quantify the relative difference in size of support structures in HAWT and VAWT applications.

A review of previous VAWT research and pilot projects to highlight current technology and provide a grounding for the study is also provided.

Commercial Viability

Using public domain details for FOW (HAWT), a review is conducted to compare the development and operating costs between HAWT and VAWT systems.

Economics

Using public domain market forecasts for offshore wind and a methodology supported by Scottish Enterprise personnel, economic scenarios to estimate the Gross Value Added (GVA) are prepared to demonstrate economic potential.

Industrial

A brief industrial engagement strategy is also presented to highlight the potential for Scottish industry.

This Techno-economic review employs a systematic approach with key milestones enabling working groups to focus on core expertise to bring recommendations to the whole team, drawing upon collective decisions as a collegiate team and ensuring a balanced perspective. This experience draws upon both Technical Readiness Level and Commercial Readiness Level elements, within the wider offshore and marine sector.

The review is based on public domain information and specific subject matter analysis, adopting a similar structure and methodology applied across other renewable industry assessment studies, within both fixed bottom and floating offshore wind applications.

Note: As there is a very limited data-set for floating offshore wind projects, the costing assumptions for the turbine were based on public information for fixed bottom application as a benchmark. An LCOE model approach was considered, however, upon assessment of a range of published figures there was significant inconsistency across the main sub–systems level costs. The Consortia concluded not to bench–mark on LCOE, instead focusing on cost differences of the structures and turbines, as these figures could be 'fair and reasonable' and well understood by the team. LCOE should be considered in a more detailed study.

The Technology Assessment uses the Technical Readiness Level (TRL) scale as a bench-mark, as TRL is used universally for technology assessment across many industry sectors. As much as the TRL process can be subject to judgement, for the purpose of this high-level screening it is considered appropriate by the consortia.

- The subsea structure analysis and associated costing was led by Wood and supported by the University of Strathclyde and NSRI. Wood used a costing model drawing upon industry figures.
- The turbine analysis and system review was led by the University of Strathclyde and supported by Wood and NSRI.

The Economic Impact Assessment reflects on the economic potential, reviewing the market trends, analysing the macroeconomics opportunity to estimate the range of GVA and the economic potential.

- This section was led by NSRI and peer reviewed by Subsea UK.
- The macroeconomics was performed in-line with the UK Government Green Book and Scottish Enterprise Guidelines. The macroeconomics was performed by NSRI and subsequently peer reviewed by Scottish Enterprise's economic analyst.

The Industrial Engagement Consideration was led by NSRI and Subsea UK providing an appreciation of the opportunity in the wider marine and offshore sector, reflecting upon the key findings and how these could be applied, along with potential way forward and relative timelines.

2
Technical Assessment

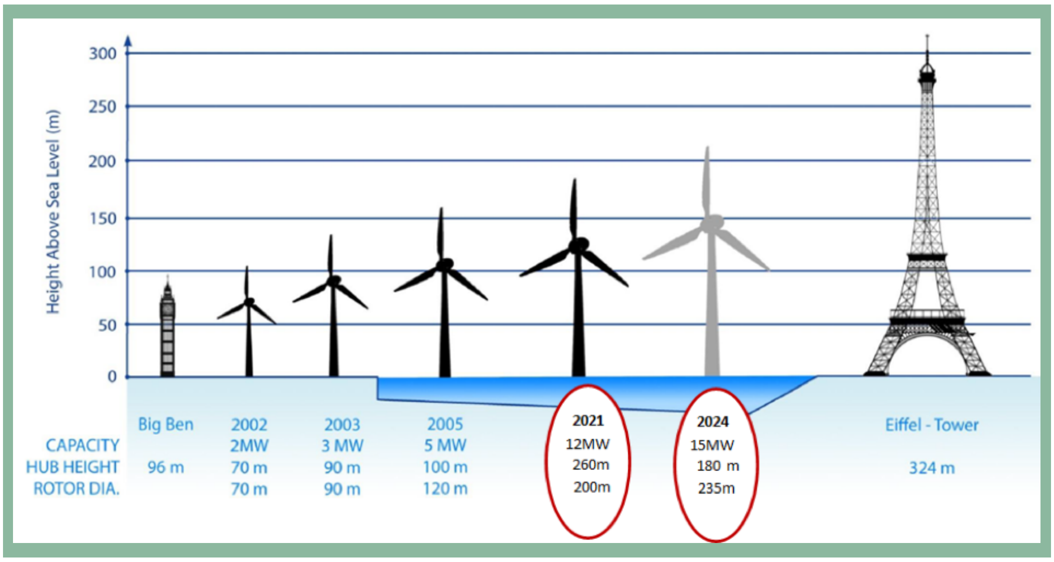
2.1 Introduction

Refer to appendices 6.1 and 6.2 respectively for the University of Strathclyde and Wood reports.

Vertical Axis Wind Turbines (VAWT) and Horizontal Axis Wind Turbines (HAWT) have been used throughout history for harvesting wind energy. Whilst relatively low-powered, VAWTs are not uncommon in small-scale urban or domestic supply settings where capital investment is limited and the wind supply variable. Whereas HAWTs operate more successfully in environments with steadier wind supplies which is why they tend to be located in remote, isolated areas. In the 1980s the capabilities of the technologies were comparable, however, HAWT has become the dominant technology and up-scaled its capacity and capability.

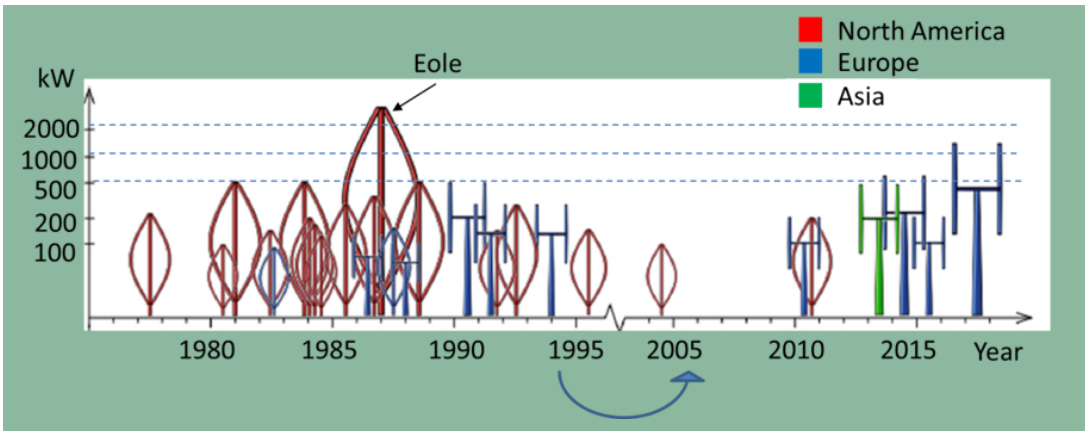
During the recent rapid expansion of both onshore and offshore wind, the three bladed HAWT configuration with the nacelle and drive train supported by a vertical tower has evolved to dominate the market. Within excess of 2000 offshore HAWT units deployed in North European waters, the size of these systems has steadily increased from 0.5MW with the latest installations around 10MW and 15MW. By default, HAWT has become the design of choice for the first generation of floating systems.

Figure 3 - Evolution of HAWT Size



VAWT, by contrast, has developed slowly, onshore systems rarely exceed 2MW and convergence is still required to determine optimal drive train, location and blade shape ('straight' H-blades or curved Darrieus type as illustrated in Figure 4 below).

Figure 4 - Timeline of VAWT Development



Source: Mollerstrom et al., *A historical review of vertical axis wind turbines rated 100 kW and above* (RSER, 2019)

Attempts to use VAWT configurations for offshore applications has not progressed beyond a handful of demonstration projects as summarised in Table 1. Current manufacturers of onshore VAWTS tend to target domestic or small industrial users with turbines offering 30-60 kW such as 4navitas (UK), ArboWind (Canada) and Gual StatoEolian (France).

Table 1 - VAWT Demonstration Projects

Year	Project	Demonstrator	System Target
2010	Nova (UK)	6KW (tank)	10MW
2011	Vertiwind (France)	35KW (offshore)	2MW
2014	Deepwind (Denmark)	1MW (offshore)	6MW
2015	Seatwirl (Sweden)	30KW (offshore)	2MW

However, with the move to floating offshore wind farms in deeper water, interest in the technology may offer some strategic advantages, such as:

- Reduced mechanical complexity and increased reliability, with no requirement for turbine yaw and blade pitch mechanisms and potential to remove the drive train gearbox.
- Reduced host structure size, through the VAWT's lower Centre of Gravity (COG) and the reduction in transmitted thrust force.
- Reduced assembly, installation and O&M complication, with the drive train and major electrical systems at lower levels rather than in the top of the tower nacelle.

This technical screening review focused on the turbine and the support structure - items such as cable arrays and offshore substations would be similar for VAWT and HAWT concepts and have not been included. This review assesses the following aspects:

- Power Generation and Turbine system
- VAWT turbine technology status
- Floating structure review
- Complementary benefits
- SWOT and review analysis (VAWT versus HAWT)
- VAWT development areas

2.2 Power generation and turbine system

Table 2 summarises the findings of the technical review comparing the power generation attributed of HAWT and VAWT concepts.

Table 2 - HAWT versus VAWT Power Generation

Categories	Subcategory	Offshore HAWT	Offshore VAWT	Preference
Aerodynamic efficiency	Power coefficient	0.5	0.4	HAWT
	Power density	3-5 W'Km2	>10 W/km2	VAWT
	Directionality	Yaw control	Omnidirectional	VAWT
Structural integrity	Gravitational cycle loads	Yes	No	VAWT
	Cyclic thrust loading	No	Yes	HAWT
Reliability	Failure rate	Known	Up to 20% lower	VAWT
	Downtime	Known	Up to 20% lower	VAWT
Stability and dynamics	Centre of gravity (COG)	High	Low	VAWT
	Size of support structure	Known	15-30%	VAWT
	Gyroscopic effects	Low	High	HAWT
	Excitation frequencies	1	>1	HAWT

Aerodynamic Efficiency

The primary disadvantage of VAWT is its lower aerodynamic efficiency compared to HAWT. In full isolation and in open jet unidirectional free stream conditions, the power coefficient of HAWTs at 0.5 is typically higher than that of VAWTs at 0.4. Assuming the same swept area of the rotor and the same free stream velocity, HAWTs are able to convert more wind energy into mechanical energy. However, this measure may not translate directly into a difference in Annual Energy Production (AEP) for a single turbine or a full wind farm. To compensate for the reduced aerodynamic efficiency, the swept area of a VAWT H-rotor, and therefore its power output, can be adjusted by modifying either the height or the width of the turbine. Increasing the swept area of a VAWT would increase both weight and thrust, consequently requiring a larger host structure, however, as detailed in section 2.4, this could be negated by the reduction in overturning moment for a VAWT design.

In field conditions, HAWTs need to be isolated from each other to optimise their performance and negate downwind effects of wind turbulence, when placed in close proximity their power outage decreases significantly. Typical spacing for HAWTs is 8 diameters in the crosswind direction and 10 diameters in the downwind direction (2). Through simulated studies, wind tunnel tests and small-scale onshore trials it has been demonstrated that VAWTs by comparison benefit from being placed closer together, typically 3-4 diameters and in counter rotation to each other, to provide a 15% increase in output power when compared to units in isolation (3). The effect is to increase the potential power density of a wind farm from 2-3 Wm-2, for a HAWT wind farm, to one order of magnitude higher, for a VAWT wind farm over an equivalent area (4). Currently ocean real estate may not be a significant issue but the ability to reduce the footprint would lessen environmental impact, reduce infrastructure (shorter array cables), and reduce wind performance variability across the field area.

One of the major differences between HAWT and VAWT is the orientation of the rotor in relation to wind direction to extract power. A HAWT needs to yaw into the wind so that the blades are optimally placed to extract maximum power. A VAWT, by contrast, is omnidirectional and extracts the same power regardless of wind direction. The yaw system required to rotate the nacelle adds mechanical complexity and cost to the system and contributing to HAWT downtime. In addition to the requirement to yaw the full rotor, the blades need to pitch to maintain rotor rotation as the wind speed changes and to feather the blades to stall in excessive wind conditions. This system also contributes to HAWT downtime. VAWT does not have this issue, although rotational control and braking needs to be incorporated into VAWT designs which could introduce a cost and complexity component.

In onshore settings, VAWTs have proven to operate in very low wind conditions compared to HAWTs and, depending upon geographical location, this could translate to an important number of operationally available days and hence improved up-time.

(2) W. Musial, " "Offshore Wind Energy Facility,"," NREL, 2018

(3) Hansen JT Mahak M, Tzanakis I "Numerical modelling and optimisation of vertical axis wind turbine pairs: A scale up approach" Journal of Renewable Energy Vol 171 1371-1381, 2019

(4) J. O. Dabiri, "Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays," Journal of Renewable and Sustainable Energy, vol. 3, 2011.

Further work is required to compare the performance of VAWTs against HAWTs on a farm-scale basis. Simulation models, using computational fluid dynamics (CFD), have the advantage that once built they can run multiple scenarios and sensitivities to generate an operational envelope. Additionally, there is an opportunity to evaluate the kinetic energy conversion, through the system similar to what society has experienced with modern car engines delivering more torque with smaller engines; this may be an alternative to going bigger.

Structural Loading

The load paths in a HAWT design are well understood, as power, weight and size increase, the support structures will have to increase accordingly. VAWT designs may offer reductions in support structure size as the overturning moments are likely to be smaller by comparison, but to do so the systems will have to evolve to counter their differing loading response.

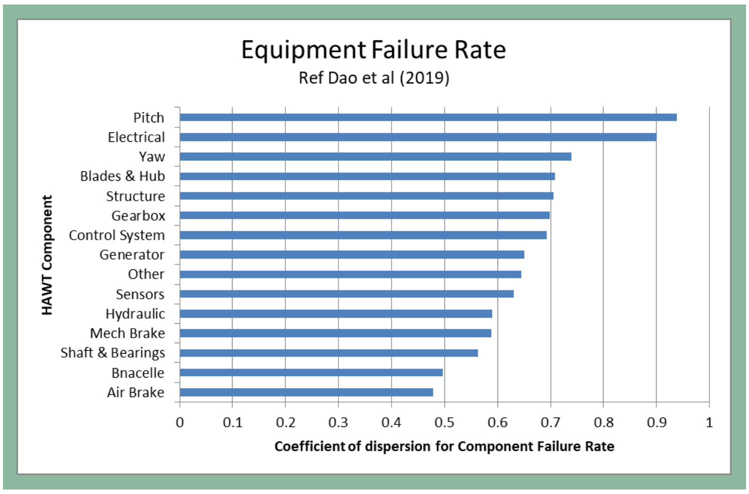
A potential issue in 2-bladed (H-rotor) VAWT designs is cyclic thrust loading, so called torque ripple. The blades incur two maximum peaks of thrust at 90 and 270 degrees of rotor azimuth where the blades are in line with the direction of the wind introducing structural fatigue risks. A number of solutions such as compliant couplings, bearing-less VAWTs and 3 blade configurations, have been offered to counter this effect, however, further investigation is required before a design optimum can be selected. HAWTs and VAWTs with 3-blade designs do not have this issue as there is always at least one blade 'active' into the wind.

With the increase in HAWT blade length and mass, gravitational loads are an important design consideration as they become a source of blade fatigue loading with peaks occurring in a cyclic fashion when the blade is in the horizontal position. This phenomena could become a limiting factor as HAWTs grow in size. VAWTs by comparison do not exhibit similar gravitational loadings due to the orientation of the blades and their line of action with respect to gravity.

Reliability

Figure 5 as detailed in appendix 6.1 outlines the distribution of downtime and failures for each component in the HAWT system as determined by Dao et al (2019) (6).

Figure 5 - Equipment Failure Rate



The gearbox, translating 'low' speed rotor rotation into high speed electrical generator, is a notable source of equipment failure and downtime. The arrangement within the VAWT system lends itself to direct drive and a permanent magnet generator that obviates the need for the gearbox. In VAWT, downtime due to pitch and yaw systems is eliminated because these systems are not needed. Additionally, downtime related to mechanical breaks and structure and blade failures is likely to be reduced substantially because blade fatigue loading cycles are reduced by about 50% due to the decreased rotational speeds of VAWTs.

The requirement for a turbine braking system for VAWT will introduce a downtime/failure risk given this component is not present in HAWT, although at this early stage of concept design it is not possible to attribute a value.

Removing the yaw and pitch items and halving the structural element could have the impact of reducing VAWT failure rates and downtime by up to 20% due to their reduced mechanical complexity when compared to HAWT although a consideration is required for the braking system's failure rate. Similar reliability improvements have been suggested by Sea Twirl (5) however this study has not investigated these claims.

Stability and Dynamics

One of the key differences of VAWT in comparison to HAWT, is a reduction in the size of a host structure due to redistribution of loading forces.

Lowered Turbine Centre of Mass

HAWT's centre of mass is effectively at the nacelle located at the top of the tower assembly. As HAWTs use larger blades, the impact of this effect becomes more pronounced. VAWTs provide an opportunity to place turbine equipment at a lower elevation, closer to the floating structure and in doing so, lower the total turbine centre of mass. This makes the floating structure more stable under similar thrust force loading.

Thrust Force Lever Arm

The thrust force generated by wind action on the turbine blades provides an overturning moment on the floating foundation. The overturning moment is directly proportional to the effective thrust force elevation, or lever arm from the point of rotation. For some VAWTs (H-rotor and curve-bladed Darrieus), the thrust force can be considered to act at the midpoint of the blade height. With comparable horizontal thrust forces this results in VAWTs providing a net reduced overturning moment.

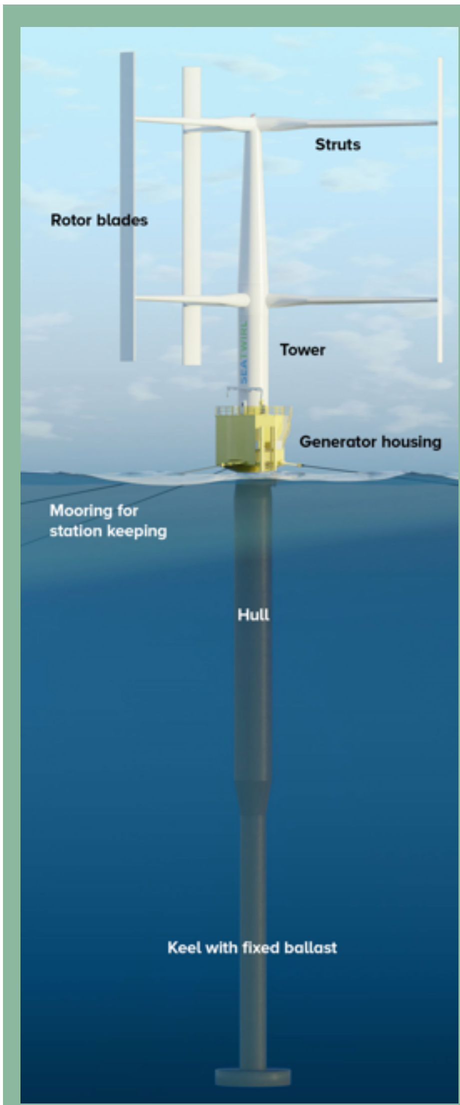
As turbine capacity increases the swept areas of the turbines must also increase. VAWT H-rotors can do this by increasing either width or blade height, the former mitigates against increasing the thrust force lever arm. However, HAWTs only design option is increasing length of the blade and having a taller tower with an ever-increasing overturning lever arm for the thrust force

(5) SEATWIRL. The future of offshore wind.," [Online]. Available: https://seatwirl.com/.
(6) C. Dao, B. Kazemtabrizi and C. Crabtree, "Wind turbine reliability data review and impacts on levelised cost of energy," Wind Energy, vol. 22, no. 1, pp. 1848-1871, 2019.

The downside of VAWT is that torsional loading from gyroscopic motion is transferred to the structure and in turn into the mooring system that holds the unit in place. As turbine size increases this load case could become critical. Further study is required to assess the dynamic loading and determine mitigation solutions.

The review suggests that the Annual Energy Produced (AEP) by a VAWT farm development could equal or exceed the AEP of a conventional HAWT development. Whilst the turbine efficiency is acknowledged to be better in HAWT, the opportunities in turbine placement and operating uptime may present a more effective proposition. Recent modelling is supportive of this assertion as detailed in appendix 6.7; indicating this topic requires further research.

Figure 6 -
VAWT Overview



2.3 VAWT technology review

Table 3 summarises the key findings of the turbine Technology Readiness Level (TRL) comparison between VAWT and HAWT in Floating Offshore Wind performed by the Consortia. For HAWT, the reference cases of the Hywind Scotland (7) and Hywind Tampen (8) are used. Both farms sites have HAWTs rated at 6MW and 8.8MW respectively, noting that Hywind Scotland is operational and Hywind Tampen is still under construction. Onshore VAWTs operate up to 2MW although demonstrators, rated above 1MW, have not been deployed offshore. SeaTwirl S2 is scheduled to install a 1MW demonstrator project in 2022 building on the 30kw experimental system which was installed in 2015 (9).

Table 3 - TRL Comparison HAWT and VAWT

Source: Subsea UK/NSRI/UoS/Wood 2021

System	Sub-Component	Floating HAWT		Floating VAWT	
		5MW	10-15MW	5MW	10-15MW
Nacelle and hub	Bedplate	8	7	6	6
	Main bearing	8	7	3	3
	Main shaft	8	7	6	6
	Gearbox	8	7	6	6
	Generator	8	7	6	6
	Power take-off	8	7	3	3
	Control system	8	7	3	3
	Yaw system	8	7	N/A	N/A
	Yaw bearing	8	7	N/A	N/A
	Brake	N/A	N/A	3	3
Blade	Blades	8	7	6	6
	Hub casting	8	7	6	6
	Blade bearings	8	7	6	6
	Pitch system	8	7	6	6
	Spinner	8	7	N/A	N/A
Tower	Tower	8	7	6	6
	Steel and internals	8	7	6	6
Full system	Turbine and floating structure	8	7	3	2

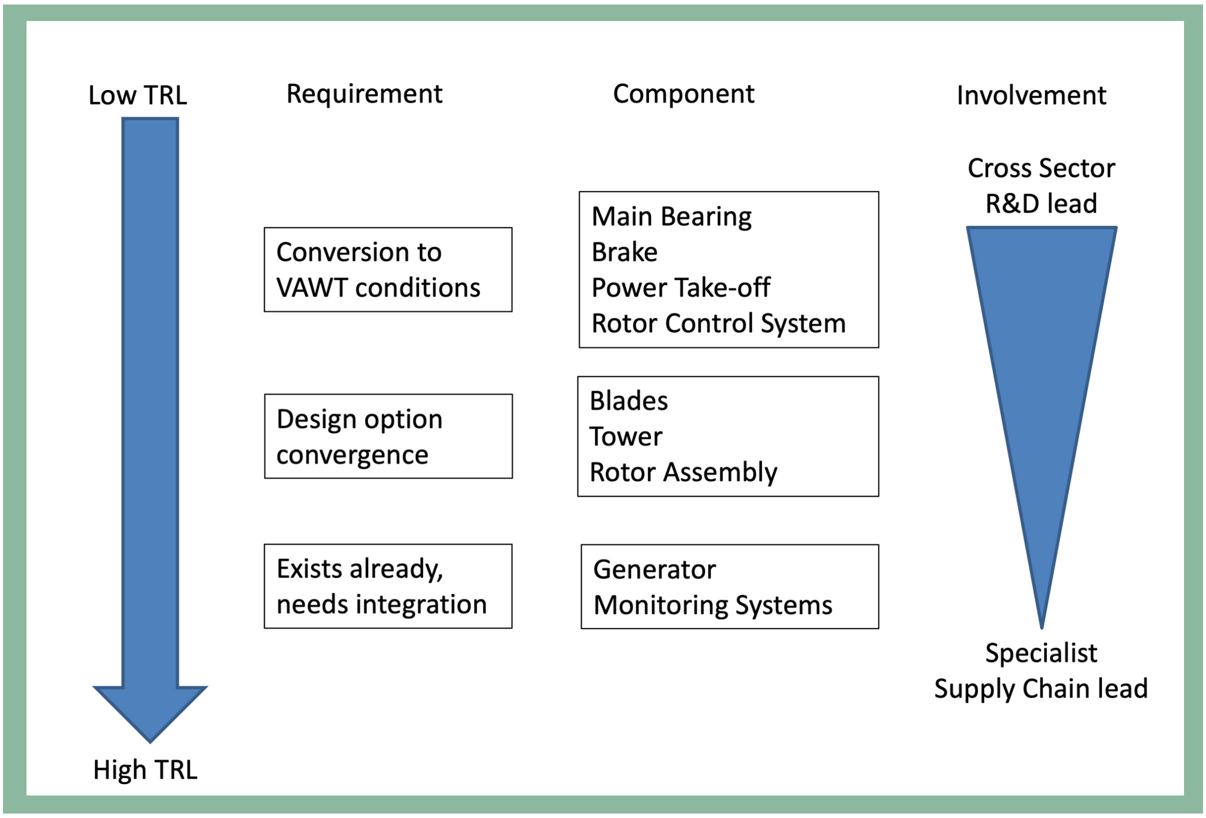
The technological maturity of VAWTs is lower than for the well-established HAWT design. The readiness of availability of HAWTs from the original equipment manufacturer (OEM) and field experience from fixed bottom offshore wind, drives the developers to select HAWTs to de-risk projects and attract finance. With VAWT systems still primarily at tank-testing stage many of the assemblies, sub-assemblies and components required in a VAWT are recognised to be at a lower Technology Readiness Level (TRL).

(7)"Hywind Scotland," Equinor, [Online]. Available: https://www.equinor.com/en/what-we-do/floating-wind/hywind-scotland.html
(8)"Hywind Tampen," Equinor, [Online]. Available: https://www.equinor.com/en/what-we-do/hywind-tampen.html
(9)"SeaTwirl - The future of offshore wind," SeaTwirl, [Online]. Available: https://seatwirl.com/

The review highlights where focus is required to mature VAWT technology and suggests that the items fall into three general categories as depicted in Figure 7.

Category 1 Technology concept selection
Category 2 Design Option convergence
Category 3 Exists Already, requires integration

Figure 7 - Technical Focus Area



Category 1

There are key components; bearings, power take-off, brake and rotor control system which will require considerable research and development to allow VAWT progression. These do not have a direct corollary with the components in HAWT and would need to be developed for large VAWT systems. While these are currently at a low TRL level, similar components developed for the onshore VAWT systems and the prototype floating VAWT systems exist so are considered to be beyond the concept phase.

Components that can be considered analogous have been matured in sectors that utilise high speed or low speed rotating equipment indicating that cross-sector transfer may be possible.

Brake – In HAWT systems the blades' pitch angle and yaw system can be varied to slow down the rotational speed to maintain operating design parameters or stop rotation in high wind conditions. VAWT systems with their advantage of omni-directionality need a braking system to regulate the rotational speed in differing wind conditions. Work will be required to develop a mechanical brake and associated rotary control systems into the design, or design-out the issue by introducing some form of blade angle control that exists in HAWT.

Main Bearing – Early VAWT systems suffered from fatigue failures of the main bearing under cyclic loading, as load and size increases fatigue will remain a key design case; however, systems design, material technology and greater industry awareness can inform new designs. Opportunity may now exist to study known concepts such as bearing-less solutions that could fast-track the process - given market pull now exists.

Power Take-Off – The power take-off adjusts the electrical energy from the generator to the required voltage and frequency for transfer to the sub-station consists of a convertor, switchgear, transformer and associated cabling. No systems exist for offshore VAWT, cross-over from onshore systems is required and then qualified to suit higher ratings required for offshore usage.

Category 2

Some of the components, such as the rotor assembly, tower and blades have not been built or tested at scale. They have the advantage that the technology principles are understood with strong cross-over opportunities from HAWT. To further the development of these components, design configurations need to be selected and full-scale demonstrators constructed.

Taking blades for example further work is required to evaluate and select an optimal design for

- configuration - curved, straight, H-rotor
- quantity - two or three
- material - strength & flexibility
- aerofoil shape – straight, linear, taper, parabolic

This will be a several stage development process but it is considered that technological uncertainty could be overcome in a reasonable timescale.

Category 3

Items such as the generator and monitoring system are well understood and there is no reason to suggest with an appropriate development programme that these could not be configured and qualified for use regardless of turbine type or orientation.

2.4 Floating structure review

Structures have evolved from the shallow water (<50m) being fixed to the seabed, where the development of deeper water requires to develop adopting floating structures. Floating structures are generally configured into one of three types; TLP (tension leg platform), Semi-Sub (semi-submersible), Spar (single point anchor reservoir), however, as the floating wind market opportunity is growing there are concept variants being developed addressing some of the challenges associated with harbour access, tow-out, installation, in-situ blade maintenance and repair.

Figure 8 below offers basic images of the structures, from shallow water progressing into deeper water and offers an indication of the comparative scale relative to a typical turbine; i.e., the majority of the structure is below the water.

Figure 8 - Offshore Structure Configurations

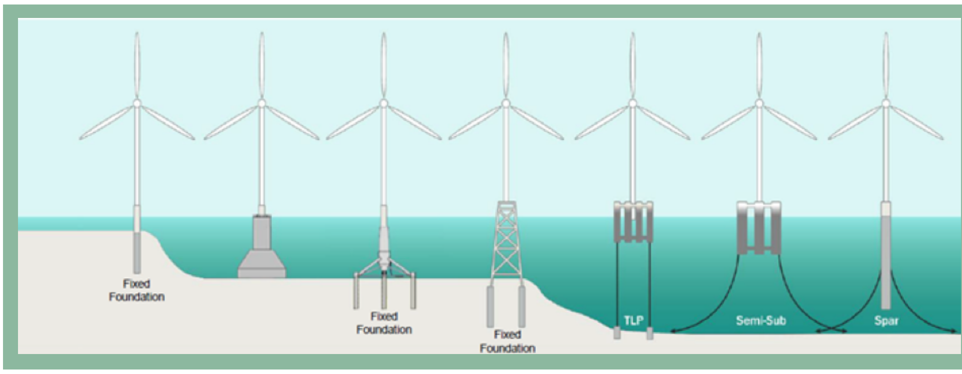
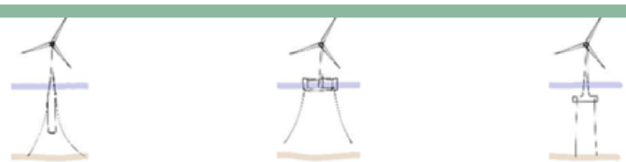


Figure 9 below offers a table of the high level considerations of the 3 types of structures.

Figure 9 - Floating Structure Considerations



	Spar	Floater	TLP
Stability	High. Counter weight with large draft	Good. Buoyancy stabilized structure with shallow draft	Tension restrained structure with relatively shallow draft
Motions	Limited	High – rides the waves	Very limited
Soil Sensitivity	Low (range of mooring anchor solutions)	Low (range of mooring anchor solutions)	High – significant vertical anchor loads
Transport and Assembly	Requires Deep Water (high draft requirements)	Quayside / Harbour	Bespoke

Figure 10 summarises the key findings of the floating structure Technology Readiness Level (TRL) comparison performed by the Consortia. TRL levels are presented for the underlying technology and its use in a number of Floating Offshore Wind scenarios considering 5MW and 10MW turbines for both HAWT and VAWT. TRL levels are judged considering a baseline of currently operational FOW developments, being Hywind Scotland, WindFloat Atlantic and Kincardine Offshore Wind Farm being at TRL 8. These are not considered as being fully proven at TRL 9 given the relatively short period for which they have been operational. Each subsystem technology is then rated at this level, or lower accordingly.

Figure 10 - TRL Comparison

Category	Item	TRL				
		Technology	5MW HAWT	10MW HAWT	5MW VAWT	10MW VAWT
Structure	Spar	9	8	7	6	6
	Semi-Submersible	9	8	7	5	5
	Barge	9	7	7	5	5
	TLP	9	4	4	3	3
Mooring	Catenary	9	8	8	6	6
	Semi-Taut	9	8	8	6	6
	Tension Leg	9	4	4	3	3
Anchor	Drag Embedded	9	8	8	6	6
	Suction Pile	9	8	8	6	6
	Driven Pile	9	6	6	6	6
	Gravity Base	9	4	4	3	3

Structure

In addition to SPAR, semi-submersible and tension leg platform, barge concepts have been included as a few designs are being developed. Within these four broad categories there are multiple different designs all seeking to reduce structure cost while maintaining operational efficiency. Semi-submersibles and SPAR structures are the furthest advanced in terms of TRL. A SPAR structure has been demonstrated at Hywind Scotland with a 6MW turbine. Semi-submersibles have been demonstrated at WindFloat Atlantic with an 8.4MW turbine. Some work is required to prove the designs for large turbines of 10MW capacity and greater. The SPAR is slightly ahead of semi-submersibles for VAWTs as there have been two concepts being built at scale demonstrator level – SeaTwirl S2 and Gwind. Further work is required to prove these are ready for demonstrator and commercial full scale wind turbines. **There is no reason to suggest that any host structure configuration which has been deployed by the oil and gas industry or for HAWT could not be used for VAWT. The TRL of the structure should therefore be considered similar to that of HAWT.**

Mooring

The main type of mooring systems are centenary, semi-taut and tension leg. Each of the three potential mooring systems and variants are fully qualified and proven. The additional requirement for VAWT is that each of the mooring categories will have to prove their ability to handle the additional consideration of torsional loading through both suitable mooring connector technologies at the hull and the system availability to provide yaw restoring force. **However, there is no reason to suggest that any mooring configuration employed by the oil and gas industry or for HAWT could not be used for VAWT.**

Anchoring

The anchor technology categories are: drag embedded, driven pile, suction pile and gravity base anchors are fully qualified and proven TRL 9 technologies. They are used extensively in a number of industries including in oil and gas for the anchoring of large floaters and smaller subsea structures. **It is considered that all systems developed for anchoring oil and gas structures or HAWT would be equally applicable to VAWT.**

Key findings:

A floating foundation comparative sizing assessment was performed to assess the potential for reductions in VAWTs compared to HAWTs. Details of calculation methodology and data inputs can be found in the Wood Appendix. The opportunity to lower the turbine centre of mass and, more importantly, the thrust lever arm and associated overturning moment under wind loading, enables a smaller structure that can provide similar levels of stability for the same size VAWT and HAWT, with the differential increasing with turbine size.

- **SPAR tonnage saving 31-35% (see table 5.5 in appendix 6.2)**
- **Semi-submersible tonnage saving 14-16% saving (see table 5.7 in appendix 6.2)**

This, in turn, has a consequential cost benefit to VAWT Floating Offshore Wind projects. Reducing the size of the floating structure also has the knock-on effect of reducing the required size of the mooring and anchoring system, as wave and current loadings reduce with the smaller structure size, drag, area and inertial loading.

2.5 Complementary benefits

A number of secondary benefits of using VAWTs for Floating Offshore Wind have been identified in the course of the review and a selection are highlighted below:

Construction, Integration and Installation

VAWT systems with lower centre of gravity and smaller host structure size offer the opportunity to expand the weather window for the offshore tow and installation activities. The smaller mooring and anchoring systems should enable greater flexibility in design and installation specification.

Blade Modularity and Transport

Transportation of long, thick shaped blades is a logistical issue for the transportation of HAWTs. VAWT blades would be a similar size and could be manufactured in segments that can be flat-packed, transported and assembled on site.

Operations and Maintenance

The reduction in mechanical complexity of the system directly reduces repair and maintenance effort of the turbine system. Additionally, benefits may be gained by having access to the complex electrical and mechanical systems at low elevations, close to deck level.

Blade Technology

Blade replacement is a major undertaking. For floating systems this will likely require return to a suitably deep, sheltered location. VAWT systems will likely have shallower drafts than HAWT systems with easier access to blade rotors enabling greater availability of suitable locations.

Environment

Research in this area is still at early stages, but the lower blade top speed of VAWT technology has the potential to reduce both noise and bird strike. The closer turbine spacing allows developments to occupy smaller areas reducing their physical footprint offshore.

Access – Safety Improvement

VAWTs provide the potential for developments to have key equipment such as generators and gearboxes on or near the deck providing a positive access and safety benefit for operations and maintenance, reducing the need for working at height and potentially removing expensive specialised vessel support.

2.6 SWOT analyses

Reflecting on the work performed across the study, the tables below capture the major technical and commercial differences between VAWT and HAWT in the application of floating offshore wind for 'current' (strengths and weaknesses) and 'future' (opportunities and threats) views.

HAWT in Floating Offshore Wind Context

Strengths	Weaknesses
• Established, incumbent technology • Existing supply chain • Developers aware of capability • Knowledge transfer from fixed bottom wind • 6-9MW proven	• High LCOE • FOW applications are not matured, not yet at commercial scale • Assembly & installation complications • Minimal local content

Opportunities	Threats
• Strong demand forecast, UK & global transposes to increased Scottish GVA • Increased deployment should reduce costs • High likelihood of 15MW (by 2030 in FOW) • Knowledge transfer from O&G and other marine sectors • Capacity for indigenous turbine manufacturer	• Unknown technical limit • Ability to reduce LCOE to be competitive against fixed bottom wind

VAWT in Floating Offshore Wind Context

Strengths

- Smaller structures potentially possible
- Easier personnel access to turbine (offshore)
- At field level majority of infrastructure is similar to HAWT (cables, moorings, etc)

Weaknesses

- Very few offshore prototypes
- Prototypes onshore or offshore at significantly lower power rating
- No existing (or very small) supply chain
- Poorer aerodynamic efficiency in steady-state conditions
- Low TRL for some key components
- Research legacy has not progressed concept, no real convergence on design choice

Opportunities

- Strong demand forecast, UK & global transposes to increased Scottish GVA
- Potential for increased reliability and in-field annual energy produced (AEP)
- Potential for higher power density
- Knowledge transfer from HAWT, O&G and other marine sectors
- First mover advantage for turbine manufacturer if concept successfully matured

Threats

- Needs considerable investment to mature concept
- Considerable technical & business risk on ability to mature concept to commerciality
- Needs to displace or work alongside incumbent HAWT market providers
- Technical show-stoppers not yet identified
- Cost base to be fully developed

An alternative presentation of the comparison is outlined in Figure 11 which compares the main system components of a VAWT floating offshore against the HAWT benchmark. The majority of the items are technically pretty similar to HAWT with the obvious exception being the uncertainty around the turbine unit itself, however this is potentially offset by the commercial attractiveness the solution may offer.

Figure 11 - System Component Comparison

	TC	COTS	Cost	EVA	
Development and Project Management					Same engineering requirements as HAWT Established existing supply chain Marginal, but short lived export benefit of early adopter
Turbine					Limited onshore, and no offshore developments Multiple designs but no established preference Potential for simpler manufacture No established manufacturing supply chain Export potential
Host Structure including mooring & foundations					Potential for smaller structures and moorings Size reduction does not change supply chain Limited export potential
Substation					No difference to HAWT in complexity or supply
Subsea Cables					Potential marginal advantages in reduction on infield cables due to condensed array and reduced host motions
Installation and Commissioning					May facilitate easier mating of host and turbine Tow to site potential Unlikely to change installation supply chain
Operation and Maintenance					Major machinery more accessible Blade longevity Subsea IRM requirements similar Established supply chain already export services
Decommissioning					No difference to HAWT in complexity, supply chain not yet established for either

TC – Technical Complexity, combination of TRL and industrial capability
COTS – Component off the Shelf
GVA – Gross (Economic) Value Added, to Scottish industrial sector

- Same as HAWT
- Major technical uncertainty
- Moderate technical uncertainty
- Little technical uncertainty
- Considerable value
- Moderate value
- Minor value

2.7 VAWT development areas

Where there is an identified economic prize time, commercial implementation can be reduced and an industrial infrastructure rapidly built to meet demand. In the 1980's the oil and gas industry, prompted by desire to develop smaller and deeper water reservoirs combined with high cost of surface piercing infrastructure, built the subsea industry we know today. Initially adapting onshore oil and gas hardware, defence control technology and marine engineering expertise, this rapidly developed into a muli-billion-pound industry centered in Scotland and the UK. High value manufacturing of subsea equipment was established by companies like GE and TechnipFMC, which continue to be based in Scotland, providing global supply based on local innovation. Subsea and marine engineering expertise, largely based in Aberdeen, continues to have a global reach supporting projects across the world. This impetus driving an industrial infrastructure of companies engaged in the subsea sector providing all manner of equipment; sensors, umbilicals, valves and services to a global marketplace. This combination of a local new frontier opportunity with supply chain capability and a global market potential is where VAWT is today.

The HAWT systems being used offshore have taken several decades to develop, progressing blades, generators, control systems and drive trains into larger and more reliable systems. Much of this technology is directly adaptable and transferrable to VAWT which will considerably shorten the timescale to deployment readiness. While the components unique to VAWT (bearings, brakes and power take-off) have industrial analogues, the development timescale will be longer. However, as seen with the subsea industry, this development can be accelerated when the prize is sufficiently large and government, industry and academia align to create the opportunities and conditions for rapid expansion.

Clearly VAWT has a notable number of issues to resolve before it can be considered equivalent to the HAWT, however uncertainty remains on the ability of the HAWT in floating offshore wind to reduce its LCOE to be competitive against offshore fixedbottom wind. At present VAWT is an unknown quantity, meaning further work isrequired to determine if VAWT can offer a potential alternative. The key areas of research from a technical perspective could include the following:

Integrated System Simulation

Simulation studies are recommended as they have the ability to assess a wide range of conditions and sensitivities in a timely and cost-effective manner without having to undergo expensive field trials. Integrated simulation is important not only to prove the concepts before proto-typing at a technical level, but to build confidence and de-risk the opportunity for the industrial investor community. A number of recognised centres exist across Scotland both within academic institutions and industry, and a coordinated programme could be established looking at topics such as;

Assessing the energy output of VAWT in a field setting - given that variations exist between HAWT and VAWT on aspects such as directionality, turbine spacing, aerodynamic efficiency and turn-on and off wind speeds but work is required to study and optimise the field performance of VAWT in an array.

- Understanding the response of the floating VAWT to dynamic wave and wind loading in comparison to HAWT. For example, pitching motions may be more critical in VAWT whereas wind forces may be more receptive. Understanding survivability criteria is required for FOW to operate in harsh, deep water environments all-year round, whether this be North Sea winter storms or typhoons in South East Asia.

- Assessing what VAWT blade configuration is most suited to FOW. The range of blade quantity and shape variants in VAWT design restricts convergence on a unified concept. Understanding in detail the issues with each configuration would assist the sector in selecting a preferred concept. For example, doubly supported VAWT blades are likely structurally superior to singly supported HAWT blades.

- Assessing the dynamic behaviour of the structure and moorings to the torsion element of the rotary forces (gyro-effect). These phenomena do not exist in conventional floating systems in HAWT or oil and gas systems, analysis is required to determine what mooring concepts are most suited to VAWT.

Note: There requires to be given due consideration to the life cycle from design, manufacture, installation, access and decommissioning/repurpose.

Mechanical

Focus is required on the components that have been identified in the study as low TRL to ensure these issues can be resolved or that options exist. Similar to simulation, a number of facilities exist such as High Value Manufacturing Catapult centres that can be tasked to deliver innovative designs.

- Bearings – In the 1980s VAWTs were susceptible to fatigue failure due to cyclic loading on the central shaft and main bearing. Technological innovation has already identified a number options to resolve this ranging from compliant couplings to bearing-less solutions. This would address bearing options that can improve the reduction rotational resistance, thereby achieving performance with lower wind speeds and also support the power improving efficiency.

- Braking – Rotational control is required to slow or stop rotation in unsuitable wind conditions. Whilst braking systems are considered analogous in other industrial applications, their integration into a wind turbine is new. Further work is required to assess the operating requirements of a typical system and outline the integration of appropriate designs into the VAWT concept.

- Materials – Advancements in materials technology could inform on new or modified designs for items such as blades, bearing and moorings to increase their strength or increase fatigue resistance or simplify manufacturing. For example, smart materials that flex, stretch and compress in response to external loads can attenuate energy by deformation, in the case of blades this can help the reduce the loading on a rotational cycle which in turn increases fatigue life of the turbine. This technology has been replicated in the laboratory but not tested at scale.

Electrical

Power and controls are key elements to improve operation efficiency and field uptime. Similar to the mechanical components, these areas require clear simulation and build into the overall system integration.

- The power take–off system would be reviewed to understand the issues associated with integrating and siting the system components close to the structure deck. In addition due consideration is require to power generation is not uniform through the full rotation of the blade, so the reaction torque (which generates the electricity) will need to be cyclic to match the rotation. It is anticipated that if the existing HAWT component and equipment designs can be used, configuring for a VAWT application is required.

- This would also include kinetic power efficiency and also the cable systems as a result of the consequence to the structure and turbine dynamics being considerably different, as an integrated system.

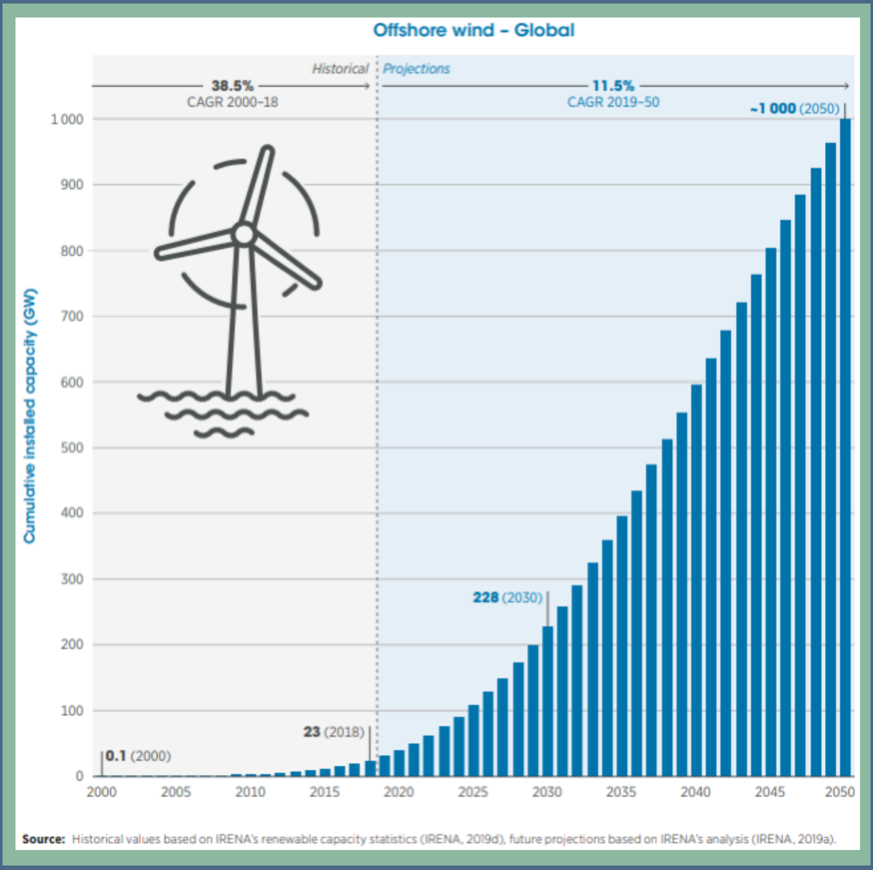
- The controls system would be using adaptive controls to control the rotor speed, which will need to be assessed relative to the free movement and breaking system, which can build in limits to the change in external conditions and influences; this shall build in typical fatigue analysis and wind patterns. This should be considered as standard building in deep learning and artificial intelligence.

3 Economic Impact Assessment

3.1 Market

Scotland and the UK - amongst other leading nations - have set ambitious targets to address climate change by the middle of the century, which rely on the wholesale decarbonisation of the energy system. Offshore wind is set to play a significant role in achieving these targets. Offshore wind has grown significantly in the past decade and is projected to reach up to 1000GW of installed capacity by 2050. This figure includes both shallow water and deep water, however, it is generally recognised that deeper water will maximise the opportunity in harvesting offshore wind. Generally, further from shore means greater water depths and beyond 50m economically requires the wind turbines to be installed on floating structures. Floating wind will generally be further from the coast and be exposed to potentially significantly harsher environment.

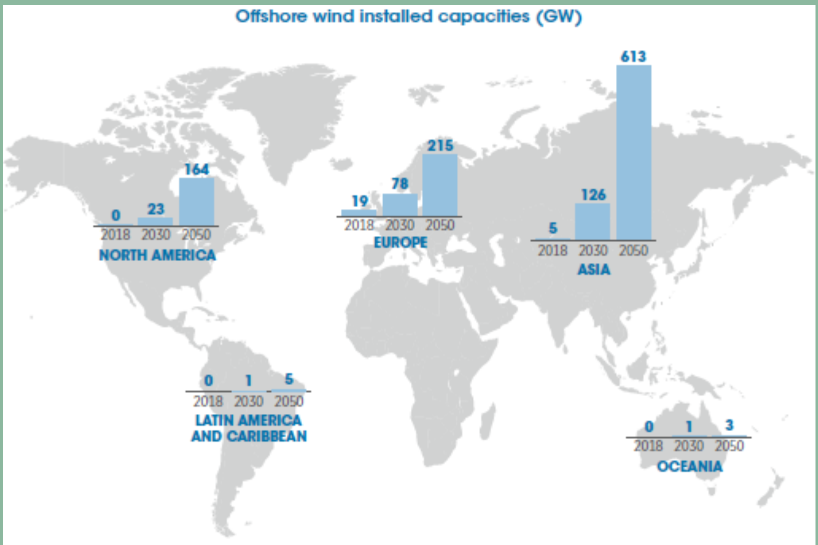
Figure 12 - OffshoreWind Global Growth Projection



Scotland is currently leading the way in regard to hosting Floating Offshore Wind demonstrator projects. This potentially offers a once in a generation opportunity for Scottish industry to take a world leading position. This is especially the case with ongoing licensing rounds in Scottish waters including sites suitable for Floating Offshore Wind. Scottish waters are currently estimated to host an additional 15 sites of which a significant proportion will be suitable for Floating Offshore Wind. If successful, this will build significant experience in floating offshore wind technology demonstrating the ability to commercialise in deeper and harsher environments.

That said, we cannot be complacent, as the momentum for Floating Offshore Wind internationally is building with approximately 25 projects across Northern Europe, South Korea and USA planned to be online between 2024 and 2026.

Figure 13 - Global Distribution of Offshore Wind



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Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d), and future projections based on IRENA analysis (IRENA, 2019a).

3.2 Commercial viability

As discussed in Section 2, Floating Offshore Wind remains at demonstrator stage and with only a few developments at scale, cost benchmarking both capital and operations carries significant uncertainty. Table 4 below summarises the published capital expenditure of existing North European projects.

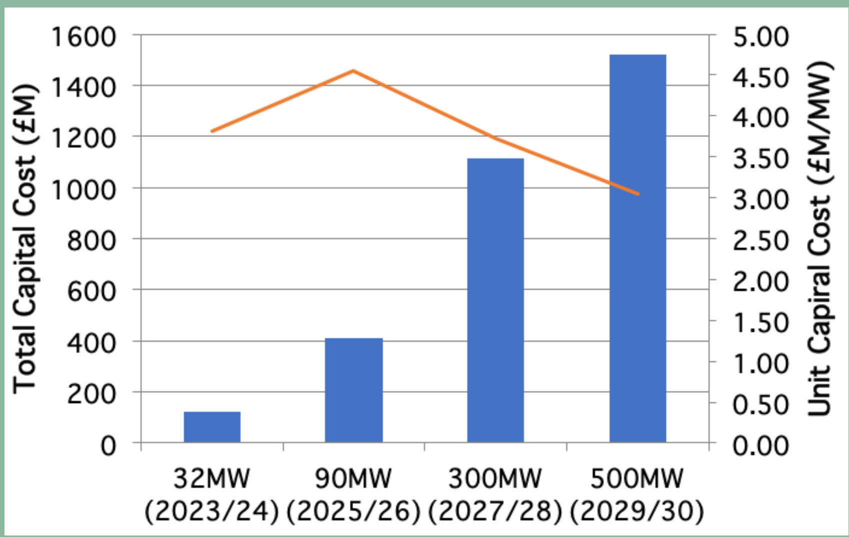
Table 4 - Capital Costs of Current North European FOW Developments

Development	Turbine	Capital Cost	Equivalent £M/MW	On-Line
Hywind Scotland	5 turbines at 6 MW	£193M	£6.4	2017
Kincardine	5 turbines at 9MW	£500M	£10.6	2021
Hywind Tampen	11 turbines at 8MW	£440M*	£5.0	2022

*includes 45% contribution from Norwegian Sovereign Wealth Fund

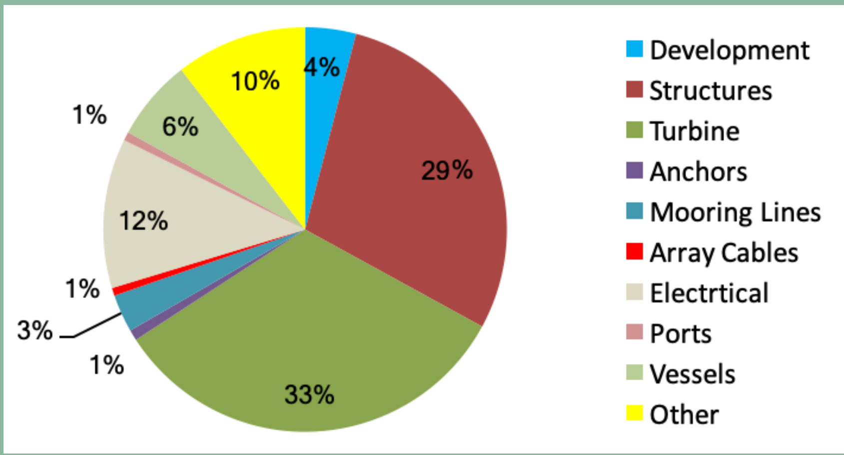
The Offshore Renewable Energy Catapult (OREC) has published a number of documents outlining the challenges floating offshore wind faces coupled with strategies for long-term cost reduction (10). For the purpose of estimating the potential impact that switching to VAWT could offer, the data published by OREC is considered to be representative of the impact floating offshore wind could have on a commercial scale beyond 2030 (11). OREC forecast that the costs of HAWT floating offshore wind will fall as the concept gains market share to the point that a 500MW development comprising 15MW turbines would cost around £1.55bn equivalent to £3m per MW as outlined in Figure 14. Globally, the trend and order of magnitude is similar as forecast by Quest in their 2021 industry review (12).

Figure 14 - FOW Capital Cost Projection



Analysing the cost components in the OREC data, Figure 15 highlights that one third of the capital cost is associated with the turbine system and one third with the structure and its mooring system. These two high-cost and critical components are areas where VAWT may offer a strategic benefit.

Figure 15 - FOW Capital Cost Breakdown (15MW)



Drawing on the component breakdown in Figure 15, a review by the Consortia was performed to identify the cost differences between the VAWT and HAWT concepts.

Table 5 - VAWT Systems Cost Differences

System	VAWT Cost	Rationale
Turbine system	Similar	Component parts are generally similar between HAWT and VAWT
Support structure	Potential reduction	Analysis by Wood identifies cost savings of 5% (see appendix 6.2)
Array cable system	Similar	Possible reduction if units can be located closer to each other
Export cable system	Similar	No change
Offshore sub-station	Similar	No change
Development/consent	Similar	No change
Assembly and load-out	Potential reduction	Smaller structures could offer a greater range of port locations to complete load-out
Installation	Similar	No change
O&M logistics	Similar	Structure access/egress is similar
O&M turbine maintenance	Possible reduction	VAWT component parts are less mechanically complex and introduces safety and reliability benefits

For the 500MW case in the referenced OREC study, the savings in VAWT compared to HAWT could be in excess of £50m per development project. Although VAWT technology is less matured, the opportunity does exist for VAWT to be a lower cost alternative.

The Levellised Cost of Energy (LCOE) approach is commonly used to compare different concepts and technologies. The calculation takes into account the total life cycle cost (capital and operating) and the energy generated over the field life. However, quoting different LCOE sources should be treated with caution, as there are many inherent assumptions that may vary when comparing models, both financial (discount rate, cost of capital, time and inflation) or technical (assumed uptime, power output, grid connection and concept). The Consortia is of the opinion that the LCOE for a VAWT development could be similar to a HAWT development for the following reasons;

- The capital and operating costs are similar with VAWT cost reduction opportunities identified.
- The Annual Energy Production (AEP) of a VAWT wind farm could be commensurate or exceed that of the HAWT equivalent when factors such as reliability/uptime, power density and response to wind forces are taken into account.

Further study is recommended at a later stage to verify this reasoning, noting that in a VAWT technology review for the US Department of Energy, Sandia National Laboratories (13) concluded that a 20% reduction in LCOE could be achieved below HAWT.

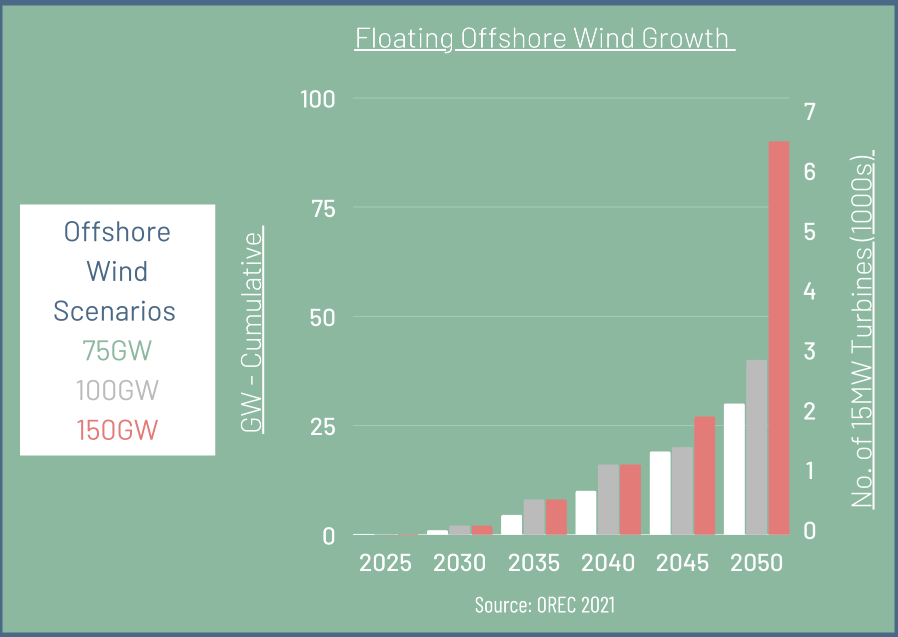
(10) ORE Catapult, Cost Reduction Pathways to Subsidy Free
(11) ORE Catapult, Benefits of Floating Offshore Wind to Wales & South West
(12)Quest 2021 Global Floating Wind Market and Forecast Report 2021-2034
(13) Sandia, August 2018, System Levellised Cost of Energy Analysis for Floating Offshore Vertical Axis Wind Turbines

3.3 Economic potential

The Scottish and UK governments have strong growth targets for offshore wind. The low, medium and high growth scenarios developed by the Offshore Renewable Energy Catapult (OREC) for the offshore wind in the UK up to 2050, sets out three deployment scenarios namely 75GW, 100GW and 150GW and the portion which Floating Offshore Wind could capture.

To date the UK has only 0.03GW of Floating Offshore Wind deployed (Hywind Scotland), with the mid-case scenario presenting growth to 8GW by 2035 and then 40GW by 2050, this illustrates the huge growth potential for Floating Offshore Wind.

Figure 16 - UK Floating Offshore Wind Growth Scenarios



The assessment of potential gross value added (GVA) to the Scottish economy is based on an approach approved for use by Scottish Enterprise and is developed from H.M. Treasury Green Book principles. Subsea UK and NSRI would like to acknowledge the support and input provided by Scottish Enterprise in the development of the model.

Developing VAWTs in Scotland to seed an industrial sector would support the growth of Floating Offshore Wind across the UK and establish Scotland's reputation internationally. This would align with the Government's Green Energy strategy. To assess the economic impact, the methodology adopts an income-driven approach, combining projected turnover of a quantity of VAWTs installed on a proportion of the projected Floating Offshore Wind capacity in the UK from the period 2035- 2050 (14) as illustrated in the Table 16 below. Based on having a minimum of three incumbent offshore turbine (including nacelle) manufacturers remaining in HAWT (Vestas, Siemens Gamesa, and GE), the model assumes that a new entrant to the market at the mid-case has the potential to capture an equal share of the market by 2050. The low and high case are sensitivities around the mid case.

Table 6 - Assumed Market Share of VAWT Scenarios

VAWT Share of FOW	2030	2035	2040	2045	2050
Low	0%	5%	15%	17%	20%
Mid	0%	5%	17%	20%	25%
High	0%	5%	17%	25%	30%

Source: Subsea UK / NSRI

This provides a low, medium and high case scenario for the amount of GW deployed. Cost data from OREC (15) is used as the basis for projected turnover. Potential activity that could be attributed to the Scottish economy based on the manufacture and installation of key turbine elements including CAPEX activities and OPEX are as follows:

Table 7 - VAWT Deployment for Each Scenario

	Low Case	Mid Case	High Case
Cumulative VAWT Deployment by 2050	6GW	10 GW	27GW
No of VAWT Turbines (assume 15MW)	400 units	667 units	1800 units

CAPEX

- 100% of blade manufacturing could be carried out in Scotland
- 50% of additional turbine related manufacturing and assembly activity could be carried out in Scotland given this is a mix of specialised and non-specialised components
- 25% of the value of substructures could be manufactured or assembled in Scotland as the smaller structures may be within the water depth capabilities around Scottish shores
- 10% of the remainder of CAPEX activity could be carried out in Scotland

Note: These percentages are indicative based on general market studies

OPEX

- 75% of turbine maintenance value could be carried out in Scotland (this component has 25% of the total value of O&M activity)

This outcome creates a significant opportunity for Scotland. The outcome of the Gross Value Add (GVA) based on the assumptions presented in this report identifies the potential GVA (Present Value) that could arise from the economic activity associated with the creation of an internationally recognised centre of excellence for VAWT and the installation and operation of a manufacturing and servicing hub over 15 years from 2035-2050 in the range of £2-£8bn.

(14) https://ore.catapult.org.uk/wp-content/uploads/2021/01/FOW-Cost-Reduction-Pathways-to-Subsidy-Free-report-.pdf (2021)
(15) https://ore.catapult.org.uk/wp-content/uploads/2020/01/8996-OREC-Wales-Report-WEB.pdf (2020)

Globally, OREC has one scenario for offshore floating wind, being 9GW deployed by 2030 and 71GW deployed by 2040. Quest Offshore projects upwards of 180GW of floating offshore wind to be deployed by 2050. Taking a low case 20% market share for VAWT, would result in a total of 30GW (excluding UK 6GW) of additional VAWTs being installed by 2050. Assuming the Scottish supply chain associated with the development of a centre of excellence in VAWT captured 20%, that could deliver the equivalent GVA (PA) of £2bn as the UK low case scenario.

A full explanation of the analysis and methodology is provided in appendix 6.3.

Figure 17 - VAWT GVA for Each Scenario

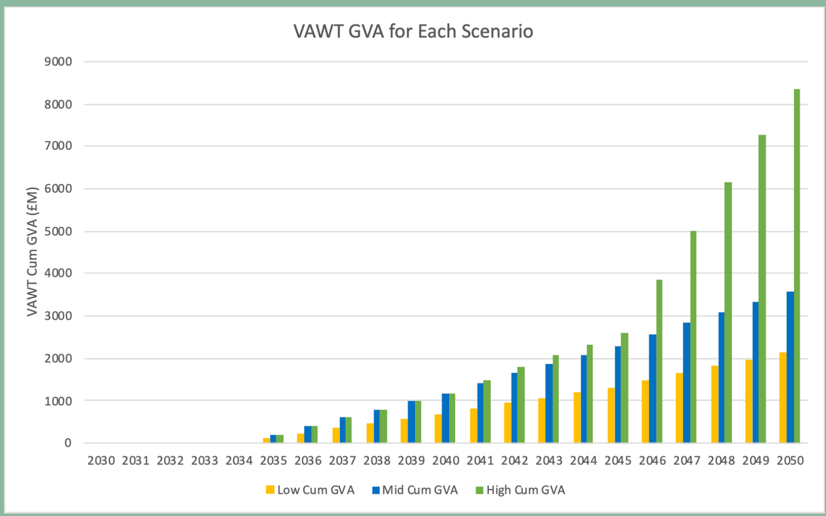
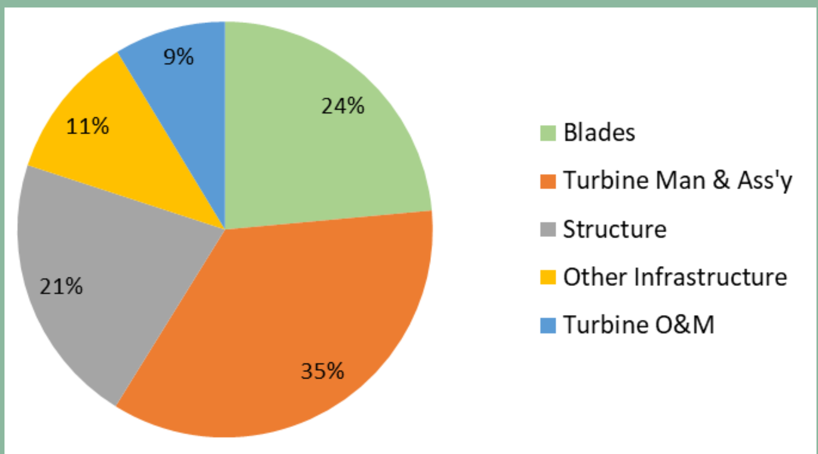


Figure 18 - Breakdown of Component Contribution



<u>Low Growth Scenario</u>
£2.11 billion of net additional GVA (PV) by 2050

<u>Medium Growth Scenario</u>
£3.57 billion of net additional GVA (PV) by 2050

<u>High Growth Scenario</u>
£8.34 billion of net additional GVA (PV) by 2050

The GVA is allocated across the sub-components as outlined in Table 8 below in the medium growth scenario. With reference to a recent BVGA study, UK and Scottish content baseline and roadmap for offshore wind using similar scenarios highlighted that relative installed capacity in Scotland and the rest of the UK to those assumed for 2030 revealed that the Scottish would be 18% and UK would be 48%.

Table 8 - BVGA UK and Scottish Local Content Roadmap

		%cost	Scottish content	UK content
DEVEX	Development and project management	2%	27%	83%
CAPEX	Turbine	19%	1%	7%
	Substations	3%	6%	19%
	Foundations	9%	3%	7%
	Cables	2%	0%	7%
	Turbine and foundation installation	6%	3%	5%
	Cable installation	4%	4%	7%
	Installation Other	3%	30%	75%
OPEX	Operations and maintenance	49%	31%	81%
DECEX	Decommissioning	2%	12%	30%
TOTEX	Total	100%	18%	48%

3.4 Economic assessment reflection

The economic assessment clearly highlights that the opportunity for a fourth turbine system (including nacelle) supplier is significant, both within the UK and internationally. Securing a manufacturer significantly increases the local economic growth. Whether that manufacturer focuses on HAWT given it is the proven accepted design in onshore and shallow water applications or selects VAWTs which may be more suited for deep water application is open to debate. However, the prime move advantage of VAWT are likely to be export potential.

Why has VAWT not been commercially available at scale today ?

- The reality with any technological innovation is that it needs to be championed, invested, and adopted by corporate organisations which can be enabled by policy creating market demand. This is exactly the scenario with regard to the commercialisation of three bladed HAWT systems in fixed bottom offshore wind which has grown exponentially in response to addressing climate change issues.

- Developers and the supply chain are familiar with HAWT; given the large capital investments and long-term electrical delivery commitments being made, there will be an unwillingness to introduce 'new technology' risk without there being significant added value.

If Scotland was going to invest in a turbine manufacturer, should it be HAWT or VAWT?

- With respect to increasing local economic growth both HAWT and VAWT would bring different levels of opportunity. VAWT, if successfully developed, could host a strong position internationally with Scotland benefitting from being a leading player in Floating Offshore Wind. However, the downside is that VAWT could offer a higher risk of failure.

- VAWT will require additional innovation and research to achieve industrialisation, requiring a high-skilled labour skills force.

- VAWT could be developed building in specialisms centred around materials technology, advanced manufacturing, automated assembly and testing processes.

- VAWT could be developed as an integrated system for Floating Offshore Wind which includes the structure. The structure selection could be designed to improve Scotland's competitive position.

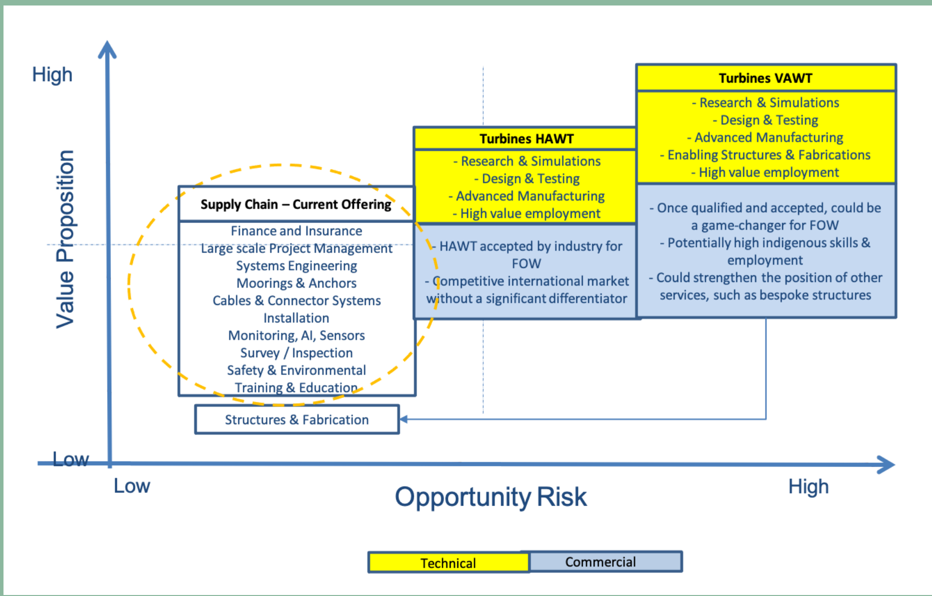
- HAWT incumbent companies are already well positioned within the UK (Teesside, Hull and Isle of Wight), therefore unlikely to require another facility in the UK. VAWT could create an alternative inward investment opportunity, from other regions such as Asia, who have a high interest in Floating Offshore Wind. A HAWT alternative supplier may be challenged to displace the current mainstream HAWT suppliers, both in UK and internationally.

- HAWT may not offer a game-changer to Floating Offshore Wind although it is lower risk.

- SPAR structures (as currently designed and if selected for FOW) are unlikely to be compatible with water depths around Scottish ports. However, it is recognised that there are creative innovations being developed which are at the concept stage, that may be suitable.

Figure 19 below highlights the prospective fields of value for HAWT and VAWT; VAWT ultimately has a higher opportunity value given the advantage of being first to develop, but in conjunction, this strategy should be offset with its higher risk of success. It is recommended that this would require further assessment. Additionally, the scopes circled are areas that Scotland is already engaged in to various levels within floating offshore wind and can be considered turbine-agnostic, note this excludes structures in which it is generally recognised Scotland is not currently competitive enough, although a VAWT compatible design may offer an in-road.

Figure 19 - Assessment of Potential Value of HAWT and VAWT



Does FOW in deeper and harsher environments call for an alternative to HAWT and are the merits of VAWT suitably understood?

It is probably fair and reasonable to suggest that HAWT in Floating Offshore Wind is still being assessed in over-coming the challenges both technically and commercially. Equally, the interest to exploring VAWT should be continuously explored whilst there are positive signs for Floating Offshore Wind. Research over that last decade has accelerated as market interest in Floating Offshore Wind has grown, this has extended beyond core research with organisations familiar with the offshore marine industry now showing interest.

"The new entry companies such as Equinor, Repsol, Aker Offshore Wind, Shell, Total Energies and BP are most likely leading to a step-change for this young industry's aviability and ultimate capability to produce 100 to 200 (or even 500 plus) FloatingTurbine Units (FTU's) on a serial manufacturing basis."

Quest, 2021, 'Global Floating Wind Market and Forecast Report 2021-2023'

4 Industrial Strategy

4.1 Opportunity assessment

To evaluate the potential interest in progressing VAWT from a Scottish industrial perspective, a PEST analysis as outlined in Figure 20 has been prepared for the purpose of opening up the discussion. The analysis attempts to outline the key points both for and against the key criteria of Political, Economic, Social and Technical.

Figure 20 - PEST Analysis of Industrialising the VAWT Opportunity

	Influencers	**Blockers**
Political	• Increase local content • Increase export opportunity • Build upon industrial strategy – high value manufacturing and employment • Potentially Scotland being an industrial leader • Flagship green investment	• Low territorial position no in-country FOW manufacturing / assembly • Other countries exploring VAWT for FOW • Declining manufacturing sector
Economic	• FOW demand exists & growing • LCOE comparable once proven • Scottish / UK prize if first movers • O & G entrants – Operator & Supply Chain • Investor community highly focused on green energy	• Incumbent turbine manufacturers low incentive to change • High development investment • Investment outcome uncertainty • Clear prize for wind developers
Social	• O & G transition skills & offshore experience • If VAWT successful significant high value jobs and manufacturing base • Safety and environmental benefits	• Limited expertise to champion VAWT • Requires a change to adopt new technology • Societal adoption of new technology
Technical	• Engaged international research & development • Build on analogues and O&G success • Reduced size / cost of structures	• Key components at very low TRL • No single adopted VAWT design • History of not getting beyond demonstrator stage • Disruptive technology being adopted

The analysis indicates that there are many aspects to consider. The main blockers (negative aspects) orientate around the uncertainty that a VAWT solution can be competitive against HAWT given the notable time and the difficulties in quantifying the financial investment to mature the technology to an appropriate commercial readiness level as outlined earlier in the report. The key influencers (positive aspects) orientate around the strong demand-led growth potential that exists in offshore wind for the next 30 years plus, with many organisations seeking to enter and invest in the sector.

Leaving the Technical aspects aside the points below from the PEST have been expanded upon in the following sections:

- Local Content (Political)
- Industrial Centre of Excellence (Political)
- Turbine Manufacturing (Economic)
- Investor Patterns (Economic)
- Supply Chain Transfer (Social and Economic)

4.2 Local content as a policy lever

Having an indigenous VAWT manufacturer offers the Green Energy and Blue Economy supply chains the opportunity to capture a larger share of the emerging Floating Offshore Wind market in Scotland, the UK and internationally.

The UK share of project CAPEX is just 29% and a significant element of this has come through foreign-owned companies with bases in the UK. Going forward, the 2019 UK-wide Offshore Wind Sector Deal (16) sets out a requirement for the sector to have at least 60% lifetime UK content in domestic projects, and targets increasing UK content in the capital expenditure phase. The UK government announced proposals in May 2021 to remove subsidies in the CfD process if firms do not use British manufacturers (17). Section 3.2 identified that the majority of the expenditure is associated with the turbines and the structures. Securing these items in Scotland would greatly increase the local content.

Having the appropriate government policy mechanisms is critical to enabling developers to move forward with confidence and for the supply chain to invest in long-term innovation. A review of the two ongoing Floating Offshore Wind non-commercial pilot demonstrator projects currently being deployed in the Norwegian North Sea, namely Hywind Tampen and, in the UK North Sea, Kincardine, highlights that the Scottish supply chain has been unable to capture any substantial contracts. This lack of involvement of the Scottish supply chain in high-value CAPEX activities is further evidenced via a review of the developers and turbine suppliers and their respective locations which can be found in appendix 6.6. Investment within Scotland is progressing however, the question is, is it quick enough?

Artist Impression: Forth Ports Announced 25th May 2021 - £40m Private Investment: 35 acres site

(16) https://www.gov.uk/government/publications/offshore-wind-sector-deal/offshore-wind-sector-dea

(17) UK to strip offshore wind subsidies from foreign supply chains (power-technology.com)

Case Study 1: Hywind Tampen

Equinor championed its own spar technology for the pilot Hywind Scotland project off the coast of Peterhead. The next stage, Hywind Tampen (off the coast of Norway), will be the world's largest 88MW FOW project with 11 8MW turbines designed by Siemens Gamesa to provide power to oil and gas platforms. Aker Solutions are providing the structures and moorings. DOF has been contracted to carry out the installation in water depths of 300m with JDR Cable Systems responsible for design and manufacture of the 66ō̃kV dynamic inter-array cables along with static and export cables. Seaway 7 is responsible for the installation of the cables. The project is due to begin producing electricity in late 2022. The project cost is estimated to be NOK 5billion, Norwegian state fund Enova has agreed to fund NOK 2.3billion and Norway's NOX fund will provide NOK 566million (18).

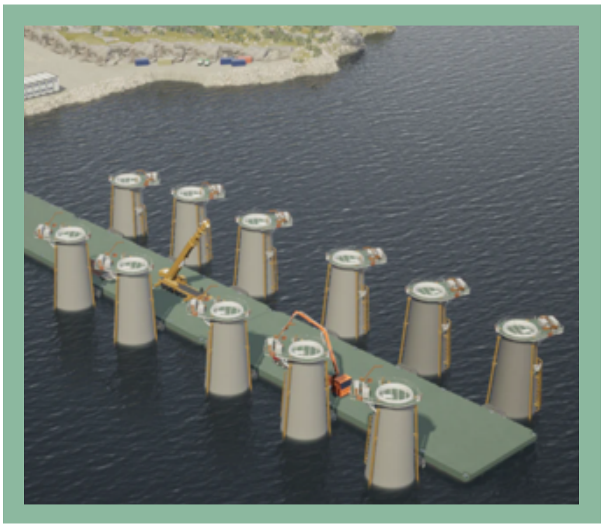


Figure 21 - Illustrative impression of Hywind Tampen structures

Case Study 2: Kincardine Offshore Wind

The second largest pre-commercial FOW project is the Kincardine Offshore Wind Farm being developed by Cobra Group off the coast of Aberdeenshire in 70m water depth. Upon completion, the 50MW project will comprise five Vestas V164 9.6MW turbines on the WindFloat semi-submersible structure developed by Principle Power and built in Spain at Cobra's fabrication yard in Ferrol, Spain. Dutch company, Boskalis was responsible for the transportation of the floating foundations from Spain to Rotterdam. The floating structure, tower and turbine were then assembled in the Netherlands and towed to site. Cable installation and commissioning is being performed by Global Offshore which is due to begin providing power to the national grid in summer 2021. When sanctioned in 2016, the project was expected to cost £250million but will now come in closer to £500million (19).

Figure 22 - Source: Boskalis Manta Anchor handler in tow off the coast of Aberdeenshire

(18) https://www.equinor.com/en/news/20201001-contruction-start-hywind-tampen.html
(19) https://www.pressandjournal.co.uk/fp/news/aberdeenshire/2561968/worlds-largest-floating-wind-farm-off-aberdeenshire-delayed-by-six-months/

4.3 Turbine manufacturing is key to unlocking high-value CAPEX

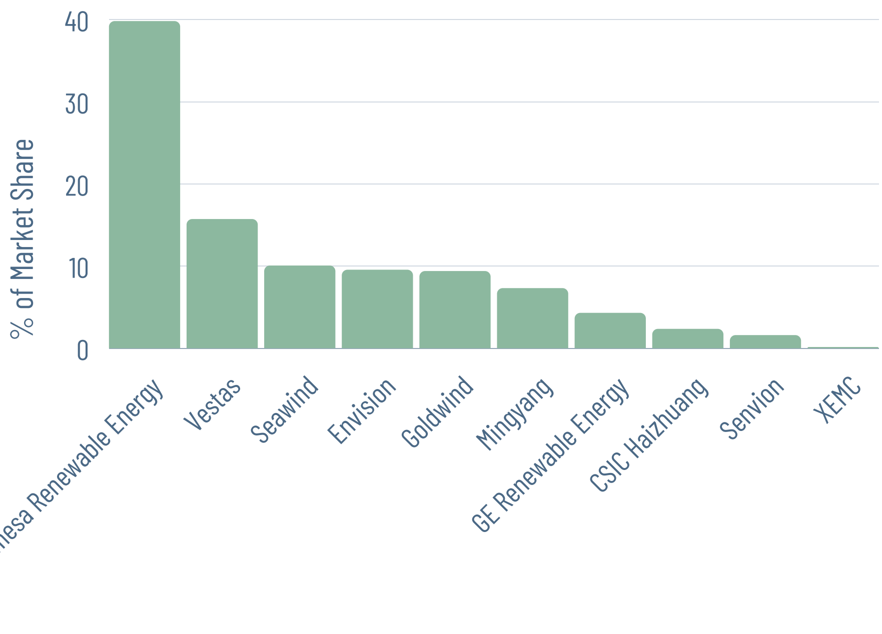
VAWT has the potential of building sustainable growth in high-value manufacturing and engineering. As Section 3.2 highlighted, one third of the capital expenditure and one quarter of the operational expenditure is associated with the turbine. As shown in Figure 13 below, Europe and China are home to the majority of offshore wind turbine original equipment manufacturers (OEMs) with the European offshore market dominated by Siemens Gamesa (Spain), GE Renewable Energy (USA) and Vestas (Denmark) who currently specialise in HAWT technology. Options that exist to explore the VAWT opportunity could include:

- Engaging with existing European players looking to diversify
- Engaging with foreign investors for inward investment
- Engaging with major Scottish and UK industrial indigenous manufacturers such as Rolls Royce and civil engineering mining companies

An industrial engagement strategy focused on developing an indigenous VAWT manufacturer would be centred around the development of intellectual property, using locally based R&D, design, manufacturing and integration expertise. Such activity would have far reaching benefits across the Blue Economy, the GVA to the wider economy (as highlighted in Section 3.4) and be capable of achieving significant export revenues.

Figure 23 - Top 10 offshore wind turbine suppliers in annual global market in 2019

Source GWEC: https://gwec.net/wind-turbine-sizes-keep-growing-as-industry-consolidation-continues/



4.4 Create an industrial centre of excellence

A large portion of R&D expertise, design and manufacturing supply chain is co-located close to the turbine OEMs, as are turbine assembly facilities. Developers and installers require the majority of components to be ready prior to project construction to reduce risks to the offshore deployment programme. To date, the HAWT manufacturers have sought quayside facilities in the UK to extend their operations in continental Europe. These facilities enable manufacturing and assembly of large components such as blades and towers. Siemens Gamesa has a manufacturing facility in Hull and Vestas is based on the Isle of Wight. GE have just announced that they are opening a new blade manufacturing facility at Teesside (20). Similarly they have announced a major deal with Toshiba to enter into Japan to give them a foothold in its developing offshore wind industry (21). The requirement for quayside space also applies to other large components such as electrical infrastructure and there will be a significant benefit to any innovator located nearby.

Figure 24 - Green Port Hull is a recent £310million redevelopment Associated British Ports and Siemens of Alexandra Dock to repurpose it for the production of offshore wind turbines.

Green Port Hull in Grimsby and Able Port in the Humber estuary provide an example of how proximity to a critical mass of the supply chain and facilities can help develop an embedded manufacturing, delivery and operations "centre of excellence" around offshore wind. At 3059 acres, the Humber has the largest Enterprise Zone in the UK comprising a package of 30 sites located adjacent to the Deepwater port (22). The UK Government have been actively involved in working with regional leadership, developers, OEMs and the supply chain enabling this to happen through financing and co-investment (23).

An opportunity exists for Scotland to create a similar "centre of excellence" focused on VAWT technology and gain a unique foothold in this emerging market. The centre of excellence would not necessarily be a single centre, more a 'hub and spoke' bringing together expertise and knowledge centres from industry to academia across the regions from the central belt, north east and highland and islands. The emergence of the 'energy transition' and commitments to a cleaner energy future by the oil and gas sector, including companies such as Equinor, could potentially create investment in new VAWT technology working with the best from advanced manufacturing and the green economy.

(20) General Electric (GE) Signs Offshore Wind Deal With Toshiba - May 12, 2021 - Zacks.com
(21) https://www.ge.com/news/press-releases/ge-renewable-energy-plans-open-new-offshore-wind-blade-manufacturing-plant-teesside-uk
(22)https://static1.squarespace.com/static/5faa9db24824a917c7e06a4c/t/5faac0f953e983236a938b9e/1605026053460/The+Humber+Offshore+Wind+Cluster+Prospectus.pdf
(23) https://www.gov.uk/government/news/second-wind-for-the-humber-teeside-and-uk-energy-industry

4.5 Supply chain cross-over opportunities

The Floating Offshore Wind industry has obvious synergies with other well-established industries in the UK such as offshore oil and gas. Companies such as Shell, BP, Total, Repsol and Equinor are active in the offshore wind sector and could bring support for investment in new VAWT technology. Working with the best from advanced manufacturing companies such as Rolls-Royce in the automotive, aerospace and civil engineering construction sectors, in particular around precision engineering, rotating equipment, materials and high value manufacturing could bring positive advances in technology. It is understood that some of these companies previously looked at certain aspects of wind turbines, however, this was before the market opportunity and industry was mature enough; today the market opportunity is considerably different and Floating Offshore Wind offers a different dimension.

Whilst Scotland and the UK may struggle to compete against the lower costs offered by some overseas countries for fabrication; the design, manufacture and assembly of specialised machinery for application in complex environments is a proven and world leading skill, with examples such as jet engines manufacture in aerospace, subsea tree manufacture in the oil and gas sector and multi-sector pumping technology exist. Offshore wind turbine technology is similar and although there may be challenges to be overcome when competing directly with the existing HAWT OEM specialists, VAWT does not have those restrictions.

As the offshore wind market has grown so too has the size of turbines, structures and projects; with an added increased risk in regard to project execution, safety and environmental challenges. This brings a major change in the complexity of offshore wind projects; and the need for a supply chain that has the experience and capability of working in deep water; including project management, design, manufacture, installation and maintenance. TechnipFMC is a good example and one of many; a major player who are not only an installation contractor, but a supplier of offshore systems equipment. TechnipFMC are a multinational organisation with an international presence with a high–end advanced manufacturing plant in Dunfermline who have had the capabilities to manufacture around 250 subsea trees per year; this does not include their installation vessel interests in Aberdeen. During this study, NSRI was approached by the TechnipFMC's New Energy Ventures Team, who wished to explore why VAWTs are not being developed as an alternative considering on face–value there appears to be merit for VAWT for the application of Floating Offshore Wind – see appendix 6.5.

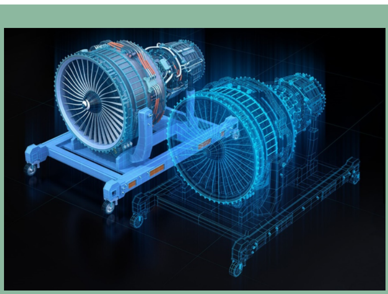
TechnipFMC are only one of a number of major players who have invested in Scotland and are developing their long–term strategic position transitioning from oil and gas to renewables. TechnipFMC who did pursue some early opportunities in offshore renewables a decade ago only to pullback when the market for their skills was not required, however with the emerging Floating Offshore Wind being more closely aligned to its experience of operating within harsh deepwater environments, TechnipFMC are considering re-entry (24). Another similar organisation is Baker Hughes who host a high-end manufacturing plant within Montrose. These advanced facilities during the peak of the oil and gas industry manufactured, built and tested circa of 200 to 250 subsea trees per year and, to put a subsea tree into commercial context, these would generally be similar to a large power generation wind turbine. Similarly, Subsea 7 have also announced increased focus on the emerging Floating Offshore Wind opportunity. Having recognised and experienced contractors competing for market share will leverage cost reduction and create opportunities down the supply chain (25).

(24) https://www.technipfmc.com/media/press-releases/2021/03/technipfmc-enters-partnership-with-magnora-to-develop-floating-offshore-wind-projects/
(25) https://www.offshorewind.biz/2021/03/29/simply-blue-energy-and-subsea-7-to-develop-floating-wind-project-in-scotland/

Figure 25 - Transition Manufacturing Examples

Source: TechnipFMC Subsea Tree Post Manufacturing

Source: TechnipFMC



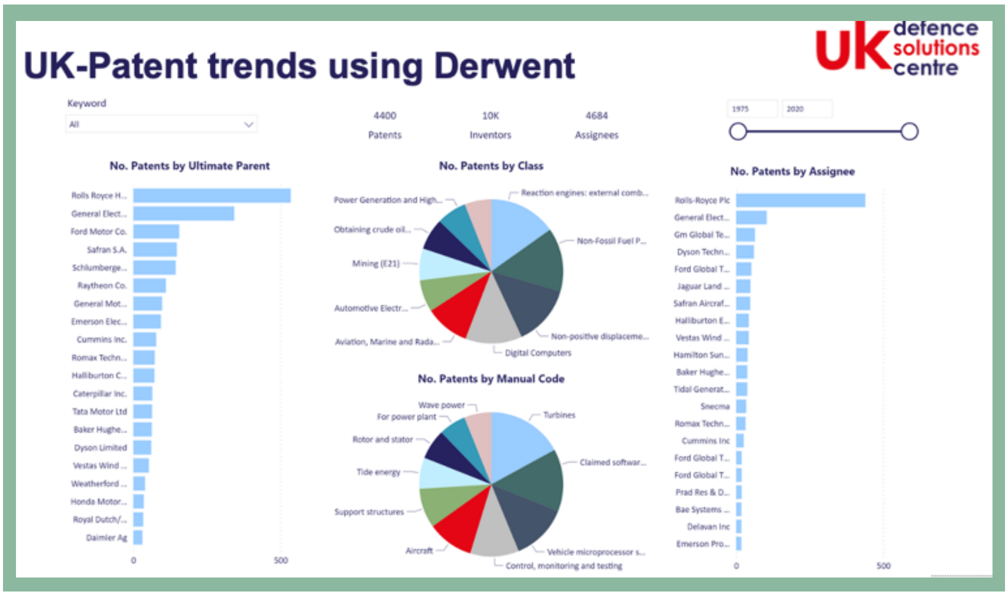
Source: Advanced Manufacturing Research Centre

4.6 Adopt and adapt

The strong growth projections for renewable energy and, in particular offshore wind, are enticing investors to engage with the sector. VAWT technology being applied in Floating Offshore Wind is no exception and whilst it could be considered higher risk given its disruptive nature, there is likely to be a notable number of small-scale entrepreneurs or larger corporate investors who see the potential opportunity.

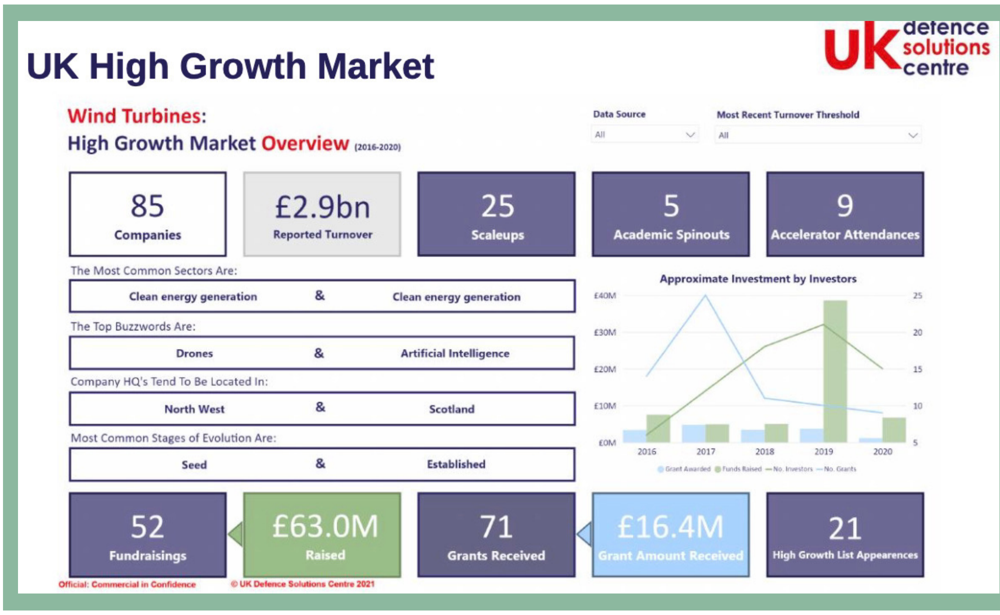
Subsea UK and NSRI have been working with the UK Defence Solutions Centre (UKDSC) to develop a tool that will enable improved visibility of existing technical capability and enable greater collaboration between the underwater community based to identify both at global and national level who are the key investors, what they invest in and sizes of investments being made. Having a similar market-led intelligence, regarding technology focused investment, including the "who's who", will provide a strong informative starting point for VAWTs future industrial engagement. To showcase the tool, Subsea UK, NSRI and UKDSC have used the existing tool to perform a high level analysis of investment patterns for offshore wind turbines opportunities as detailed in Appendix 6.4 and the example in Figure 26 and 27.

Figure 26 - UK Patent Trends



Engagement with the potential investor and entrepreneur community was out with the scope of this study, however a more in-depth review is recommended to identify key interested parties and explore their appetite to progress further VAWT development. Indeed, the increased focus on climate change related aspects has brought together organisations that would not previously have been closely associated. For example, Baker Hughes a multinational oilfield service company are working closely with Google to identify areas of mutual interest.

Figure 27 - Wind Turbine Locations



5 Conclusions and the way forward

5.1 Conclusions

Following the methodology outlined in Section 1.5, this study has reviewed the current technology and the economic potential for the application of VAWT in Floating Offshore Wind against the following key areas.

Is the concept of VAWT in a Floating Offshore Wind application technically feasible?
Is the concept of VAWT in a Floating Offshore Wind application commercially viable at scale?
Is there an economic case for industrial investment?

The technical assessment for VAWT, did not provide a compelling argument to displace HAWT given existing VAWT turbine capacity is an order of magnitude lower; however it did show that the VAWT concept is technically feasible and may offer system benefits thereby offering the potential for VAWT to offer a disruptive alternative if it can be up-scaled. There is no doubt that the floating wind market offers different technical and commercial challenges to conventional offshore fixed bottom wind as further from shore exposes the turbines to higher wind speeds and harsher marine environments. The study has shown that the size of the floating structure and mooring systems may be lower for VAWT systems which is likely to result in lower cost solutions compared to HAWT. HAWT turbines as a product have moved significantly from 2MW in 2002 with 10MW units currently being installed and 15MW under development for launch in 2024. The 15MW turbine's blade span will be circa 235m and with 20MW turbines mooted the current practices and equipment associated with manufacture, assembly and test, installation, operation and decommissioning will need to be re-evaluated, possibly suggesting that a point of inflection may be nearing.

A more in-depth analysis, is required to analyse the technical and commercial performance of a multi-GW VAWT wind farm over the full life-cycle to compare against the HAWT equivalent taking into consideration aspects including up-time, reliability, wind and sea forces. The assessment identified the key areas that require a deeper-dive, not only with respect to turbine components, but also clearly highlights the requirement to continuously evaluate the direct relationship with subsea mooring and structures. Opportunities for cross-sector learning exist that could significantly advance both the turbine and floating system designs.

The economics demonstrate that there is significant opportunity for a 4th major turbine manufacturer as the floating wind gains market share from offshore fixed bottom wind. In the scenarios considered which align with industry projections for the UK, the gross value add (GVA) ranges between £2.1bn to £8.3bn with upwards of an additional £2bn when international markets are considered.

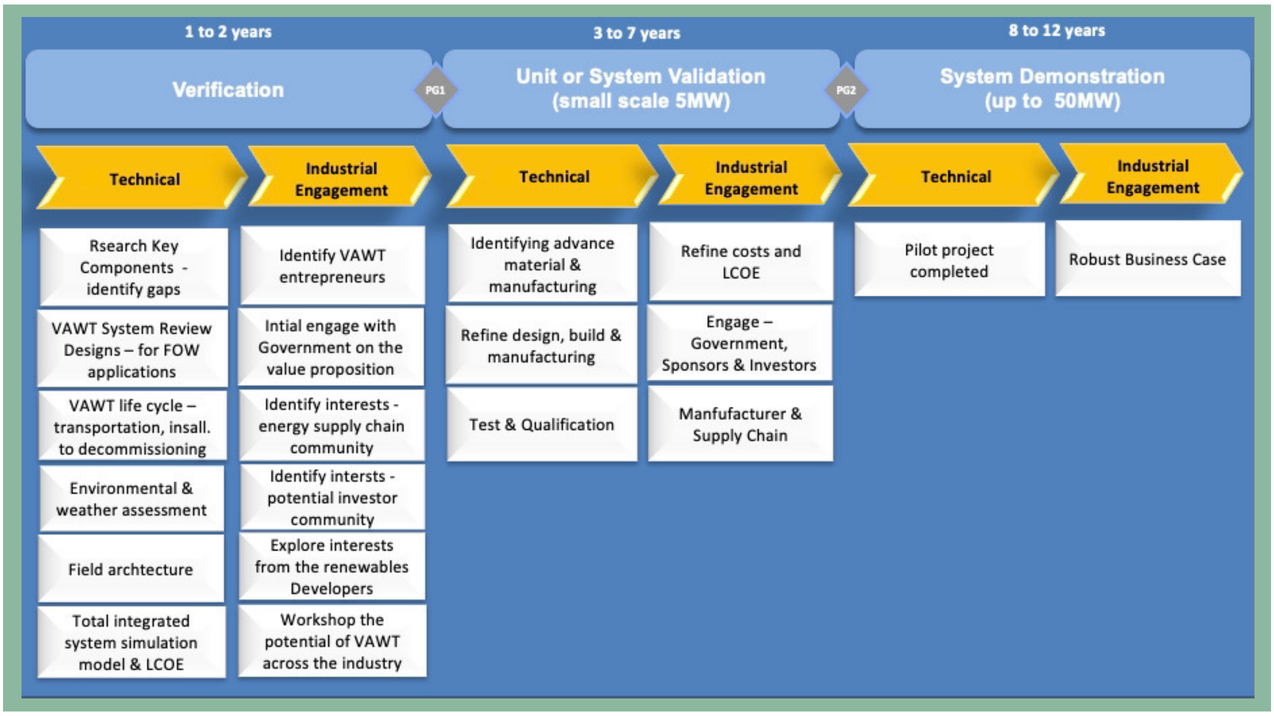
5.2 The way forward

Scotland has the opportunity to be a market leader in floating offshore wind hosting a Centre of Excellence for VAWT and advanced simulation and manufacturing. This strategic vision will deliver high-value green jobs, however, there are many considerations to be addressed, as discussed in the report and to that end, the following action plan that offers a structure.

The proposed way forward takes a 3 phased systematic approach that offers phase gates to make informed decisions both with respect to technology and industrial engagement, thereby de-risking any investment. The 3 phases of 'Verification', 'Unit and System Validation' and 'System Demonstration' enables a logical technical and commercial readiness level to be continuously assessed. It is important the both the Technical Readiness Level (TRL) and Commercial Readiness Level (CRL) run in parallel thereby enabling and facilitating the opportunity; this approach will assist not only accelerating the opportunity, but also provide appropriate investment decisions.

The diagram below outlines the type of activities and the proposed time scales. These have been identified as result of this study, however also draw from experience of developing technology and commercialisation within the offshore engineering industry. It is recommended there should be a review of the activities that will define and scope them appropriately, which includes an initial industrial engagement workshop to discuss and present this report.

Figure 28 - Proposed Technical and Commercial Roadmap



Verification Phase:

This phase will require a significant amount of technical and industrial engagement, not only sharing experience and knowledge within the energy sector, but also identifying learnings from across other industrial sectors. It is anticipated that during this phase there will be a significant focus on using simulation techniques, where an entire integrated system from the seabed to blade tip can be developed and scrutinised, thereby enabling multiple input scenarios to be applied to access innovation and offering flexibility. Such an integrated systems model could also be used for any turbines and floating structures, enabling visualisation of external influences such as weather, environment and associated interactions with sub-systems (such as cable and mooring systems). Scotland has a number of simulation centres being established including the Darcy Thomson Centre at St Andrews, who have already engaged with offshore renewables simulation and virtual reality (VR) with regard to cable and mooring systems. This could be developed as a leader in renewable simulation and VR providing connectivity between the theory and the influences that demonstrate reality. This type of simulation will not only demonstrate the technical developments, but will fundamentally provide visualisation of the value proposition for investors.

The industrial engagement will require a close relationship across wider industry building the problem statements and buy-in addressing;

- Sector leadership - developers, Government and investment community
- Technology developers – OEM's, R & D and commercialisation
- Project delivery expertise – primes, Tier 1's, SME's – CAPEX and OPEX
- Supply chain – indigenous and international
- International partners – research, funding and development

This is both technically and commercial engagement, including the investment community. It is estimated that the cost for this phase would be in the region of £1M to £3M. It is anticipated that the investment for this phase would be predominately government funded, with industrial support to stimulate and nurture the opportunity.

This phase is critical and in many respects will define the reality of VAWT within the Floating Offshore Wind market, if it brings a viable compelling alternative to HAWT or does VAWT provide niche opportunities for offshore wind in specific areas or geographical locations.

Unit or System Validation Phase:

This phase will refine the technology concepts, into the build of unit prototype where state-of-the-art design and advanced manufacturing would be assessed. The industrial engagement will require to build upon potential supply chain and investor interests.

It is estimated that the cost for this phase would be in the region of £15M to £20M, this estimate is based on similar capital investments, however these will be refined during the verification phase. It is anticipated that the investment community would be fully engaged and some support from government.

Output: The prototype demonstration will complement the systems simulation with physical evidence in a real environment.

System Demonstration Phase:

This phase will deliver a pilot project operating offshore to demonstrate the technological, installation and operational aspects of VAWT. The industrial engagement will require to be focused on the developer and investor communities.

It is difficult to estimate the cost for this phase, but it should be considered analogous to the Kincardine Offshore Wind project which has seen an initial turbine trialed followed by a series of others.

Output: The pilot project will demonstrate the viability or otherwise of the concept, hopefully unlocking the way to full commercialisation.

5.3 Recommendation

This high-level screening review has provided enough evidence both technically and economically to suggest that although the Vertical Axis Wind Turbine concept requires development, it could offer a game changing disruptive influence for the Floating Offshore Wind sector not only within the UK market, but internationally. On this basis, it is recommended that further work is required to fully assess and map a route to resolve the technical uncertainties and risk as the market potential is significant.

The outcome of this study suggests there is an opportunity for a fourth turbine manufacturer in Scotland and for VAWT to be explored further developing robustness to the key areas with engagement from industry and investors. This study has highlighted the potential for VAWT and for Scotland to create a paradigm shift for Floating Offshore Wind. The timeline for achieving commercialisation by 2035 will require focus both technically and industrial engagement, therefore it should be considered critical to progress the next phase.

The next phase requires a Consortia approach the brings a robust technical systems knowledge (from underwater, marine to turbine) and commercialisation knowledge. The Consortia requires to be impartial, with repersentatives from industry, research, trade representation and investment.

6 Appendices

6.1 University of Strathclyde: Opportunity Study: Vertical Axis Wind Turbines for Floating Offshore Wind

6.2 Wood: Vertical Axis Wind Turbine for Floating Offshore Wind: Structure and Subsystems Report

6.3 Subsea UK/NSRI: Vertical Axis Wind Turbine: Economic Impact Assessment: GVA Report

6.4 UK Defence Solutions Centre: Interactive Analysis Toolset: Vertical Axis Wind turbine Supply Chain Development

6.5 TechnipFMC: Expert Opinion on Installation Challenges for Floating Offshore Wind

6.6 European Offshore Wind Developer and Turbine Manufacturer: Supply Chain Review

6.7 Oxford Brookes University: Numerical modelling and optimisation of vertical axis wind turbine pairs - a scaled up approach

Appendix 6.1

University of Strathclyde: Opportunity Study: Vertical Axis Wind Turbines for Floating Offshore Wind

DEPARTMENT OF NAVAL ARCHITECTURE, OCEAN & MARINE ENGINEERING

University of Strathclyde Engineering

Opportunity Study: Vertical Axis Wind Turbines for Floating Offshore Wind

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Submitted to

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Department of Naval Architecture,
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Executive Summary

This report constitutes the technical section on Vertical Axis Wind Turbines (VAWTs) of an opportunity study on VAWTs for floating offshore wind. The study is part of a collaborative work between the National Subsea Research Initiative (NSRI), Subsea UK, Wood and University of Strathclyde. This section of the report was led and carried out by the University of Strathclyde.

The aim of this report is to assess VAWT technology and to answer the question whether VAWTs could become a feasible alternative to deep water floating offshore wind farm developers. The motivation behind this question is the current challenges that horizontal axis wind turbines (HAWTs) are encountering in deep water, given that their increasing size is pushing the limits of their structural integrity and increasing the size and cost of their floating structures.

To try to answer the question above, we first present an introduction to VAWT technology, followed by an explanation of the basic differences between VAWTs and HAWTs from the power efficiency perspective. We note that the efficiency definition changes when referring to one single machine in isolation, as opposed to the efficiency of multiple machines in an array.

Subsequently, we discuss further differences between VAWTs and HAWTs, and identify those points that could be advantageous for VAWTs in a deep water offshore environment. We also identify the areas in VAWTs where research and development need to be performed. We assess the current technology readiness level (TRL) of VAWTs and HAWTs in the offshore floating context, to further identify those areas that will need to be developed. We present some innovative solutions that can help in this respect.

A reliability assessment is performed to show that the reduced complexity of VAWTs can significantly reduce the failure rate and downtime due to maintenance. Both of these aspects, usually not included in levelised cost of energy (LCOE) calculations, contribute greatly to the feasibility of VAWTs in a floating offshore environment.

Finally, a summary of the points above is presented in the last section. Two appendices are included at the end of the report. The first appendix shows the historical development of VAWTs, from the 80s until now. The second appendix shows theoretical estimations of the thrust force and the thrust bending moment experienced by VAWTs and HAWTs. These values are later used, in the structural section of the report, to compute the over-turning moments of the floating wind turbines.

TABLE OF CONTENTS

1 ABSTRACT

Deep water floating offshore wind farms present challenges to horizontal wind turbines (HAWTs) that were never encountered before. Maintaining the structural integrity and reducing the levelized cost of energy (LCOE) of floating HAWTs seems increasingly difficult. Mostly due to the increasing blade and support structure size required to harvest energy in the megawatt range and to keep the turbine afloat. An alternative to these challenges could be found in floating offshore vertical axis wind turbines (VAWTs). It is known that VAWTs have certain advantages over HAWTs, and in fact, some small-scale developers are now exploiting VAWTs and their advantages onshore. It remains to analyse and understand whether VAWTs can also offer a significant advantage for deep water offshore floating wind applications. This is the intention of this report. To present an analysis of VAWT technology and to assess whether VAWTs could offer a competitive advantage for floating offshore wind applications.

1.1 INTRODUCTION

VAWTs can be classified into four main groups: Savonious, curved bladed Darrieus, straight bladed Darrieus and H-type turbines. The first one is a drag-based turbine, whilst the latter ones are lift-based turbines. Figure 1a-d show the schematics of these turbines, respectively. The figure is adapted from Islam et al. [1]. Early offshore VAWTs developers in the 80s worked namely with the curved bladed Darrieus turbine in North America and with the H-rotor turbine in Europe and Asia. Developers in North America included companies such as, DAF Indal, Sandia National Laboratories, ALCOA, Adecon, FloWind, EOLE and in Europe, included Heidelberg and Musgrove [2]. The largest existing VAWT was the Eoele turbine in Canada. It was a curved-bladed Darrieus turbine rated at 3.8MW, that operated at 2.5MW for five years. The turbine worked with direct drive technology and had steel core blades, contrarily to most of its predecessors that operated with aluminium blades. After a few years of VAWT research inactivity, recent years have shown an uptake towards their research and development. Lately, VAWT small-scale developers (< 0.1 MW), such as 4Navitas [3] and Swift TG Energy [4], have developed successful commercial onshore VAWTs through technological innovations. And over the past few years, there has been a world trend to scale up VAWTs for deep water floating offshore applications, such is the case of Swedish company SeaTwirl [5], that aims to have a 1 MW prototype VAWT in 2022. Several VAWT research projects in America, Europe and Asia [3,4,5,6,19] have performed laboratory and technical feasibility studies for large scale floating offshore VAWTS, showing promising results towards VAWT scalability. For interested readers, a more detailed timeline of VAWT development is included at the end of the report, in Section 5.1 of the Appendices.

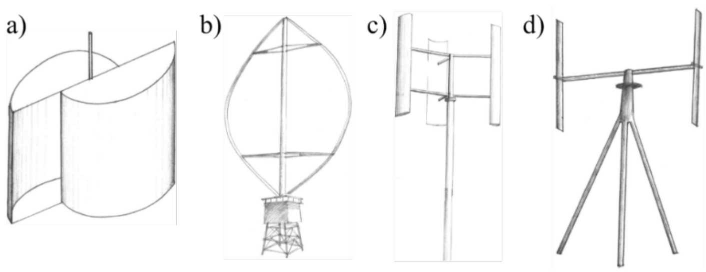

Figure 1 Vertical axis wind turbines a) Savonious turbine, b) Curve bladed Darrieus turbine, c) Vertical bladed Darrieus turbine and d) H-type of rotor adapted from Islam et al. (2008).

2 METHODOLOGY

Firstly, we present an introduction to the basic differences between VAWTs and HAWTs from the power efficiency perspective. We then present further aspects that can differentiate VAWTs and HAWTs in the floating offshore wind context. Subsequently, we analyse the technology readiness level (TLR) of VAWTs versus HAWTs and identify areas in VAWTS that need development. Finally, we present a summary of the VAWT value points in the context of floating offshore wind, where we highlight the potential advantages that VAWTs could bring to the floating offshore wind sector. Lastly conclusions are given where we assess whether VAWTs could offer a useful alternative to the current challenges that HAWTs encounter in the floating offshore wind environment. Two appendices are included at the end of the report. The first appendix shows the historical development of VAWTs, from the 80s until now. The second appendix shows theoretical estimations of the thrust force and the thrust bending moment experienced by VAWTs and HAWTs. These values are later used, in the structural section of the report, to compute the over-turning moments of the floating wind turbines.

2.1 BASIC DIFFERENCE OF VAWT VERSUS HAWT

2.1.1 Power coefficient

The governing factor that determined the success of HAWTs over VAWTs was the power coefficient of a single turbine. In full isolation and in open jet unidirectional freestream conditions, the power coefficient of HAWTs ($C_p \approx 0.5$) is typically higher than that of VAWTs ($C_p \approx 0.4$). Assuming the same swept area of the rotor and the same free stream velocity, HAWTs are able to convert more wind energy into mechanical energy. There are, however, a few caveats to this efficiency approach. Firstly, HAWTs need to be isolated (8 diameters in the cross-wind direction and 10 diameter in the downwind direction [6] [7]. Secondly, HAWTs should be aligned into the wind direction, which means that they require a yaw mechanism to orient the rotor into the wind direction. Figure 2 shows the swept area of a HAWT rotor (blue dotted line) plotted against the swept area of a similar height curved-bladed Darrieus turbine (black dotted line) and a H-rotor turbine (red dotted line). Assuming the same rated speed, the Darrieus turbine produces less power. In contrast, the H-rotor matches the rated power of the HAWT because the width and the height can be sized independently to each other [6].

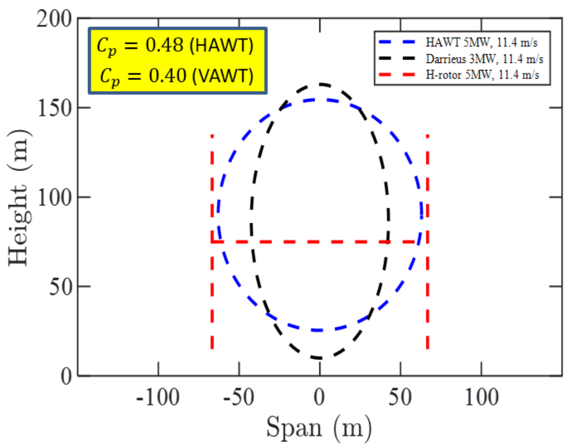

Figure 2 Swept areas of Darrieus VAWT turbine (black dotted line) and H-rotor turbine (red dotted line) plotted against swept area of NREL 5MW HAWT (blue dotted line). Rated velocity is 11.4 m/s.

2.1.2 Power density

Although for individual machines in undisturbed flow, the power coefficient is the governing factor to determine power efficiency. The governing factor in a wind farm is the power density. Power density is a measure of how much power per squared kilometre a wind farm will produce. Because VAWTs can be placed next to each other in counter-rotation in the cross-wind direction, whilst in the downwind direction a spacing of 4 diameters is enough to recover power performance [6], the power density of a VAWT wind farm can outperform that of a HAWT wind farm. In fact, it has been shown that the ability of VAWTs to stand closer to each other could increase the power density of a wind farm one order of magnitude. A typical power density of a HAWT wind farm is about 2 to 3 Wm^{-2} [6]. A higher power density can translate into a reduction of the levelized cost of energy (LCOE), and according to Sandia Lab and Sea Twirl, this reduction could be in the order of 20%.

2.1.3 Wind directionality

Another major difference is that VAWTs are omnidirectional, while HAWTs need to yaw into the wind direction to maximise power extraction. This increases the complexity of HAWTs since they require a yaw mechanism at the base of the hub, as well as pitch mechanism for each blade to control the power output. Contrarily, VAWTs are less complex turbines since they do not need to yaw into the wind, and therefore have less components than HAWTs. Reliable and simplified systems are preferred in deep water offshore deployments, where complex systems might incur into higher failure rates and higher downtimes [8]. Hence, VAWTs have an increased reliability and an operational advantage. In addition to increased reliability due to less complex systems, omnidirectional operation means that the power density of the wind farms is not dependent on the direction of the wind.

Figure 3 shows a schematic from Walt Musial from National Renewable Energy laboratory [7], where the importance of spacing between turbines and wind directionality in HAWT wind farms is highlighted. Both aspects would not pose a significant concern in a VAWT wind farm due to the considerations presented above.

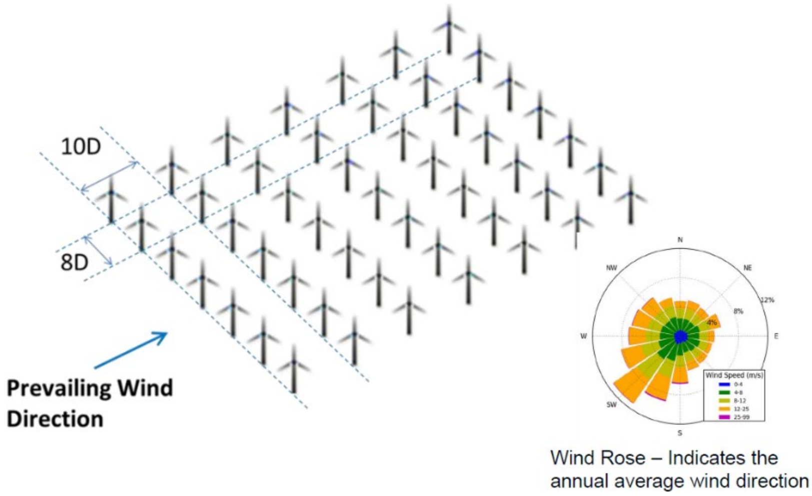

Figure 3 Spacing in HAWT wind from Offshore Wind Energy Facility Characteristics, NREL [7]

2.2 VAWT IN THE SYSTEMS APPLICATIONS OF FLOATING OFFSHORE WIND

In addition to the previous considerations, in the context of floating offshore wind, VAWTs offer distinctive characteristics that could reflect in a reduction of LCOE and in an improved reliability performance. This section addresses some of these aspects.

2.2.1 Operational loads

Here, we consider that the largest component of the over-turning moment in a turbine is the thrust or drag force. The line of action of the thrust force is higher in HAWTs than in VAWTs. This is because the thrust line of action in HAWTs is the hub height, whilst the thrust line of action in some VAWT designs is mid-height of the blades. This could translate into a reduction of over-turning moment (OTM) and hence, a potential reduction in the size of the supporting structure. This is an advantage of certain VAWTs over HAWTs for floating offshore deployments. We note, however, that not all VAWT designs will have a reduced over-turning moment and therefore the moments on the particular selection of VAWT design need to be assessed.

In contrast, a potential issue for two-bladed VAWTs is the cyclic thrust loading experienced by two-bladed VAWTs [9] or from the torque point of view, the "torque ripple" [10]. Two-bladed VAWTs incur into two maximum peaks in thrust at 90 and 270 degrees of rotor azimuth, when blade 1 and blade 2 are furthest upwind, respectively [11]. However, several mitigation strategies exist to reduce this type of cyclic loading. For example, increasing the blade number or incorporating compliant couplings between the rotor shaft and the gearbox shaft [10]. Lately new solutions have emerged, for example adaptive controls for smart blades. Examples of this type of technology are morphing blades [12] or tubercle blades [13]. These technologies can provide peak-to-peak load alleviation and attenuate the change in torque and thrust of VAWTs. Additionally, innovative VAWT designs, such as bearingless VAWTs [14] can also contribute to eliminate this type of cyclic loading.

Gravitational loads in deep-water offshore applications are an important source of fatigue loading in HAWTs due to the increasing length and mass of blades. In fact, gravity loading in HAWT blades results in sinusoidally varying edgewise bending moments that reach maximum values when the blade is horizontal [15]. Gravity loading in VAWT blades is not an issue of concern due to the orientation of the blades and the line of action of gravity with respect to the blades. This can also translate in lower maintenance rates and a reduction in LCOE. It is also worth pointing out that gravitational loads are likely to limit the maximum size that HAWTS can achieve, i.e. HAWT is self-limiting in scale whereas in theory VAWTs are not.

2.2.2 Transportation and installation

Transportation of long and thick blades is a logistical issue for road transportation in HAWTs [16]. For example, the length of blades of a 15 MW HAWT is in the order of 115 m, as shown in Table 4 of Section 5.2. In contrast, VAWT blades have uniform cross-section and could be manufactured in segments that can be transported in small lorries and assembled on site.

In principle, installation of floating offshore VAWTs does not seem to present any significant difference to its HAWT counterpart. Ideally the structure is assembled near-shore and towed to site. It could be possible however that VAWT offshore transportation presents an opportunity to tow at faster speeds.

This is because the increased resistance to a heeling moment and to their lower centre of gravity. This is an aspect that requires further study.

2.2.3 Stability and system dynamics

VAWTs have a lower centre of gravity (CoG) and therefore, they are more stable than HAWTs. This is potentially beneficial both for towing and station keeping. Furthermore, the upright orientation of the blades allows for additional stability devices, such as transverse sails [17] that can reduce further operational over-turning moments.

In terms of system dynamics, gyroscopic effects could amplify pitching motions in VAWTs [18]. However, demonstrative small scale floating VAWT projects, such as Deepwind [19], have shown that gyroscopic effects are not detrimental to operation. We note that two-bladed VAWTs could have more than one excitation frequencies (frequencies where the system becomes resonant), where pitching motions could be amplified [9]. There are, however, mitigation strategies that can be implemented, such as VAWTs with more than two blades and variable stiffness moorings (smart materials) that can help coping with these effects.

2.2.4 Maintenance access, Inspection and Safety

Access to the generator in VAWTs is closer to sea level than access in HAWTs, which occurs at hub height level. This ease of accessibility can therefore reduce downtime due to maintenance [5]. Ease of accessibility can also impact safety aspects of offshore maintenance. According to the G+ Global Offshore Wind Health and Safety Organisation 2019 incident data report [20], high potential incidents occur mostly accessing the wind turbine generator, specifically in the nacelle, tower, the hub and the blades. VAWTs offer a radically new approach to maintenance, avoiding working at heights and having a significant impact in high potential incidents.

2.2.5 Environment

According to Manning [21], the major environmental impacts of HAWTs are safety, electromagnetic interference, visual acceptability, bird and other collisions, noise and microclimate.

Safety is a matter of concern in terms of missiles ejected from the turbine, such is the case of icicles or blade fragments. Although icicles have been reported to be thrown in both HAWTs and VAWTS [21], It is possible that missiles or icicles from VAWTs would reach shorter distances because of the lower rotational speeds. This is however an area or research that needs to be further investigated.

Collisions with structure are classified into aircraft collisions and wildlife collisions. An advantage of VAWTs over HAWTs is that warning lights could be placed at the same height as the tallest structure, whilst in HAWTs, the warning light is located at hub height, which is about 100 meters lower than the turbine's full height. In terms of bird strikes, it has been suggested that VAWTs have a lower impact in bird mortality rate, as opposed to that of HAWTs.

Because VAWTs have lower tip speed ratios (TSR) than HAWTs and most of the noise in HAWTs is emitted at the tip of the blade which travels at TSR; it is expected that lower levels of aerodynamic noise are emitted from VAWTs. Additionally, fluctuations in the lift force due to changes in the angle of attack of the blades, such as the changes in angle of attack present in VAWT blades, can be a source of noise. It is expected, however, that the low TSR helps in mitigating this effect. Additionally, technology that tackles variation in the blade angle of attack (tubercle blades, morphing blades) can help in the mitigation of this type of noise.

2.3 VAWT TURBINE TECHNOLOGY

2.3.1 Market Design Status

Small-scale VAWT developers such as 4Navitas [3] and Swift TG Energy [4] have commercialised small-scale turbines for the onshore market successfully. At the same time, small-scale floating offshore VAWT technologies have successfully been deployed and demonstrated in recent years [3,4,5,6,19].

Among these small-scale demonstrative projects, the VAWT turbine of Swedish company SeaTwirl [5] is closest to large scale deployment. They are currently developing a guyed 1 MW straight-bladed Darrieus turbine with three blades. The turbine has a 50 m diameter and a 40 m diameter blade length. If successful, this would be the first large scale floating offshore VAWT ever deployed. To further visualise the range of dimensions that VAWTs could reach in the future, if they are to be operated in the MW scale region, Table 3 of Section 5.2 shows the dimensions of three two-bladed Darrieus and three H-rotor turbines sized at 3, 9, and 11 MW, and at 5, 10, and 15 MW, respectively. Figure 4a shows the 30 kW small-scale guyed prototype manufactured by SeaTwirl and Figure 4b shows the schematic of their 1 MW prototype. Both figures area available on their website [5].

a) b)

Figure 4 a) Small-scale SeaTwirl S1 rated at 30 kW and b) SeaTwirl S2 turbine concept with underwater spar and ballast. Both figures were taken from the SeaTwirl website [5].

2.3.2 Technical Review

The technology readiness level (TRL) for floating offshore VAWTs was assessed versus the TRL level of floating offshore HAWTs based on existing operational floating offshore wind farms. Of course, for VAWTs there are no deployments to this date, and so the assessment was performed based on individual components, lessons learnt, and reports published by small-scale developers and research consortia. The assessment was carried out by all members of this project's consortium. The assessment was performed first through preliminary discussions and in a dedicated online session held in the first week of March, 2021.

Two size of turbines were considered for HAWTs and VAWTs: 5MW and 10MW. The TRL assessment was performed in a scale from 1 to 9, following the convention set out by the European Marine Energy Centre (EMEC) *[22]*. The reference cases for floating HAWTs were the Hywind Scotland and Hywind Tampen windfarms. Both farms have floating offshore HAWTs rated at 6 MW and 8.8 MW, respectively. This resulted in high TRL levels for the evaluated HAWT cases of 5 and 10 MW. The rating was kept high for individual subcomponents and also, for the full integral system of floating HAWTs turbines.

The TRL level at the subcomponent level of floating VAWTs was ranked at an average level of 6. This is because most of the turbine components have been proven to be operational onshore. Some subcomponents such as the main bearing, power take-off and control systems, depend on the specific design of the turbine and were ranked accordingly at a lower level. Although the ranking for these subcomponents could be higher, however, a specific design of a VAWT turbine is required.

The biggest gap between floating HAWTs and VAWTs was found at the integral level. This is because a large-scale deep water floating VAWT has not been implemented yet. However, the industry trends that we have identified show that this might change soon. Furthermore, rapid progress between TRL levels is now possible given that the individual turbine components and the knowledge and technology readiness of floating structures is high.

Smart solutions can help to develop the TRL of VAWTs and contribute to alleviate cyclic loading of floating offshore VAWTs. For example, VAWTs without central bearings [14] [23] [24] or the use of compliant couplings [10] could increase the TRL level of those individual VAWT components that require research and development.

Results of the technical review assessment are presented in Table 1. In the table the first column shows the main turbine components: nacelle and hub, blades, tower and the full system category. The last row category refers to the integral system of the turbine and the floating structure. Each of the main categories of the first column is further divided in subcomponents in the second column. We follow the subcomponent classification of the CATAPULT Offshore Renewable Energy guideline to offshore wind farms *[25]*.

		Floating HAWT		Floating VAWT	
Turbine part	Subcomponent	5 MW	10 MW	5 MW	10 MW
Nacelle and hub	T1.1 Bedplate	8	7	6	6
	T1.2 MainBearing	8	7	3	3
	T1.3 Main Shaft	8	7	6	6
	T1.4 Gearbox	8	7	6	6
	T1.5 Generator	8	7	6	6
	T1.6 Power Take-Off	8	7	3	3
	T1.7 Control System	8	7	3	3
	T1.8 Yaw System	8	7	N/A	N/A
	T1.9 Yaw Bearing	8	7	N/A	N/A
Blades	T2.1 Blades	8	7	6	6
	T2.2 Hub Casting	8	7	6	6
	T2.3 Blade bearings	8	7	6	6
	T2.4 Pitch System	8	7	6	6
	T2.5 Spinner	8	7	N/A	N/A
Tower	T3.1 Steel	8	7	6	6
	T3.2 Tower Internals	8	7	6	6
Full system	Turbine + floating structure	8	7	3	2

Table 1 TRL level for 5 and 10 MW FOW HAWTs and VAWTs

The outcome of the TRL analysis showed that floating VAWTs need to be developed at larger scale levels to provide a benchmark case that demonstrates their feasibility. At the time of this report, SeaTwirl in Sweden seems to be leading the way towards this goal. If this is achieved in 2022, it will provide a solid stepping stone to development of the floating offshore VAWT market.

Secondly, reliability of VAWTs due to their decreased number of induvial parts (visible also in Table 1, where N/A stands for not applicable) can be exploited further through technological developments. As previously stated, technology to alleviate cycling loading in the generator can be incorporated. Several technologies have been tested already (compliant couplings by Sandia National Laboratories) and others are being developed (smart blades, smart VAWT designs).

2.3.3 Manufacturing and recycling

The TRL study showed that the individual components of VAWTs are, from the manufacturing point of view, at a high TRL level. And there are, in fact, several opportunities that arise in terms of recycle friendly materials and simplification of the manufacturing process in the turbine components.

Because VAWTs use uniform cross-section throughout their span, blades can be manufactured in segments, as opposed to varying cross-section single piece blades used in HAWTs. VAWT blades can be manufactured with carbon/fiberglass composites. Whilst the segments can be joined with adhesives in small scale prototypes, or with mechanical fixtures, such as rivets, in large scale prototypes. This modularity in the manufacturing of the blades could translate into a significant reduction of manufacturing costs [16].

Lighter materials can also be considered for VAWTs, such as those proposed by sail-inspired blades company Actblade [26], which utilises textiles used in the sailing industry. This type of material would reduce the weight and manufacturing times of the blades, whilst at the same time, would provide a sustainable recycling framework.

One of the challenges in HAWTs decommissioning is the recycling of the blades. This is in part due to their complex shapes. In contrast, VAWT straight and curved blades can be reutilised as support or reinforcing material for housing and shelters in areas of the world where construction materials are required. The simple shape of the blade can easily be incorporated to reinforce vertical and horizontal surfaces. Alternative uses of blades (Figure 5) are also being explored for the complex shapes of HAWT blades [27], however, their non-uniform cross section complicates their adaptation to the human-made landscape. Hence VAWT blades have the shape advantage in terms of establishing a circular economy.

Figure 5 Google maps screenshot from Meidoorn playground in Rotterdam, Netherlands with decommissioned HAWT turbine blades. Straight and curved shapes of VAWT blades offer more versatility towards housing and shelter construction options.

2.3.4 Reliability

Recent studies have shown that improved reliability has the potential to decrease the levelized cost of energy (LCOE). VAWTs are inherently more reliable than VAWTs because of the reduced number of parts needed to operate. The omnidirectionality of VAWTs obliterates blade pitching systems and full turbine yaw mechanisms. In fact, it has been shown that these two turbine subcomponents account for about 50% of the failure rate of offshore HAWTs [8] [28].

The reduced mechanical complexity and potential reduction in failure rate from VAWTs, would compensate for the lowest power coefficient (C_p) that in principle make VAWTs a less attractive option when compared to HAWTs. The effect of a lower failure rate and therefore a lower downtime is most of the times missed out by developers, given that the typical LCOE calculations do not take into account failure rate and downtimes due to maintenance [8].

Most importantly is the downtime due to failures. Downtime offshore is about twice of that than downtime onshore. In particular, the parts that take up most of the down time offshore are related to turbine generator access [8]. Downtime can also be affected due to accessibility, and as shown previously, accessibility to VAWT generators is easier due to their position closer to the sea level.

We introduce first the findings presented by Dao et. al. [8], which were based on different databases of offshore HAWT wind farms. Table 2 shows the quartile coefficient of dispersion (COD) computed by Dao et. al. [8] for failure rate and downtime for different HAWT subassemblies. The COD is a key performance indicator that shows how failure rates and downtimes vary between different subassemblies in different windfarms. A reliable or predictable system should have a low COD.

Subassemblies	Failure Rate COD	Downtime COD
Blades and Hub	0.708	0.866
Air brake	0.478	0.593
Pitch	0.938	0.789
Shafts and bearings	0.563	0.099
Mech. Brake	0.588	0.882
Gearbox	0.698	0.552
Generator	0.651	0.678
Hydraulic	0.59	0.373
Yaw	0.74	0.888
Control system	0.693	0.687
Electrical	0.9	0.443
Sensors	0.631	0.742
Nacelle	0.496	0.691
Structure	0.705	0.955
Other	0.645	0.552
Total	**10.024**	**9.79**
Total excluding Yaw, Pitch & 50% structural	**7.9935**	**7.6355**
Reduction in Failure Rates/Downtime	-20.26%	-22.01%

Table 2 Quartile coefficient of dispersion for failure rates and downtimes of HAWTs subassemblies

In Table 2, the low COD of electrical subassemblies shows for example, that the variability in downtime due to electrical aspects is low between different wind farms. However, downtime COD of pitch, mechanical brakes, yaw and structural systems have a higher COD.

This is because of the variability in designs and diversity of potential issues in these subsystems. In VAWTs some or all of this variability is eliminated. Firstly, downtime due to pitch and yaw systems is eliminated because these systems do not exist in VAWTs. Secondly, we expect failure rates and downtime COD related to structural aspects to be reduced to about half of the HAWT COD value, because of the reduced number of fatigue cycles (slower rotation of VAWTs) but also due to the relative insensitivity to turbulent air conditions.

Given these assumptions, it is expected that VAWTs show a significant reduction in failure rate and downtime due to their reduced mechanical complexity. Our analysis from Table 2, shows that a drop of about 20% in both failure rate and downtime COD could be expected for floating offshore VAWTs.

3 VAWT TURBINE VALUE SUMMARY

This section presents a summary of the aspects that make VAWTs an attractive option for deep water offshore developments. We present these aspects in a comparison table, where we assess which turbine between HAWT and VAWT has the competitive advantage in the specific subcategory. The subcategories are grouped in the first column of Table 3 into global categories, which we refer to as: aerodynamic efficiency, structural integrity, reliability, stability and dynamics, transportation and operation and maintenance (O&M) costs. Table 3 shows the summary of the assessment.

Categories	Subcategory	Offshore HAWT	Offshore VAWT	Value
Aerodynamic efficiency	Power coefficient	0.5	0.4	HAWT
	Power density	3-5 W/km2	> 10 W/km2	VAWT
	Directionality	Yaw control	Omnidirectoinal	VAWT
Structural integrity	Size of support structure	Large	Small	VAWT
	Gravitational cyclic loads	Yes	No	VAWT
	Cyclic thrust loading	No	Yes	HAWT
Reliability	Failure rate	High	Low	VAWT
	Downtime	High	Low	VAWT
Stability and dynamics	Center of gravity (COG)	High	Low	VAWT
	Gyroscopic effects	Low	High	HAWT
	Excitation frequencies	1	> 1	HAWT
Transportation	Length of blades	Full blade	Segmented blade	VAWT
O&M costs	Accessibility to generator	Hub height	Close to sea level	VAWT

Table 3 Summary of value points of VAWTs versus HAWTs

Table 3 shows highlighted in green, the subcategories where we believe that VAWTs hold the competitive advantage. It is clear that the power density, directionality and the reliability, through reduced mechanical complexity, position VAWTs as an attractive option for deep water floating offshore wind farms to harness wind energy.

Highlighted in yellow are the categories where VAWTs might be criticised and where development needs to be carried out. We note however, that we considered two-bladed VAWTs on this analysis. In addition, most of these aspects, have been investigated or are being mitigated, through innovative technological solutions. For example, the variation in thrust loading of VAWTs has been dealt previously through compliant couplings [29]. Similarly, innovation in VAWT design, through three-bladed rotors or smart blade designs with adaptive controls can mitigate or eliminate the ripples in thrust loading.

In terms of stability and dynamics, both gyroscopic effects and excitation frequencies can be dealt with new technology, such as variable stiffness moorings, and through laboratory testing. In fact, gyroscopic effects are not detrimental for VAWT performance [19].

In summary, the positive aspects of VAWTs will reflect in a decrease in LCOE and they should overcome the negative aspects that VAWTs could have. Furthermore, the negative aspects can be alleviated through new technology and innovation in technology and design.

4 POTENTIAL FOR FURTHER DEVELOPMENTS

This section presents a summary of the potential areas where further developments for floating offshore VAWTs could be attained. We also provide an answer to the question whether floating VAWTs can become an alternative to floating offshore HAWTs or not.

It is clear from the TRL analysis that the current state of the art for floating offshore VAWTs at the integral level is behind the TRL level of floating offshore HAWTs. We recall, however, that the wind industry is a relatively new industry, and that the development of contemporary offshore VAWTs has only about twenty-years in the making.

In contrast, whereas contemporary offshore HAWT systems have taken over twenty-years to develop, the primary developments in offshore structures, blades, generators, control and drive trains are all transferrable to VAWT and it is therefore considered that the same learning curve experienced by HAWT is not necessary and that VAWT could with the right investment and resolve present a commercial alternative by 2030.

Furthermore, this timescale can be reduced if more entrepreneurial and less risk adverse approaches are considered by energy companies. It has been shown, for example, in the case of oil and gas, that cases of high interest occur quickly with appropriate funding. For example, the introduction of remote underwater intervention technologies (ROVs) in the late 1980s/early 1990s eliminating divers from normal operations subsea in the North Sea. The technology development and implementation happened in a few short years revolutionising offshore working.

As such, the climate change crisis will also lead to power companies to prioritise investments in technology to increase their readiness level, and therefore an opportunity lies ahead for floating offshore VAWTs. More so, HAWTs are self-limiting in terms of scale, due to gravity loading, we believe that VAWTs do not have this limitation, as such it is possible to develop large scale VAWTs within higher power density arrays.

As mentioned earlier, there are areas where technology from HAWTs is transferable to VAWTs, for example, floating structures, electronics, blade manufacturing techniques, and of course, there are specific areas where investment is needed. We believe that most of these development areas lie within the turbine itself, rather than in the floating structure. This is because the floating structure characteristics for VAWTs will not change majorly from what is commercially available for floating HAWTs.

The areas of opportunity for investment in floating VAWTs, that we have identified, are:

Improving the understanding of fluid structure interactions, in particular interactions of wave and turbulence with an integral floating VAWT system to optimise structural fatigue.

This first aspect needs to be developed to better understand the full system dynamics of a floating offshore VAWT, when subject to wave and turbulent loading. It has been stipulated that two-bladed floating VAWTs could be more susceptible to induced pitching motions in the range of frequencies of the ocean waves. In contrast, two-bladed floating VAWTs could but less susceptible to turbulent frequency fluctuations. As mentioned earlier in the report, there are some mitigation strategies to reduce the impact of motion amplification due to different wave frequencies, for example, the inclusion of three blades into the design and also, the use of variable stiffness moorings. These aspects, however, need to be carefully assessed in a laboratory setup first, and then into larger scale prototypes. The understanding of these aspects will then enable us to characterise the wave or turbulent induced loading and measure their impact in the fatigue life of the VAWT design.

Development of bearingless VAWT solutions to extend the fatigue life of VAWTs and improve further their reliability.

This second aspect is of paramount importance. In addition to better understanding the effects of wave and turbulence loading on floating VAWTs, one of their most criticised points, and the reason why VAWTs stopped being developed in the 80s, has been the promptness to fatigue failure due to the cyclic loading concentrated in the central shaft or main bearing. Technological innovation has shown several options already on how to deal with this problem. Ranging from compliant couplings, used by Sandia laboratories, to VAWT designs that get rid of any bearings. For example, Salter's design [14]. His design gets rid of the bearing with a novel power take-off (PTO) mechanism. In his design, two floating cylinders hold the vertical blades. One of the cylinders holds a quad-cam ring that rotates, pushing in and out displacement cylinders to pump hydraulic fluid into a generator. Hence this system is innovative in design and by using existing technology, eliminates the need of any bearing. In addition to that, the doubly supported blades are structurally superior than single HAWT held blades.

Development of smart flexible materials to alleviate peak to peak mechanical loading, through morphing structures and variable stiffness moorings.

Finally, the use of smart materials tailored towards floating offshore VAWTs. These smart materials can help to alleviate any change in loading that occurs during a full rotation cycle. The change in loading is typically due to angle of attack oscillations in the blades and due to motions in the floating structure. Smart materials that flex, stretch and compress in response to external loads have the ability to attenuate the energy absorbed by the structure, by means of deformation. In the case of smart flexible blades, the angle of attack oscillations due to blade rotation can modify the shape of the blade at the trailing edge. This deformation will dimmish the change in loads sensed by the blade and therefore prolong the fatigue life of the turbine. These technologies have not been implemented in large scale previously but have been demonstrated already in laboratory settings [12]. Hence, new and exciting possibilities lie ahead to improve the structural design of floating VAWT developments.

In summary, we believe that given that some of the technology for floating VAWTs is already developed and transferable from other industries, and given that the opportunity areas where investment is needed have feasible solutions; there is no reason why floating offshore VAWTs of large scale cannot be developed. However, securing sufficient funding is needed to reach a commercial stage within 10 years or less. Contrary to what happened in the 80s, technology levels now are high and most of the VAWT technology is transferable from other industries, and also, technology innovation have offered nowadays solutions that did not exist before.

5 CONCLUSIONS AND RECOMMENDATIONS

This report presented a study on vertical axis wind turbines (VAWTs) to address the question whether VAWTs can offer a solution to the challenges encountered by horizontal axis wind turbines (HAWTs) in floating deep-water deployments. These challenges include the increasing structural challenges and increasing costs, associated with very large structures to make floating HAWT wind farms profitable.

We first presented the basic differences between HAWTs and VAWTs from the energy efficiency perspective. We showed that power density and omnidirectionality of operation in VAWTs is different to HAWTs. These two aspects, on their own should over-compensate in a wind farm, for the lower power coefficient of individual VAWT machines.

In addition to this, several other aspects of VAWTs can help in decreasing the levelized cost of energy (LCOE) from a developer perspective. One of these crucial aspects is improved reliability of VAWTs. The reduced complexity of VAWTs (no yaw and no pitching mechanisms) will reduce the downtime due to failures associated to these components. Furthermore, additional downtimes due to mechanical breaks and structural aspects should be lower for VAWTs, given that they are exposed to about 50% less fatigue loading cycles than HAWTs. This is because of their reduced rotational operational velocity and their relative insensitivity to turbulent air conditions.

Finally, we demonstrate that the aspects where two-bladed VAWTs have been criticised such as thrust cyclic loading and dynamic stability effects, can be tackled through well-known technology (compliant couplings) or through innovation in design and technology, such as three-bladed VAWTs or passive adaptive control in blades, such as leading-edge tubercles or morphing technology, and variable stiffness mooring lines made with smart materials.

In terms of further recommended work, the following points have been identified.

1) Although there has been some pioneering work in terms of understanding fluid structure interactions of floating VAWTs [9] , there is a need to better understand these interactions for VAWT configurations in order to optimise structural fatigue. For examples aspects, such as, turbulence and wave-VAWT interactions need to be further analysed.
2) Bearingless VAWT solutions, such as the VAWT models proposed by Akimoto or Salter [14], [23] [24] need to be developed to fully capitalised the potential of floating offshore VAWTs.
3) Advanced materials with particular application to blade morphing and variable stiffness moorings need to be studied.

6 APPENDICES

6.1 HISTORICAL BACKGROUND ON VAWT DEVELOPMENT

6.1.1 Historical background of onshore VAWTs

Early offshore VAWTs developers in the 80s worked namely with the Darrieus turbine in North America and with the H-type turbine in Europe and Asia. Developers in North America included DAF Indal, Sandia National Laboratories, ALCOA, Adecon, FloWind, EOLE and in Europe, included Heidelberg and Musgrove [2]. The largest existing VAWT, the Eoele turbine in Canada, was a Darrieus turbine rated at 3.8MW, but operated at 2.5MW for 5 years. The turbine worked with direct drive technology and had steel core blades, contrarily to most of its predecessors that operated with aluminium blades.

Limited range of materials and two bladed rotor configurations contributed to the fatigue related issues that VAWTs encountered in the late 80s and therefore the HAWT sector took off. At the time, HAWTs were small, and the length of the blades was not an issue. These factors contributed to the growth of the sector. Figure 6, adapted from Möllerström, et al. (2019) shows a snapshot of the historical development of VAWTs during the 80s and the fall of interest during the 90s and 2000s. The early 90s saw the first offshore wind farm *Vindeby* with a capacity of almost 5 MW.

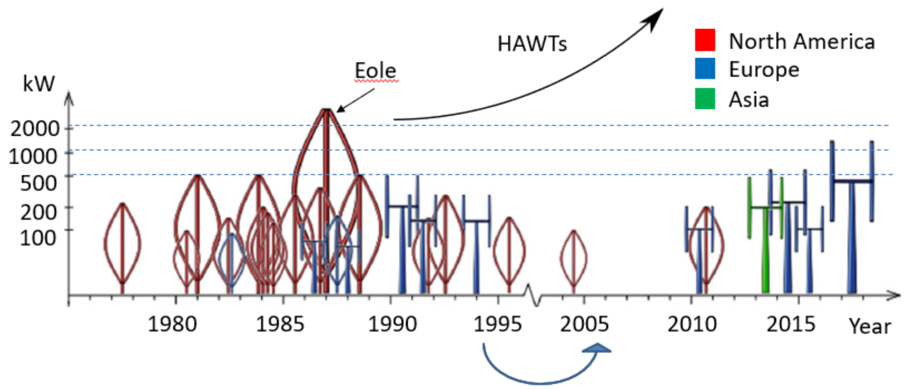

Figure 6 Timeline of onshore VAWTs, Source: Möllerström et al. ,
A historical review of vertical axis wind turbines rated 100 kW and above [2]

6.1.2 Offshore VAWTs recent studies

In recent years, offshore VAWT research has emerged. This resurgence in VAWT research is driven by the challenges that HAWTs are encountering offshore. Blade lengths of modern HAWTs are above 100 meters, and therefore, turbine heights have increased as well.

Although turbine heights are these days site specific, a taller HAWT represents a higher cost for the floating structure. Recent efforts in research and development of offshore VAWTs have occurred between 2010 and 2020. Most of these examples were developed as floating offshore developments. We present here some of the most significant examples, although we recognise there could be more.

- VertAx Wind is an H-type fixed offshore three bladed wind turbine developed by VertAx Wind Limited in the UK [30]. The support structure is a monopile and the turbine has a helipad on the top of the tower. The design of the turbine aims to minimise moving components and incorporates the novel C-Gen generator. This is a direct drive multi-stage air-cored permanent magnet. The generator technology has been developed at the University of Edinburgh and has been demonstrated at a 1 MW scale (website: https://www.cgen.eng.ed.ac.uk/).
- The NOVA project delivered a feasibility study of a 5 MW and 10 MW floating V-shape VAWT. The turbine had sectional sails throughout its arms to provide additional restoring moment. The prototype had a significantly low centre of gravity (COG) and a reduced overturning moment. The research consortium was formed by OTM Consulting Ltd, Wind Power Ltd, Centre for Environment Fisheries and Aquaculture Science and the Universities of Cranfield, Sheffield and Strathclyde. Further details on the project can be found in Shires (2013) and Collu, Brennan and Patel (2014).
- Vertiwind was a joint project between French start-up Nenuphar and French-based oil and gas firm Technip. Only onshore prototypes of small scale (35 kW) turbines were tested. The company had secured a €7M governmental grant to develop a 2MW prototype [31] before going bust in 2018. The large 2MW prototype featured a low COG with a 50 ton generator located 20 meters above sea level.
- Deepwind was a vertical axis Darrieus turbine developed by the Danish Technical University (DTU). Their largest design was rated to 5 MW [19] and the turbine was supported by a rotating spar buoy. Preliminary results show that the turbine does not present stability problems, has structural resilience and the magnus effect on the rotating spar is controllable. There were still some challenges in terms of electrical systems, due to low rotational speeds of the rotor and the underwater electrical parts.
- Skwid was a hybrid wind-tidal device rated at 500 kW manufactured by MODEC. The device consisted of a floating straight bladed VAWT turbine connected to a submerged Savonious turbine. The generator was above mean sea level and was kept afloat by a floating disc. The device sank twice during deployments and MODEC stop further attempts of installation.
- Lastly, a floating axis wind turbine (FAWT) concept has been developed by Akimoto et al. (2011). The concept exploits the buoyancy force to support the weight of the rotor axis and gets rid of the central VAWT bearing by having an externally mounted generator with rollers coupled to the rotating shaft. Details on this concept can be found in [24] and [23].

A timeline summarising some of the above-mentioned concepts is depicted in Figure 7.

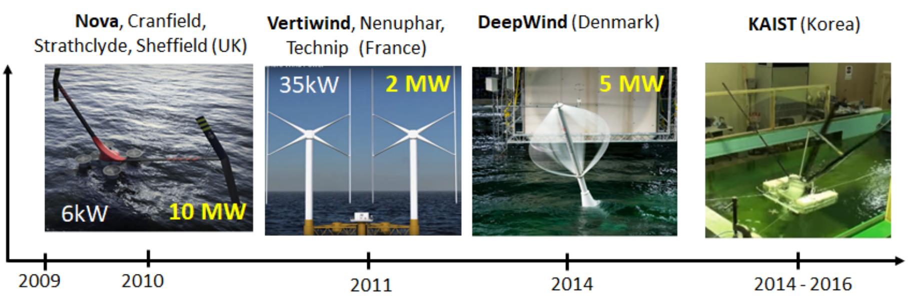

Figure 7 Timeline of research developments in offshore floating VAWTs

6.2 LOAD ASSESSMENT

6.2.1 Thrust assessment of HAWTs

Considering an actuator disc model, the thrust force on a turbine is computed as

$$T = 2\rho A u^2 a(1 - a),$$

where ρ is the density of air, A is the swept area of the rotor, u is the free stream velocity and a is the axial induction factor. For the Betz limit $a = 1/3$. Here, we consider $a = 0.3$ to account for aerodynamic losses for both HAWTs and VAWTs. We consider three HAWT cases. The first case is the NREL 5MW HAWT rated at 11.4 m/s, for which thrust and overturning moment data can be found in Borg and Collu [9]. The second case is a 10 MW Siemens Gamesa HAWT and the third case is a 15 MW VESTAS HAWT.

Table 3 shows the hub height, rotor diameter, height, blade length, hub diameter, swept area, rated wind speed and the computed thrust and thrust moment (TM) for the three HAWT cases. The rated wind speed (u) at a height z is computed with a power law

$$u = u_{5\mathrm{MW}} \left(\frac{z}{z_{5\mathrm{MW}}}\right)^{\frac{1}{7}}$$

where $u_{5\mathrm{MW}}$ and $z_{5\mathrm{MW}}$ are the rated wind speed and the hub height of the NREL 5WM turbine. The thrust moment (TM) is computed only with the thrust force by multiplying the thrust force (T) by the hub height (h). The power extracted from the actuator disc representing each turbine can be estimated with

$$P = 2\rho A u^3 a(1 - a)^2.$$

and the fraction of P that gets converted to electrical power is defined as the power coefficient C_p.

HAWT category	5 MW (NREL)	10 MW Siemens Gamesa	15 MW VESTAS V236
Hub height	90	140	150
Rotor diameter	126	193	236
Height	153	236	268
Blade length	61.5	94	115
Hub diameter	3	5	6
Swep area (m^2)	12,468	29,300	43,742
Rated wind speed (m/s)	11.4	12.1	12.3
Thrust (N)	8.00E+05	2.20E+06	3.30E+06
TM (Nm)	7.40E+07	3.10E+08	5.00E+08

Table 4 Main dimensions, thrust and thrust moment (TM) of HAWT study cases: NREL 5MW, Siemens Gamesa 10 MW and VESTAS 15 MW

6.2.2 Load assessment VAWTs

We project the swept areas of curved-bladed Darrieus and H-rotor turbines over the swept area of HAWT turbines of 5, 10 and 15 MW. This is shown in Figure 1, for the 5 MW HAWT turbine. We note that because of the lower C_p value of the VAWTs and because the rated wind speed is kept constant in every swept area comparison exercise, the extracted power of a Darrieus turbine of similar height to the HAWT will be lower. Therefore, the rated power of the three Darriues turbines presented in Table 4 is 3, 9 and 11 MW. Contrarily, because the width of the H-rotor can be increased independently to the height, the output power for these turbines match the HAWT ratings of 5, 10 and 15 MW.

Results from Table 5 show that the thrust between Darrieus and H-rotor turbines is similar to that of the HAWT turbines counterparts of Table 4. However, for VAWTs, there is a reduction in the thrust moment (TM) due to the thrust force (T), because of the lower line of action of the thrust force in the turbine. The line of action of the thrust force in a HAWT is the hub height, whilst the line of action in a these VAWT examples is considered to be the mid height of the blades. We note however, that this assumption might differ for different VAWT designs.

HAWT dimensions	3MW Darrieus	9MW Darrieus	11MW Darrieus	5MW H-Rotor	10MW H-Rotor	15MW H-Rotor
Thrust Action Line	74	113	125	58	74	90
Rotor diameter	85	132	146	133	172	208
Height	153	236	261	120	155	187
Blade length	153	236	261	120	155	187
Swep area (m^2)	10271	24438	29889	16010	26712	38880
Rated wind speed (m/s)	11.4	12.1	12.3	11.4	12.1	12.3
Thrust (N)	6.77E+05	1.81E+06	2.28E+06	1.05E+06	1.98E+06	2.98E+06
TM (Nm)	4.98E+07	2.06E+08	2.86E+08	6.08E+07	1.48E+08	2.68E+08

Table 5 Main dimensions, thrust and thrust moment (TM) of VAWT study cases: Darrieus 3, 9, 11 MW and H-rotor 5, 10, 15MW

6.2.3 Comparison of results

Figure 8 shows the average thrust and average thrust moment for the HAWT, Darrieus and the H-rotor reference cases. No significant differences are observed in terms of the mean thrust experienced by the turbines in Figure 8a. This is because the cross-sectional area A is designed to be similar between all of the turbines. On the contrary, a reduction of approximately 40% in the average thrust moment is observed for the H-rotor, at a rated power of 15 MW in Figure 8b. A smaller reduction of about 15% is observed in the average thrust moment of the Darrieus turbines at 11 MW.

a) b)

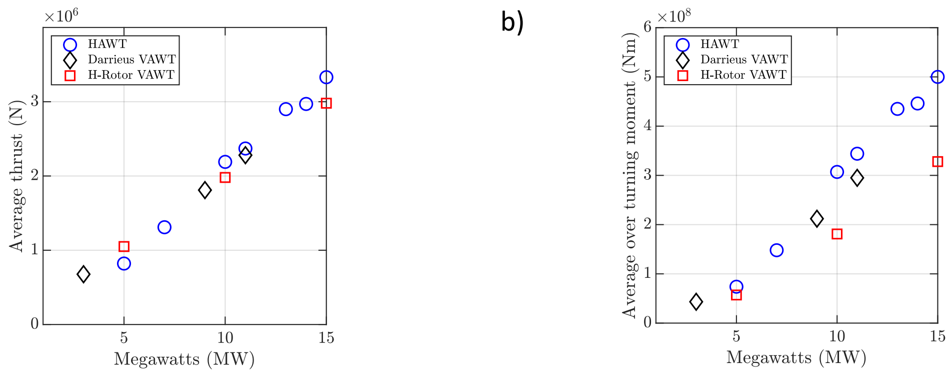

Figure 8 a) Mean thrust and b) mean thrust moment.

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Appendix 6.2

6.2 Wood: Vertical Axis Wind Turbine for Floating Offshore Wind: Structure and Subsystems Report wood.

Vertical Axis Wind Turbines for Floating Offshore Wind – Structure and Subsystems

Prepared for: NSRI
Doc Ref: 806808-00-SF-REP-001
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Report

Client	
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Vertical Axis Wind Turbines for Floating Offshore Wind – Structure and Subsystems	
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Revision	Date	Reason for Issue	Prepared	Checked	Approved
A	02/04/21	Issued for Review	JM	KA	KA

Executive Summary

Wood has been contracted to perform an assessment of the opportunity for using Vertical Axis Wind Turbines (VAWT) for Floating Offshore Wind (FOW) developments on the floating structure and associated subsystems. Subsystems within the scope of work performed include the mooring lines and anchors. This scope forms part of a wider scope of work considering the turbine technologies available and the economic potential for VAWT developments in Scotland performed as a consortium of National Subsea Research Institute, University of Strathclyde, and Wood.

There are four main types of FOW hull foundation structure typology: barge, semi-submersible, spar, and tension leg platform (TLP). Spars and semi-submersibles are the most advanced structure types in terms of technology readiness level (TRL). Each have been deployed at full scale, grid integrated FOW developments. Hywind Scotland has five 6MW spar floating turbines and WindFloat semi-submersible structures are deployed at WindFloat Atlantic at 8.4MW scale and Kincardine Offshore Wind Farm at 2MW and 9.5MW scale. These two structure designs are therefore considered for relative sizing assessment between HAWT and VAWT turbine deployments.

VAWT deployments offer a number of theoretical advantages over traditional HAWT deployments. As turbine capacity increases HAWTs get taller raising the height of the bulk of the turbines mass in the form of the rotor and nacelle assembly. VAWTs have this equipment at the base of the turbine lowering the turbines centre of mass. Wind thrust force loading for HAWTs can be considered to act at the hub height, being the centre of the turbine's swept area. As turbine capacity increases this line of action will be further from the base of the tower increasing the overturning moment lever arm under wind loading. As VAWTs are able to increase swept area through increasing diameter as well as increasing blade height, it is possible for them to keep their thrust force line of action lower for similar power outputs. Thus, lowering the overturning moment applied to the structure from the same thrust magnitude. These two aspects may allow for smaller structures to be used to provide the same level of stability, reducing the hull fabrication costs.

Wood has performed a static stability assessment comparing overturning moments generated by HAWTs and two types of VAWT (Darrieus and H-Rotor). This assessment concludes that due to their lower mass and reduced thrust force elevations H-Rotor VAWTs could realise up to a 16% reduction in structural steel mass compared with a similar power output HAWT. The saving becomes most pronounced as turbine capacity increases. As turbine capacity scales up further, the swept areas of the turbines must also increase. VAWTs can do this by increasing either increasing diameter or blade height, the former mitigates against increasing the thrust force lever arm. However, HAWTs only have the option of getting taller with an ever-increasing overturning lever arm for the thrust force. This in turn requires larger floating structures to resist the increasing overturning moment. Therefore, for larger capacity turbines in the future the advantages of VAWTs structure sizing compared to HAWTs will further increase.

The floating foundation material and fabrication costs make up a significant proportion of a FOW development lifecycle expenditure (approx. 20%). The sizing reductions indicated by Wood's comparative assessment would have a positive impact on levelized cost of energy (LCOE) of 4-5%.

There is still significant work required to sufficiently mature VAWT technology in the context of FOW. For the floating foundations, combined system models need to be developed to address increased torsional loading impacted by VAWTs compared to HAWTs that drives yaw in the hull and requires restraint from the mooring system. Full scale VAWT demonstrator projects considering spar and semi-submersible structure types (as a minimum) will be required to advance TRLs, bringing VAWTs in line with HAWTs prior to commercial scale developments being viable.

Revision History		
Revision	**Date**	**Comments**
A	02/04/21	Issued for Review

HOLDS		
No.	**Section**	**Comment**

Signatory Legend		
Revision	**Role**	**Comments**
A	Prepared	Jamie McCallum, Senior Engineer
	Checked	Keith Anderson, Specialist Engineering and Consulting – Manager
	Approved	Keith Anderson, Specialist Engineering and Consulting – Manager

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1.0 Scope

1.1 Scope

Work package Tec2 comprises all activities relating to the FOW system's structure and associated subsystems. Wood is the consortia participant leading work package Tec2 with support from the University of Strathclyde.

The scope of the work package is agreed to include the structure (also known as a substructure or foundation), mooring system and anchor. Other subsystems such as cabling and substations are deemed to be technologically independent of the turbine orientation and as such are not considered.

The work package scope comprises the following activities:

1. Reviewing existing FOW structure and subsystem technology and capability.
2. Identification and validation of technology status.
3. Assessment and comparison of structure and subsystem design, size, weight etc. for VAWT and HAWT systems.
4. Identification of structure and subsystem lifecycle cost differentiators between VAWT and HAWT systems.
5. Summarising structure and subsystem advantages and disadvantages for VAWT systems compared to HAWT systems.
6. Outlining key issues, technological gaps, and a way forward for structures and subsystems to support VAWT technological maturity.

1.2 Abbreviations

AFLOAT	Accelerating Market Uptake of Floating Offshore Wind Technology
CAPEX	Capital Expenditure
COREWIND	Cost Reduction and Increase Performance of Floating Wind Technology
FEED	Front End Engineering Design
FOW	Floating Offshore Wind
GB	Distance between Centres of Buoyancy and Gravity
GM	Metacentric Height
HAWT	Horizontal Axis Wind Turbine
HMPE	High Modulus Polyethylene
I	Second Moment of Area
LCOE	Levelised Cost of Energy
NREL	National Renewable Energy Laboratory
NSRI	National Subsea Research Initiative
OEM	Original Equipment Manufacturer
TLP	Tension Leg Platform
TRL	Technology Readiness Level
VAWT	Vertical Axis Wind Turbine
V_S	Volume of Displaced Fluid by Submerged Hull

2.0 Technology Review

2.1 Structure

Structure designs for FOW developments can be broadly categorised into four typologies: barge, semi-submersible, spar and TLP.

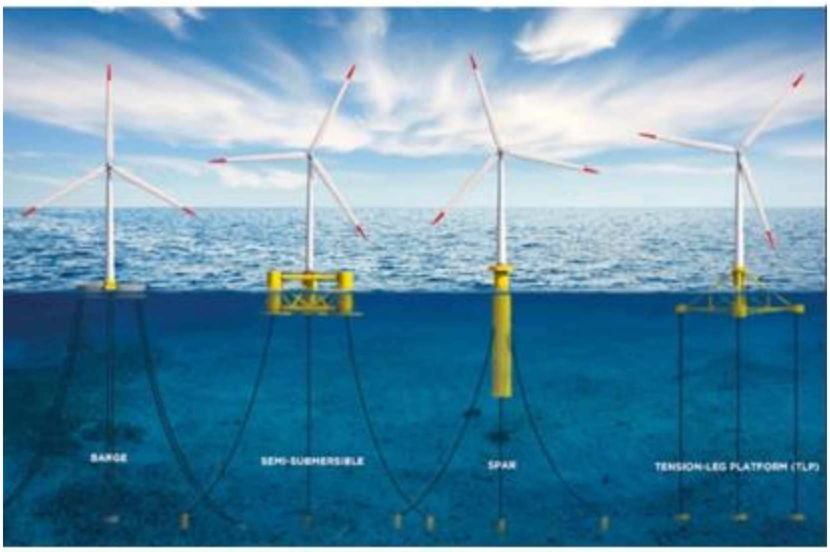

Figure 2.1 FOW Structure Typologies [1]

2.1.1 Barge

Barge structures are shallow draft, large waterplane area structures with stability provided by the large waterplane area. Some designs may include a central opening known as a moonpool. The wind turbine generator is either connected on the outer extent or the centre of the barge. Station keeping is provided by a catenary or semi-taut mooring system connected to each corner of the barge structure. Barges are used in the offshore oil and gas industry for the transport of materials offshore during installation campaigns such as steel pipelines with the barges towed into place using tugboats. These are temporary events with barges generally not used as permanent facilities in harsh wave environments. Their large waterplane area can result in large heave and pitch motions.

2.1.2 Semi-Submersible

Semi-submersible structures are ballast stabilised structures. They typically have three or four columns for ballast which are connected in either a triangle or cross arrangement with interconnecting braces. The wind turbine generator is typically connected to one of the ballast columns which can either sit on the outer extent of the structure or centrally depending on the structure arrangement. In some designs the wind turbine generator is situated centrally, supported by structural braces rather than a ballast column. Station keeping is provided by a catenary or semi-taut mooring system connected to each point or corner of the semi-submersible structure. Semi-submersible structures are used extensively in the oil and gas industry as drilling rigs, production platforms and heavy lift crane platforms. By having columns that pierce the wave zone the waterplane area is reduced compared to a traditional ship shape. This make semi-submersibles less susceptible to heave motions which is beneficial to drilling operations. Spacing the columns out provides a large lever arm to the structures centre of gravity increasing the available restoring moment.

2.1.3 Spar

Spar structures are ballast stabilised structures with the ballast material located at the base of a long, usually cylindrical, structure. The wind turbine generator is connected to the top of the cylinder. Due to their much longer draft compared with semi-submersible structures wind turbine connection usually has to be done offshore rather than at the quayside unless deep water facilities are available close to the wind farm site. Spar structures are therefore not suitable for shallow water locations. Station keeping is provided by a catenary or semi-taut mooring system, usually configured in three equally spaced sectors. Spar structures are used in the oil and gas industry as production platforms, more typically in deep water basins such as the Gulf of Mexico. Their long draft lowers the waterplane area far below the wave zone lowering heave motions. However, their length can exaggerate pitch motions. Stability against overturning is provided by including dense ballast at the base of the hull to act as a counterweight at a long lever arm.

2.1.4 TLP

TLPs are mooring stabilised structures comprising a number of arms at the base of the structure, typically numbering three or four, connected to a central column. The wind turbine generator is connected to the central column. Station keeping is provided by a taut mooring system connected to each arm at the base of the structure. Each TLP is designed such that the mooring lines remain in tension at all times to provide station keeping and structural stability. TLPs are used in the oil and gas industry for offshore production in deeper water basins such as the Gulf of Mexico. Rigid connection between the structure and anchor results in very low motion characteristics for TLPs. Low vertical motion under wave loading may require greater freeboard of the structure for FOW developments. Some TLP designs are inherently unstable with all stability coming from the mooring system. This could cause issues with towing out installations for FOW developments and also lowers TLP's ability to accommodate mooring system damage.

2.2 Mooring Systems

Mooring systems are used for station keeping of each FOW structure within a farm and in the case of TLPs for stability.

2.2.1 Catenary System (Steel Chain Lines)

Conventional mooring systems are made from links of steel chain hung from the structure in a catenary. However, in deeper water locations where FOW developments are most likely to be deployed, these can be overly heavy. Having too much weight in the mooring arrangement requires increased buoyancy in the structure to avoid the structure submerging. Heavy mooring systems require more steel mass, larger connectors and are also more complex to install requiring more time and larger vessels which increase the total cost to the project.

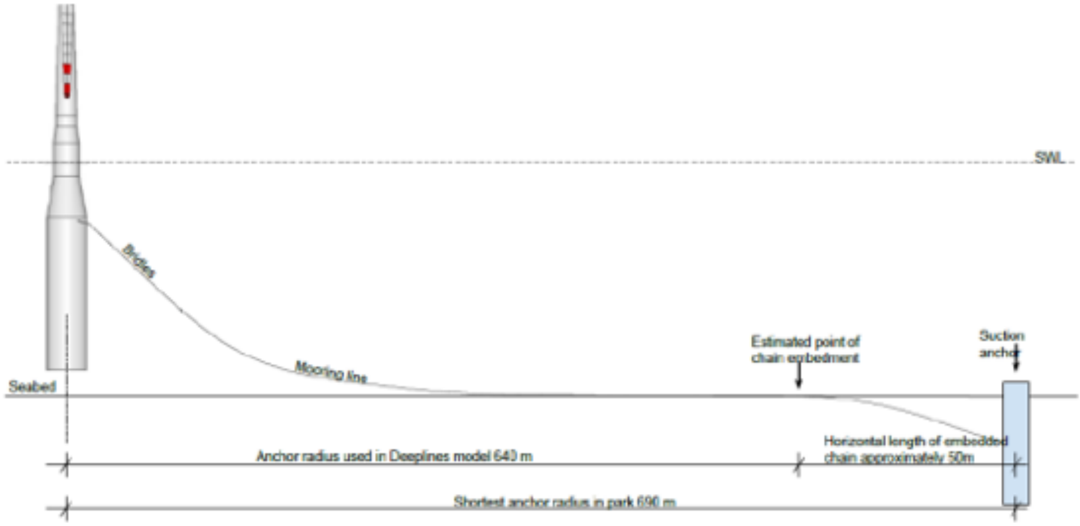

Figure 2.2 Catenary System (Steel Chain Lines) [2]

Figure 2.3 Mooring Chain [3]

2.2.2 Semi-Taut System (Synthetic Fibre / Steel Wire – Steel Chain Hybrid Lines)

Semi-taut mooring systems utilise synthetic fibres in the middle section of the mooring lines. Synthetic fibres such as polyester or HMPE fibre provide lighter weight alternatives to steel. These replace the chain in the mooring line's midsection. This reduces the overall weight of each mooring line whilst retaining the conventional steel chain for robustness of design at the seabed and structure connection points. Use of lighter materials makes handling and installation or the mooring lines easier reducing time spent offshore during installation procedures. Smaller anchors and smaller installation vessels can be used with the lighter systems to provide further cost savings to projects.

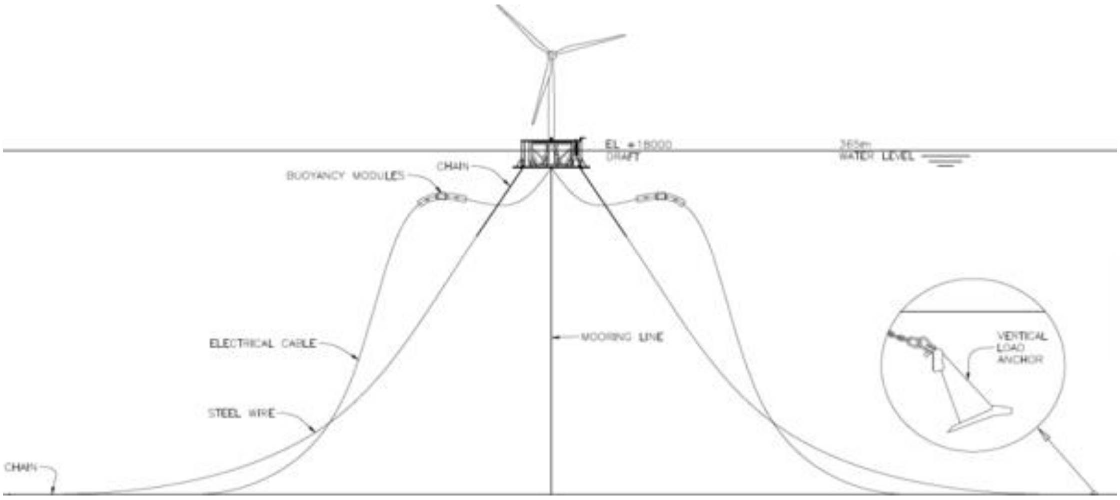

Figure 2.4 Semi-Taut System (Hybrid Lines) [4]

Figure 2.5 Mooring Fibre [5]

Figure 2.6 Mooring Wire [6]

2.2.3 Tension Leg System

Tension leg mooring systems utilise taut mooring lines of either steel tendons or synthetic fibres. The design of the structure requires sufficient buoyancy to ensure that the mooring lines in the system remain taut at all times.

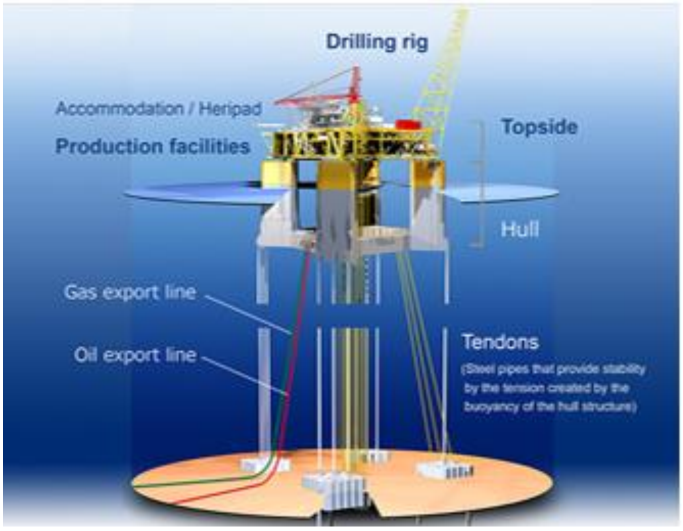

Figure 2.7 Tension Leg System (Steel Tendons) [7]

Figure 2.8 Mooring Tendon [8]

2.3 Anchor

Anchors connect the moorings lines to the seabed for station keeping. In most cases each mooring line has its own anchor. Some more recent concept developments are proposing using shared anchors between FOW structures arranged in an array. Catenary mooring systems exert more horizontal forces on their anchors parallel to the seabed. Thus, their anchors dig deeper into the seabed as force is applied meaning less initial embedment is required. Vertically loaded anchors require deep embedment in order to affect the greatest amount of soil between the anchor and the seabed. These are therefore more complex and expensive to install. However, selection of anchor type is also governed by seabed conditions local to FOW development.

2.3.1 Drag Embedded

Drag embedded anchors provide anchoring forces from embedment in the seabed following dragging by the mooring system. Installation of drag embedded anchors is relatively easy and low cost compared with other anchor types. Catenary mooring systems typically utilise drag embedded anchors as the anchor is embedded further into the seabed as the mooring system translates horizontal loading onto the anchor. Drag embedded anchors are mostly used in temporary stationing of structures where anchor positioning over time is not of critical importance. Soft soil types are required.

Figure 2.9 Drag Embedded Anchor [9]

2.3.2 Driven Pile

Driven pile anchors are commonly used for fixed bottom offshore wind developments. Piles are hollow steel pipes which are driven into the ground. They are fixed permanently at specific locations with high reliability. The use of large vibratory or impact hammers to drive the piles into the seabed can be environmentally invasive.

Figure 2.10 Driven Pile Anchor [10]

2.3.3 Suction Pile

Suction pile anchors are similar to driven pile anchors in that they are again hollow steel pipes inserted into the seabed. These tend to of larger diameter and shallower length than driven piles. Suction piles are hollow at the bottom and closed at the top. Initial, partial embedment is achieved through the weight of the pile itself. Full embedment is achieved by opening a vent in the top of the pile to release the seawater trapped between the seabed and the top of the pile, creating the suction required to pull the remainder of the pile into the seabed.

Figure 2.11 Suction Pile Anchor [2]

2.3.4 Gravity Base

A gravity base anchor relies solely on weight to supply the anchoring forces required of the structure. Thus, the size of structure required can be large to provide sufficient dead weight. Gravity base anchors are most suitable for use with vertical tendon mooring systems on TLP structures.

Figure 2.12 Gravity Base Anchor [11]

3.0 Technology Status

3.1 Summary

A summary of the assessed technology status of each subsystem is presented in Table 3.1. TRL levels are presented for the underlying technology and its use in a number of FOW scenarios considering a 5MW and 10MW turbines for both HAWT and VAWT.

TRL levels are judged considering a baseline of currently operational FOW developments, being Hywind Scotland, WindFloat Atlantic and Kincardine Offshore Wind Farm being at TRL 8. These are not considered as being fully proven at TRL 9 given the relatively short period for which they have been operational. Each subsystem technology is then rated at this level, or lower accordingly.

Further details on the technology status assessment are provided in subsequent sections.

Table 3.1 Technology Status Summary Table

Category	Item	TRL				
		Technology	5MW HAWT	10MW HAWT	5MW VAWT	10MW VAWT
Structure	Spar	9	8	7	6	6
	Semi-Submersible	9	8	7	5	5
	Barge	9	7	7	5	5
	TLP	9	4	4	3	3
Mooring	Catenary	9	8	8	6	6
	Semi-Taut	9	8	8	6	6
	Tension Leg	9	4	4	3	3
Anchor	Drag Embedded	9	8	8	6	6
	Suction Pile	9	8	8	6	6
	Driven Pile	9	6	6	6	6
	Gravity Base	9	4	4	3	3

3.2 Structure

A review of FOW structure designs is performed using the Quest Floating Wind Energy website as a starting point in identifying concepts [12]. Each design is described in subsequent sections arranged by design type.

3.2.1 Spar

Spar structures are the most advanced in terms of TRL. The underlying technology is considered to be a TRL 9 technology, with spar platforms deployed in the oil and gas industry over many years.

In a floating wind context, the spar structure type is considered to be a TRL 8 technology for 5MW HAWTs and a TRL 7 technology for 10MW HAWTs. They have been deployed in an operational wind farm at 5MW size for short demonstration periods but are yet to prove scalability to 10MW turbine sizes.

Five 6MW turbines have been deployed on spar structures at the Hywind Scotland wind farm off the coast of Peterhead (Figure 3.1). These turbines have been producing energy to the UK grid since October 2017. This structure concept is deemed to be at a TRL 8, revised down from a TRL 9 given that it has only been in operation for a short time. The structure consists of a steel cylinder filled with ballast water and heavy weight ballast materials. A further 11 planned 8MW units are to be deployed at the Hywind Tampen project in Norway. These structures will be fabricated using concrete rather than steel [13].

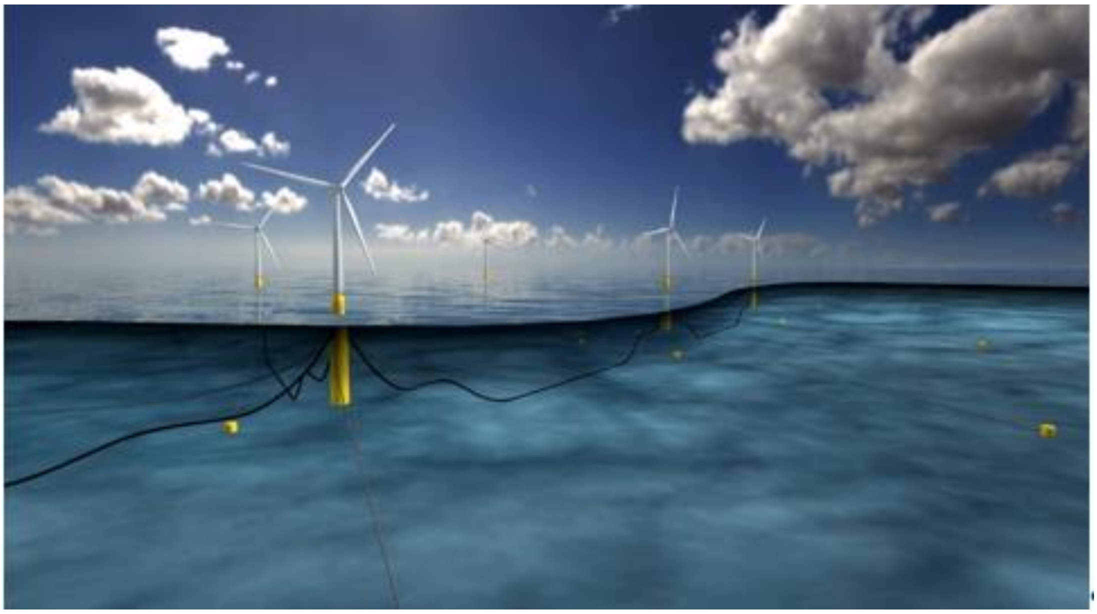

Figure 3.1 Hywind – Equinor [13]

Two further spar structure concepts have been deployed in full scale single unit demonstrators.

The second phase of the Fukushima Forward offshore wind farm deployed the Hamakeze spar concept from IHI Corporation (Figure 3.2). The Hamakeze structure is a steel spar with the wind turbine connected to a small base which widens into a large square floater at the surface. A wind turbine generator is connected to the top of the base. The floating wind unit installed at the Fukushima Forward offshore wind farm utilises a 5MW wind turbine [14].

Figure 3.2 Hamakeze – IHI [14]

Toda have developed a spar structure (Figure 3.3) which has been deployed as a 2MW single unit demonstrator offshore Japan. The spar is a cylindrical steel tower moored using a spread catenary mooring system [15].

Figure 3.3 Toda Spar – Toda [15]

The spar structure type is considered to be a TRL 6 technology for VAWTs. There have been two scale demonstrator deployments of VAWTs on spar structures. Scalability still needs to be proven with a full-scale deployment.

The S2 concept (Figure 3.4) is the second iteration of SeaTwirl's design work building on the S1 which has been successfully demonstrated in a small-scale prototype. S2 is a spar design with a VAWT connected to the structure. Unlike other spars the whole structure rotates with the wind turbine under wind loading, with only the generator housing remaining static. The structure is moored using a catenary mooring system [16].

Figure 3.4 S2 – SeaTwirl [16]

Limited information is available in the public domain on the University of Stavanger's Gwind concept. The concept proposes using a circular spar structure to support a VAWT (Figure 3.5). The spar structure is gyro stabilised. A small-scale prototype has been launched and decommissioned in Stavanger harbour [17].

Figure 3.5 Gwind – University of Stavanger [17]

Three other spar structure concepts are at various stages of development. Each of these considers a HAWT.

The TetraSpar concept from Stiesdal is a spar structure with a triangular base shape (Figure 3.6). The wind turbine is connected to a central column. Stability is provided by a triangular ballasted keel which is deployed following mooring hook up. The structure can also be utilised as a semi-submersible or TLP depending on the water depth. The concept has been tank tested and is currently in the process of prototype development ahead of planned deployment offshore Stavanger [18].

Figure 3.6 TetraSpar – Stiesdal [18]

Windcrete is a concrete spar structure (Figure 3.7). The structure is a monolithic cylinder with ballast material at its base. Station keeping is provided by a spread catenary mooring system. Windcrete is being considered as part of the COREWIND project which aims to advance concrete structure designs through a series of simulations and experimental tests [19].

Figure 3.7 Windcrete – Catalunya University [19]

Saipem's Hexafloat design concept (Figure 3.8) is a hexagonal spar structure stabilised by a pendulum weight suspended beneath it. Concept design is currently undergoing validation [20]. EU funding has been secured to deploy a demonstrator unit offshore Ireland as part of the AFLOWT project.

Figure 3.8 Hexafloat – Saipem [20]

3.2.2 Semi-Submersible

Semi-submersible structures are considered to be on a par with spar structures for HAWT deployments at both 5MW (TRL 8) and 10MW (TRL 7) scale. They have been deployed at an operational wind farm at greater than 5MW scale for a short period but have not yet been deployed at 10MW scale. No semi-submersible concepts have been developed to date considering VAWTs. The structure type is therefore considered to be a step down in readiness (TRL 5) from a spar structure in the context of VAWT deployment.

The most advanced semi-submersible structure concept is Principle Power's WindFloat design (Figure 3.9). It has been deployed at the WindFloat Atlantic project in Portugal which has been operational since July 2020. Three 8.4MW turbines have been producing power to the grid for this short period. The same structures are being used to support 9.5MW turbines at Kincardine Wind Farm where construction is ongoing. The steel structure comprises three ballast hulls configured in a triangular formation using braces. The wind turbine is connected to one of these tanks. There is no central deck space in the design. Three catenary spread mooring lines are used for station keeping [21].

Figure 3.9 WindFloat – Principle Power [21]

Two further semi-submersible structure concepts have been deployed in full scale single unit demonstrators.

Mitsui Engineering and Shipbuilding developed and built a semi-submersible structure to support a 2MW turbine for the first phase of the Fukushima Forward offshore wind farm (Figure 3.10). The structure is a triangular shape with the wind turbine connected to a central column [22]. Mitsui have since signed a collaboration agreement with Principle Power to promote FOW projects in Japan.

Figure 3.10 Mirai – Mitsui [22]

The second phase of the Fukushima Forward offshore wind farm used the Shimpuu concept from MHI (Figure 3.11). The Shimpuu structure is v-shaped with three square ballast towers at each end and at the connection of the v. A wind turbine generator is connected to the top of the tower where the v meets. The floating wind unit installed at the Fukushima Forward offshore wind farm utilises a 7.5MW wind turbine [14].

Figure 3.11 Shimpuu – MHI [14]

Three further semi-submersible structure concepts have been deployed in small scale single unit demonstrators.

Eolink (Figure 3.12) utilises an unconventional turbine configuration atop a rectangular semi-submersible base. The structure connects to a submerged single point mooring system around which the whole structure weathervanes. The design has been demonstrated up to a 1:10 scale prototype at sea with a 3:4 scale precommercial demonstrator of a single 5MW unit in development [23].

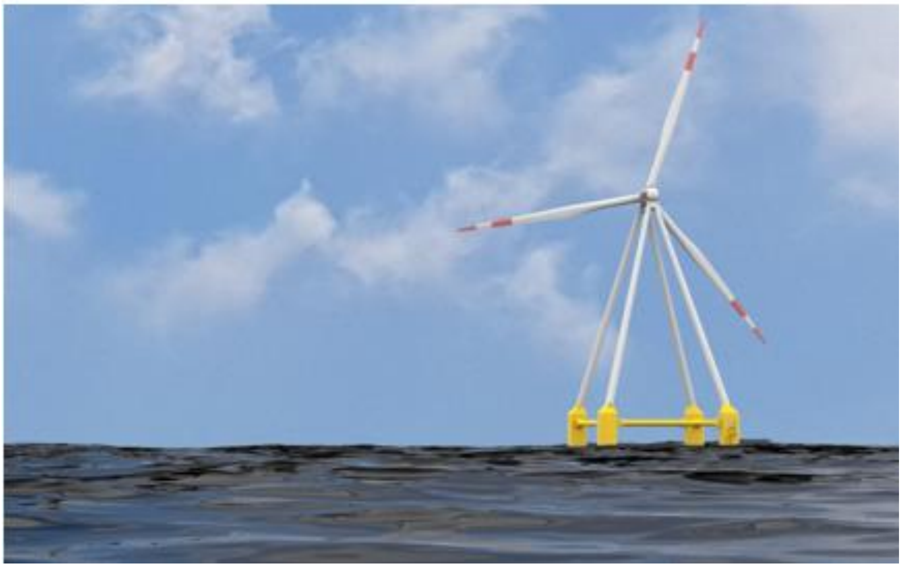

Figure 3.12 Eolink – Eolink [23]

Aerodyn Engineering have developed two FOW concepts based on the same structure design. nezzy² is the second of these designs and uses two 7.5MW wind turbines, angled, and connected to the same central column for power production (Figure 3.13). The structure itself is y-shaped with three outer columns connected by braces. A 1:10 scale prototype has been deployed in Germany with plans to deploy a full-scale demonstrator in China [24].

Figure 3.13 nezzy² – Aerodyn Engineering [24]

VolturnUS is a structure design developed at the University of Maine for demonstration at the Aqua Ventus project offshore Maine (Figure 3.14). The demonstration project will deploy a single 10MW VolturnUS unit. VolturnUS is a concrete semi-submersible design. Four ballast towers are arranged in a triangular configuration, with one in the centre, connected by braces. The wind turbine is connected to the central tower. A 1:8 scale prototype has been previously deployed in 2013 and successfully completed an 18-month period of electricity generation [25].

Figure 3.14 VolturnUS – The University of Maine [25]

Several other semi-submersible structure concepts are at various stages of development. Each of these is summarised as follows.

OO-Star is a three leg, semi-submersible structure designed by Olav Olsen (Figure 3.15). Design of the structure has been performed for steel, concrete, and a hybrid of the two. Connection of the wind turbine is made to a central column. Station keeping is ensured using a three-line mooring system, one attached to each leg. Funding has been secured to build a 10MW single unit demonstrator at the Metcentre test centre in Norway [26].

Figure 3.15 OO-Star – Olav Olsen [26]

Tri-Floater is a semi-submersible structure consisting of a y-shaped platform, upon which the wind turbine sits centrally, supported by square shaped ballast columns at each end (Figure 3.16). The structure is spread moored with mooring lines connected at each point of the y-shaped platform [27].

Figure 3.16 Tri-Floater – GustoMSC [27]

TrussFloat is a steel semi-submersible structure comprising a triangular shape (Figure 3.17). Three circular ballast tanks sit at each point of the triangle. These are connected with steel bracings which also support a central deck upon which the wind turbine sits. Tank testing of a scale model has been completed [28].

Figure 3.17 TrussFloat – Dolfines [28]

G2 is the second iteration of Hexicon's floating wind structure design (Figure 3.18). It is a triangular, semi-submersible structure with two wind turbines attached. This increases the power output of each floating wind unit with reduced cabling for the same capacity. The structure is moored using a taught, single pint mooring system which allows the whole structure to weathervane [29].

Figure 3.18 G2 – Hexicon [29]

Naval Energies concept Sea Reed (Figure 3.19) has been selected to be installed at the Groix & Belle-Île pilot wind farm off the North West coast of France. It is a y-shaped semi-structure design, similar in shape to the OO-Star concept, with the wind turbine attached to a central column. The structure is moored using a spread mooring system connected to the three outer legs [30, 31].

Figure 3.19 Sea Reed – Naval Energies [30]

ACTIVEFLOAT is a concrete semi-submersible structure (Figure 3.20). The structure has a y-shaped base with four ballast tanks protruding upwards, three on each end and one centrally. The wind turbine is connected to the central tower. ACTIVEFLOAT is being considered as part of the COREWIND project which aims to advance concrete structure designs through a series of simulations and experimental tests [19].

Figure 3.20 ACTIVEFLOAT – Cobra [19]

Nautilus is a square, four column semi-submersible structure where the wind turbine is connected to the centre of the braces between the columns (Figure 3.21). The structure is moored using a spread mooring system. The concept is undergoing validation by Ramboll [32].

Figure 3.21 Nautilus – Nautilus Floating Solutions [32]

3.2.3 Barge

Barge structures are a step down in technology readiness from the spar and semi-submersible structures. There have been a couple of full scale, single unit demonstrators at 2-3MW for HAWT deployments, but no deployments to date at both 5MW (TRL 7) and 10MW (TRL 7) scale. No barge concepts have been developed to date considering VAWTs. The structure type is therefore considered to be at a similar readiness (TRL 5) to a semi-submersible structure in the context of VAWT deployment.

The most advanced barge structure is the Damping Pool concept from Ideol (Figure 3.22). It is a spread moored, square barge with a central moonpool. There are two Damping Pool demonstrators in operation since 2018 with one constructed from steel and the other from concrete. These are of 2-3MW scale. Two precommercial wind farms of multiple Damping Pool units are currently in development [33].

Figure 3.22 Damping Pool – Ideol [33]

SATH from Saitec Offshore Technologies (Figure 3.23) is a barge platform which weathervanes around a single point mooring system. The structure is manufactured using reinforced concrete. It is being demonstrated offshore in two Spanish projects offshore Santander (1:6 scale prototype) and Bilbao (2MW prototype) [34].

Figure 3.23 Saitec Offshore Technologies [34]

P-80 is the latest in a number of iterations of design from Floating Power Plant (Figure 3.24). It is a hybrid structure incorporating a floating barge with a built-in wave energy converter. As such it behaves as a hybrid of a semi-submersible and a barge. The structure is moored using a disconnectable turret system which allows the platform to weathervane to maximise wind and wave power utilisation [35]. A 1:30 scale prototype of the P-80 design has been tested at Aalborg University.

Figure 3.24 P-80 – Floating Power Plant [35]

3.2.4 TLP

TLPs are the least advanced of the four main structure typologies. Although proven as a technology in oil and gas applications, predominantly in deep water, are yet to advance beyond tank testing stages for any FOW concept. TLPs are considered to be at TRL 4 for HAWT deployments, with small scale demonstration the next phase of development. No TLP concepts to date have considered use of a VAWT. As such VAWT deployment readiness is considered to be a stage behind HAWTs (TRL 3).

Three TLP concepts have undergone successful tank testing. These are the most advanced of the TLP concepts available.

GICON-SOF is a TLP concept from GICON which includes four large cylindrical columns arranged in a square configuration to provide additional stability to the structure (Figure 3.25). The four columns are each joined together at the turbine base using brace members. Anchoring is provided using a gravity anchor which is lowered from the base of the floater following tow to site [36].

Figure 3.25 GICON SOF – GICON [36]

TetraFloat is a wide triangular TLP structure moored by individual anchors (Figure 3.26). A wind turbine generator is connected to the structure using three towers connected to each leg. The towers are angled such that the generator is angled towards the wind loading [37].

Figure 3.26 TetraFloat – TetraFloat [37]

Axis Energy Projects are developing a TLP concept called the Tension Leg Buoy (Figure 3.27). The structure is a subsurface buoy which supports the wind turbine and is connected to a gravity base anchor for stability [38].

Figure 3.27 Tension Leg Buoy – Axis Energy Projects [38]

There are several other TLP concepts at earlier stages of development.

The PelaStar TLP concept is a pentagon leg structure with mooring tendons connected at each leg to individual anchors at the seabed (Figure 3.28). Most recent development of the concept involved completing a FEED study of a 6MW demonstrator for the Energy Technologies Institute [39].

Figure 3.28 PelaStar – PelaStar [39]

SBM Offshore is developing their Wind Floater concept in collaboration with IFPEN. The structure is a triangular shaped TLP supported by a number of cross bracings (Figure 3.29). Three tension leg mooring lines to individual anchors provide station keeping and stability. The concept has been selected by EDF to be installed as an 8MW demonstrator [40].

Figure 3.29 Wind Floater – SBM Offshore [40]

Blue H Engineering are developing a TLP structure (Figure 3.30). The structure has both a floater and anchor base both of which are triangular in shape. The floater has a large central column upon which the wind turbine is connected. The floater is connected to the anchor base by three tendon mooring legs at each point of the triangle shape [41].

Figure 3.30 Blue H TLP – Blue H Engineering [41]

Eco TLP is a concrete TLP concept developed by DBD Systems LLC (Figure 3.31). Both the floater and gravity base anchor structure are large cylindrical concrete structures. Floater and anchor are joined by four tendon moorings [42].

Figure 3.31 Eco TLP – DBD Systems LLC [42]

The Floating Wind TLP concept from Bluewater is a triangular leg structure with the legs meeting at a central column to which the wind turbine is attached (Figure 3.32). Anchoring is provided by individual piled anchors for each mooring tendon leg [43].

Figure 3.32 Floating Wind TLP – Bluewater [43]

The X1 Wind structure (Figure 3.33) is a triangular floater with three cylindrical tanks joined by bracing members. A wind turbine generator is connected to the structure using three towers connected to each leg. The mooring arrangement is setup to allow the entire structure to weathervane. The cylindrical tank at the rear of the structure is the only one which is moored using a tension leg system. The whole structure then weathervanes around this connection [44].

Figure 3.33 X1 Wind – X1 Wind [44]

3.2.5 Summary

A summary of the TRL assessment of each structure is presented in Table 3.2. TRL levels are judged for each structure based on publicly available information at each source. It should be noted that the TRL levels listed in Table 3.2 relate to the application of the system in each FOW deployment. All of the floating structure technologies (barge, semi-submersible, spar and TLP) are TRL 9 technologies when considered independent from any offshore wind considerations. They are all used extensively around the World to support oil and gas developments and marine transportation. However, this study is specifically considering their applicability to supporting FOW developments both for HAWTs and VAWTs. As such the TRL levels presented in this section consider each structure concept's TRL status in the context of a FOW system development rather than the TRL of the design type.

Semi-submersibles and spar structure types are the furthest advanced in terms of TRL. A spar type structure has been demonstrated at Hywind Scotland with a 6MW turbine. Semi-submersibles have been demonstrated at WindFloat Atlantic with an 8.4MW turbine. Some work is required to prove the designs for large turbines of 10MW capacity and greater. The spar is slightly ahead of semi-submersibles for VAWTs specifically as there have been two concepts built at scale demonstrator level (S2 and Gwind). Further work is required to prove these ready for demonstrator and commercial development for full scale wind turbines.

Barges are the next most progressed structure type. Ideol's Damping Pool has been demonstrated for 2MW and 3MW turbines. This remains to be proven for commercial scale developments and turbine sizes. Like the semi-submersible there are no concepts to date using a VAWT on a barge structure and so work would be required to demonstrate this concept. There are also no comparable designs within the oil and gas industry for permanent deployment in harsh environments such as the North Sea.

TLPs although proven as a technology in oil and gas applications are yet to advance beyond tank testing stages for any FOW concept. The Axis Tension Leg Buoy, GICON-SOF and TetraFloat concepts have all successfully undergone tank testing. Significant work is therefore required to progress TLPs to the same TRL level as semi-submersible spars and get them in the water demonstrating power production to grid. Similarly, there are no proposed VAWT concepts for TLPs and extensive work is needed to progress this concept.

Table 3.2 Structure Design TRLs

Design Name	Organisation	Design Type	HAWT/VAWT	5MW TRL	10MW TRL	Source
Hywind	Equinor	Spar	HAWT	8	7	[13]
Hamakeze	IHI	Spar	HAWT	7	7	[14]
Toda Spar	Toda	Spar	HAWT	7	7	[15]
S2	SeaTwirl	Spar	VAWT	6	6	[16]
Gwind	University of Stavanger	Spar	VAWT	6	6	[17]
TetraSpar	Stiesdal	Spar	HAWT	4	4	[18]
Windcrete	Catalunya University	Spar	HAWT	3	3	[19]
Hexafloat	Saipem	Spar	HAWT	2	2	[20]
WindFloat	Principle Power	Semi-Submersible	HAWT	8	7	[21]
Mirai	Mitsui	Semi-Submersible	HAWT	7	7	[22]
Shimpuu	MHI	Semi-Submersible	HAWT	7	7	[14]
Eolink	Eolink	Semi-Submersible	HAWT	6	6	[23]
Nezzy2	Aerodyn Engineering	Semi-Submersible	HAWT	6	6	[24]
VolturnUS	The University of Maine	Semi-Submersible	HAWT	6	6	[25]
OO-Star	Olav Olsen	Semi-Submersible	HAWT	4	4	[26]
Tri-Floater	GustoMSC	Semi-Submersible	HAWT	4	4	[27]
TrussFloat	Dolfines	Semi-Submersible	HAWT	4	4	[28]
ACTIVEFLOAT	Cobra	Semi-Submersible	HAWT	3	3	[19]
G2	Hexicon	Semi-Submersible	HAWT	3	3	[29]
Sea Reed	Naval Energies	Semi-Submersible	HAWT	3	3	[30, 31]

Design Name	Organisation	Design Type	HAWT/VAWT	5MW TRL	10MW TRL	Source
Nautilus	Nautilus Floating Solutions	Semi-Submersible	HAWT	2	2	[32]
Damping Pool	Ideol	Barge	HAWT	7	7	[33]
SATH	Saitec Offshore Technologies	Barge	HAWT	6	6	[34]
P-80	Floating Power Plant	Barge	HAWT	4	4	[35]
GICON-SOF	GICON	TLP	HAWT	4	4	[36]
TetraFloat	TetraFloat	TLP	HAWT	4	4	[37]
Tension Leg Buoy	Axis Energy Projects	TLP	HAWT	4	4	[38]
PelaStar	Glosten	TLP	HAWT	3	3	[39]
Wind Floater	SBM Offshore	TLP	HAWT	3	3	[40]
Blue H TLP	Blue H Engineering	TLP	HAWT	2	2	[41]
Eco TLP	DBD Systems LLC	TLP	HAWT	2	2	[42]
Floating Wind TLP	Bluewater	TLP	HAWT	2	2	[43]
X1 Wind	X1 Wind	TLP	HAWT	2	2	[44]

3.3 Mooring

Each of the three mooring technology categories described in Section 2.2 are considered to be fully qualified and proven, TRL 9 technologies in their own right. They are used extensively in a number of industries including oil and gas and marine transportation.

Considered in the context of FOW developments, meaning their use on permanently moored structures of this size for design lives of up to 25 years, their readiness is considered to be reduced.

A catenary chain system has been used for the Hywind Scotland development [13] and it is considered that this remains valid for scaling up to larger turbines. No major issues have been reported to date and if this continues into the future then chain will be considered to be fully proven in a FOW context.

Likewise, a semi-taut hybrid mooring system made up of chain and synthetic fibre has been used for WindFloat Atlantic [45]. This is a new installation having been installed in 2020. Therefore, it is too soon to say that this technology is fully proven at this level and in this system context.

Each of the mooring technology categories will have to prove their ability to handle the additional consideration of torsional loadings for VAWT developments through both suitable mooring connector technologies at the hull and the system availability to provide yaw restoring force.

Table 3.3 provides a summary of the mooring technology TRL levels.

Table 3.3 Mooring Technology Category TRLs

Item	TRL				
	Technology	5MW HAWT	10MW HAWT	5MW VAWT	10MW VAWT
Catenary	9	8	8	6	6
Semi-Taut	9	8	8	6	6
Tension Leg	9	4	4	3	3

3.4 Anchor

Of the anchor technology categories described in Section 2.3 drag embedded, driven pile, suction pile and gravity base anchors are considered to be fully qualified and proven, TRL 9 technologies in their own right. They are used extensively in a number of industries including in oil and gas for anchoring of large floaters and smaller subsea structures.

The FOW industry appears to be converging on the use of either drag embedded or suction pile anchors based on projects to date. Almost all concepts looked at consider one of these two anchoring concepts with the exception of some TLP concepts which use gravity base anchors and are at low TRL levels as a system.

Drag embedded anchors are used on the WindFloat Atlantic development [45]. This is a new installation having been installed in 2020. As with the mooring system it is too soon to say that this technology is fully proven at this level and in this system context. This also applies to suction pile anchors which are installed on the Hywind Scotland project [13].

Driven piles are used extensively in fixed bottom offshore wind projects such as the Beatrice wind farm for 7MW wind turbines. These have yet to crossover to FOW developments perhaps due to the advancement of suction pile technology and the advantages they bring versus driving.

Table 3.4 provides a summary of the anchor technology TRL levels.

Table 3.4 Anchor Technology Category TRLs

Item	TRL				
	Technology	5MW HAWT	10MW HAWT	5MW VAWT	10MW VAWT
Drag Embedded	9	8	8	6	6
Suction Pile	9	8	8	6	6
Driven Pile	9	6	6	6	6
Gravity Base	9	4	4	3	3

4.0 Advantages and Disadvantages of VAWTs vs HAWTs

With HAWTs and VAWTs representing significantly different technologies they provide their own unique challenges for FOW structure design and operation. This section summarises some of the potential advantages and disadvantages of using VAWTs rather than conventional HAWTs when mated to floating hulls. The relative impact on hull sizing is further explored in Section 5.0, which informs the discussion points below.

4.1 Advantages

4.1.1 Lower Turbine Centre of Mass

The turbine system's centre of mass above the water line is a driver for hull stability and performance. The generator, nacelle and blades of the wind turbine provide a significant proportion of the total topside mass, which also includes the tower and balance of plant, and is a driver for the system response characteristics. HAWT's centre of mass is effectively at the nacelle located at the top of the tower assembly. VAWTs provide an opportunity to place this equipment at a lower elevation, closer to the floating structure and in doing so lower the total turbine centre of mass. This has the effect of making the floating structure more stable under loading. As HAWTs get ever larger with larger blades and swept areas this effect becomes more pronounced with the bulk mass of the generation equipment moving higher in the air and further from the structure.

4.1.2 Shorter Thrust Force Lever Arm

The thrust force generated by wind action on the turbine blades provides an overturning moment on the floating structure. The overturning moment is directly proportional to the effective thrust force elevation, or lever arm from the point of rotation. The thrust force lever arms for HAWTs act at the hub height of the turbine, at the centre point of the rotating blades. For VAWTs the thrust force can be considered to act near the midpoint of the blade height. These are each the midpoints of their respective swept areas.

As turbine capacity increases the swept areas of the turbines must also increase. VAWTs can do this by increasing either increasing diameter or blade height, with the former mitigating against increasing the thrust force lever arm. However, HAWTs only have the option of getting taller with an ever-increasing overturning lever arm for the thrust force. Therefore, as turbine capacity increases, a VAWT will have a lower thrust force elevation than a HAWT for a similar power output. With comparable horizontal thrust forces this results in VAWTs providing a net reduced overturning moment. This in turn requires larger floating structures for HAWTs to resist the increasing overturning moment.

4.1.3 Smaller Structure and Associated Subsystems

The opportunity to lower the turbine centre of mass, and more importantly to shorten the thrust force lever arm, enables a smaller structure for stability of the same capacity VAWT and HAWT. The differential between solutions increases with increasing turbine capacity. This has a significant cost benefit to FOW projects, with substructure cost making up a sizable proportion of project CAPEX. Reducing the size of the floating structure has the knock-on effect of reducing the required size of the mooring and anchoring system. Wave and current loadings reduce with the smaller structure size drag area and inertial loading. However, moorings are a relatively small cost driver compared to the floating structure overall.

4.1.4 Easier Offshore Installation and Hook Up

Floating structures will require tow out to site and mooring line and anchor (pre)installation and hook up before commissioning. The reduced structure sizes, mooring and anchoring will require less bollard pull and back deck equipment space. However, this is not expected to be a major driver of cost differentiation.

4.1.5 Safer Operational and Maintenance Access

Offshore wind has been beset by challenging accident statistics. Working at height provides inherent risk, requires additional training and extended operation time. Furthermore, change out of components may require expensive specialised vessels to provide crane lift height capability. VAWTs provide the potential for developments to have key equipment such as generators and gearboxes on or near the deck providing a positive cost and safety benefit for the operation and maintenance of floating wind developments. More accessible equipment reduces operation time and removes the need for working at height and potentially expensive specialised vessel support.

4.1.6 Increased Hull Density per Development Footprint

The overall density of turbine numbers across a development's footprint is governed by wake turbulence effects and maximising the power from each individual turbine. VAWTs have a reduced wake field such that hull density for a given area can be increased with reduced hull spacing. Reduced separation reduces the length of cables between turbines, providing a cumulatively saving across a full development. Reducing development footprint will also reduce early-stage development and licensing costs which have increased in the latest round of auctions.

4.2 Disadvantages

4.2.1 Lower Technological Maturity

As presented in Section 3.0 the technological maturity of VAWTs is lower than for the well-established HAWTs. The ease of availability of HAWTs from the OEMs and field experience from existing demonstrators and pilot projects drives the developers along the selection route for HAWTs to reduce project risk, attract finance and insurers. To consider a VAWT it is likely that a proven demonstrator will be required to support project investment, this is expected to make projects uncompetitive in licencing round auctions.

The opportunity arising from this is to prove the concept via a demonstrator that has been developed from a local supply chain, as far as possible, from the outset which could provide local and export opportunities.

4.2.2 Increased Interface Loading

VAWTs have the potential to generate a torsional load applied in plan which is significantly greater than for HAWTs. This torsional loading will need to be managed through the mooring system design. Concepts such as WindFloat with large separation from mooring fairleads to the centre of rotation will accommodate this loading easier than a spar that has limited offset to the fairleads if the body is to be geostationary. As presented in Section 3.2.1 the SeaTwirl spar concept deals with this loading by rotating the entire turbine tower and structure as one.

4.2.3 Challenging Blade Access

Operations and maintenance for HAWT turbine blades is well understood and methodologies and techniques established. For VAWTs there will be new challenges to overcome, particular with H-type systems and the horizontal offset of the blades from the tower will impact on personnel access. However, with inspection technologies via drones progressing at pace this is not seen as a significant challenge.

5.0 Structure Comparative Sizing Assessment

5.1 Introduction

The structure comparative sizing assessment is performed to assess the potential for reductions in VAWT floating structure material requirements compared to HAWTs.

The exercise makes use of public domain information for existing deployed floating structures that is scaled to provide preliminary sizing for different turbine systems. Turbine data from NREL [46, 47] and University of Strathclyde [48] datasets is used.

Structure sizes are optimised for static stability on the basis of a nominal 5° maximum static heel under wind loading. Although active ballasting may counter this and an argument may be made for additional heel angle limitations, this is adopted to provide a benchmark on hull sizing and stability performance for this comparative assessment.

The findings as outlined below lend themselves to further detailed investigation of dynamic hull response motions for the range of activities from tow out to extreme survival along with tower sizing and fatigue loading to further assess the identified benefits of VAWTs over HAWTs.

5.2 Turbine Data

Table 5.1 and Table 5.2 presents the turbine input data considered for the structure comparative sizing assessment.

Table 5.1 HAWT Data

Parameter	NREL [46, 47]		Siemens [48]	Vestas [48]
Turbine Capacity (MW)	3	5	10	15
Rotor and Blade Mass (Te)	51	110	162	192
Nacelle Mass (Te)	89	240	390	600
Tower Mass (Te)	201	347	540	580
Total Mass (Te)	341	697	1092	1372
Hub Height (m)	80	90	140	150
Centre of Mass Height (m)	-	64	100	107
Aero Thrust Force (kN)	-	800	2200	3300
Thrust Force Line of Action Height (m)	-	64	100	107

Table 5.2 VAWT Data

Parameter	Darrieus [48]			H-Rotor [48]		
Turbine Capacity (MW)	3	9	11	5	10	15
Rotor and Blade Mass (Te)	204	630	819	70	90	110
Nacelle Mass (Te)	125	250	375	125	250	375
Tower Mass (Te)	348	540	580	348	540	580
Total Mass (Te)	677	1420	1774	543	880	1065
Estimated Centre of Nacelle Height (m)	10	10	10	10	10	10
Calculated Centre of Mass Height (m)	64	99	105	48	58	64
Aero Thrust Force (kN)	677	1810	2280	1050	1980	2980
Thrust Force Line of Action Height (m)	74	113	125	58	74	90

5.3 Structure Data

Two structure typologies are considered for sizing assessment. These are the two most advanced typologies as presented in Section 3.0 the spar and semi-submersible type. Base case structures based on publicly available information are used as the basis for all sizing assessments. Input data for these base case structures is presented in Table 5.3 with the semi-submersible option selected on the basis of a triangular hull with three columns providing the surface piercing hulls generating buoyancy for the structure.

Spar ballast is premised on heavy weight aggregates whilst semi-submersible ballast is assumed from water filled ballast compartments.

Table 5.3 Generic Base Case Structures [4, 12]

Parameter	Spar		Semi-Submersible		
Structure Concept	Spar I	Spar II	Semi-Sub I	Semi-Sub II	Semi-Sub III
Turbine Size (MW)	2.4	6	2	8.4	9.5
Draft (m)	100	78	14	20	20
Height (m)	100	91	23	30	30
Freeboard (m)	0	13	9	10	10
Column Diameter (m)	8.3	14.5	8.2	12.5	12.5
Number of Surface piercing Columns	1	1	3	3	3
Centre to Centre Length (m)	N/A	N/A	38	55	75
Steel Mass (Te)	1500	2300	1300	2500	2750
Ballast Mass (Te)	3800	9700	1300[1]	1600[1]	1700[1]
Total Mass (Te)	5300	12000	2600	4100	4450

Notes: 1. Additional ballast will be required to achieve operational draft.

5.4 Structure Optimisation

Optimisation of the structure size requires consideration of two distinct design aspects. The first is sufficient buoyancy of the structure to match the overall displaced mass of the floating wind unit. The second is the ensuring there is sufficient stability to limit overall pitch rotation of the structure that is driven by the overturning moment from wind load on the turbine.

The buoyancy is iterated through consideration of draft, diameter, and length (for the semi-submersible) of the hull selection. For the semi-sub system this requires assessment of both quayside and operational draft conditions.

Stability is premised on countering the overturning moment with the restoring moment as a function of the metacentric height. The metacentric height (GM) is calculated as:

$$GM = \frac{I}{Vs} - GB$$

The restoring moment for the hull at small pitch angles can be approximated to:

Restoring moment = GM * sin(pitch angle)

The metacentric height is a function of the hull form and centre of gravity hence is variable with draft, column size, column spacing and weight distribution including ballast. These parameters are considered for the hull optimisation iteration to hit target draft and pitch angle values.

5.4.1 Spar Optimisation

The spar hull structure is approximated to be a simple cylinder of constant diameter. Scaled structure sizes are approximated by linear interpolation of structure size with topside mass. Initial buoyancy calculations are performed to calculate the required draft to achieve sufficient buoyancy of the structure given the scaled steel and ballast mass. The overturning moment is then calculated using the thrust forces provided by the University of Strathclyde [48]. The pitch angle at which this overturning moment is equally resisted by the restoring moment from the structure's weight distribution and buoyancy force is calculated.

The ballast mass of the structure is adjusted such that the calculated pitch angle is equal to a target value of 5°. This impacts the required steel mass and draft for buoyancy which are recalculated. The diameter of the structure is iterated to reduce the draft required for buoyancy to a target limit based on the structure type and turbine size, maximising deployable water depths for application. As the diameter is increased and draft decreased the structure's steel mass is scaled based on these changes in the length and diameter of the cylinder. Increasing the diameter to decrease the length of the cylinder is more beneficial in terms of steel mass and therefore cost reduction than vice versa.

All of these steps are repeated iteratively until an optimal solution is reached.

Optimised spar structures are presented in Table 5.4. The optimised structure masses are presented relative to turbine size in Figure 5.1 for total structure tonnage and Figure 5.2 for the hull mass excluding ballast.

Table 5.4 Statically Optimised Structures – Spar

Parameter	NREL	Siemens	Vestas	Darrieus			H-Rotor		
Turbine Type	HAWT	HAWT	HAWT	VAWT	VAWT	VAWT	VAWT	VAWT	VAWT
Turbine Size (MW)	5	10	15	3	9	11	5	10	15
Turbine Mass (Te)	697	1092	1372	677	1420	1774	543	880	1065
Diameter (m)	15.9	17.5	18.4	14.6	16.3	16.1	15.2	14.2	15.3
Steel Mass (Te)	2056	3293	3992	1879	2950	3339	2157	2759	3342
Ballast Mass (Te)	9400	20330	27240	7754	17065	19950	8515	12646	18100
Structure Mass (Te)	11456	23623	31232	9633	20015	23289	10672	15405	21442
Draft (m)	60	100	120	60	100	120	60	100	120
Pitch Angle (°)	5	5	5	5	5	5	5	5	5

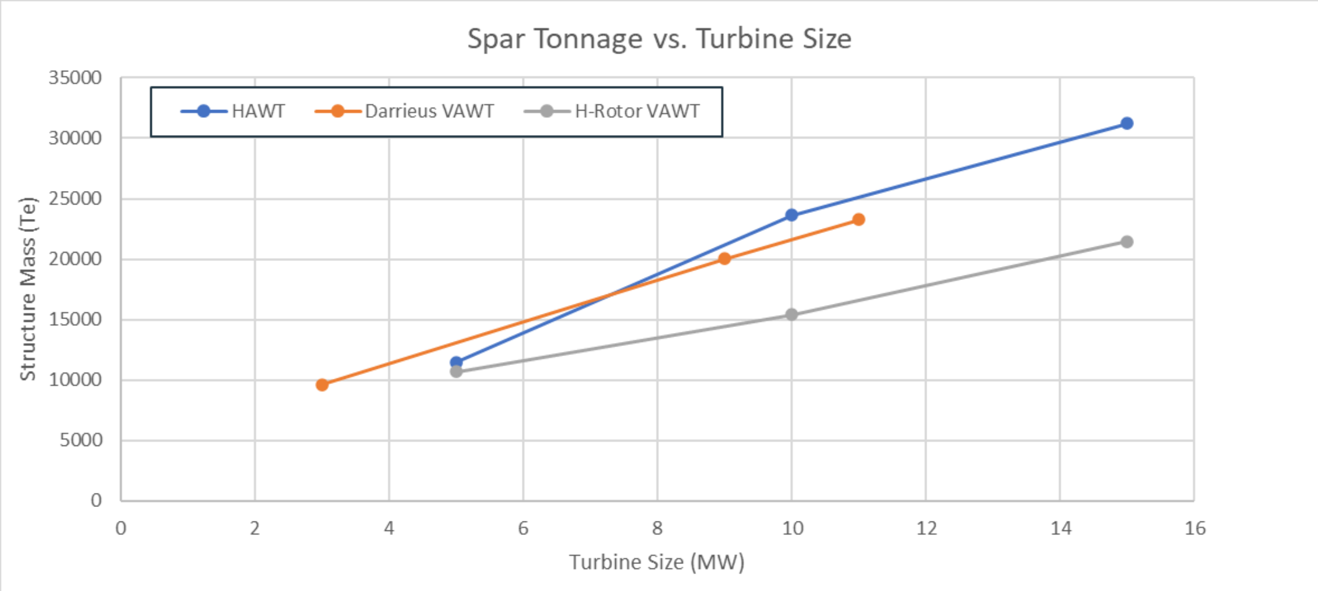

Figure 5.1 Optimised Structure Mass vs. Turbine Rating – Spar

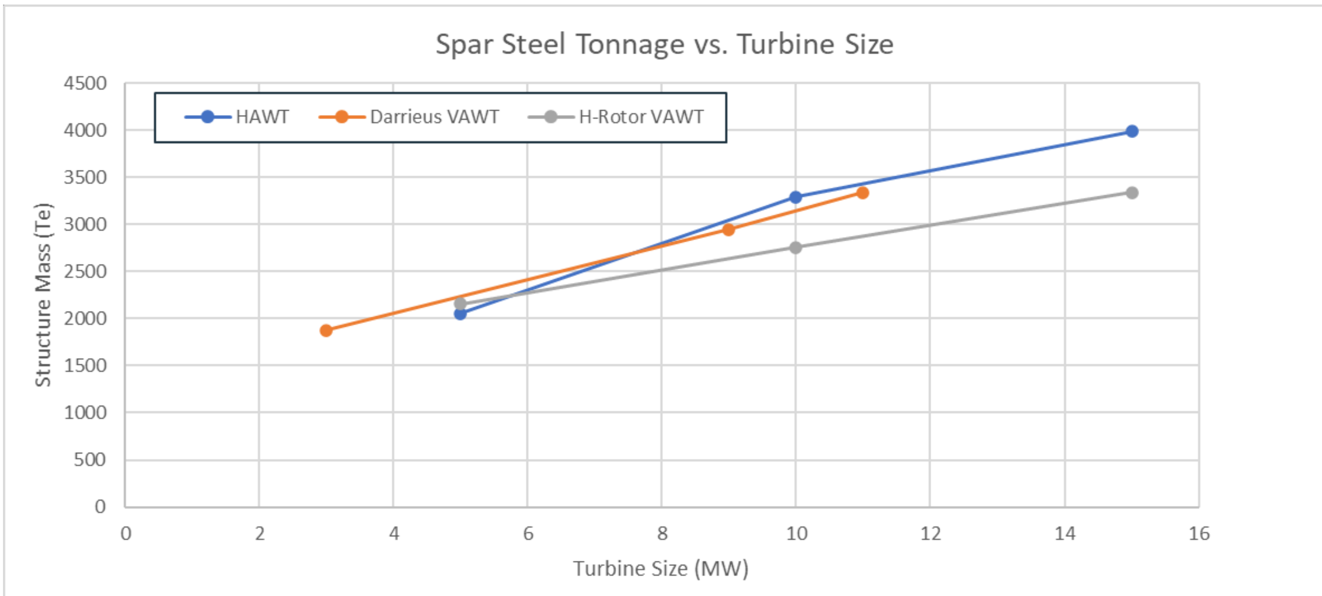

Figure 5.2 Optimised Structure Steel Mass vs. Turbine Rating – Spar

There is a reduction in structure mass required to maintain the same level of static stability for the VAWTs compared with the HAWTs considered. This is particularly evident for the H-Rotor VAWT which has the lowest aero thrust force elevation of the three turbine types considered.

Darrieus type turbines do not offer significant if any size reductions for the floating structure. The turbines themselves are heavier than similar capacity HAWTs. Their thrust force lever arm likewise does not reduce significantly compared with similar capacity HAWTs given the Darrieus type turbines considered are very tall for their rated capacity. The result is that an 11MW Darrieus turbine requires a similarly sized structure to a 10MW HAWT.

H-Rotor type turbines in contrast have a much lower thrust force lever arm compared with the HAWTs and the Darrieus type VAWTs. Their height does not increase with turbine capacity as quickly as the other turbines and so the benefits of the reduced overturning moment that this creates is particularly evident for larger turbines. For the 5MW turbines the thrust force on the H-Rotor VAWT is 22% greater than that for the similar sized HAWT and this negates any potential benefit from the reduced mass and lever arm. However, as the turbines increase in size and the swept area of the HAWTs gets larger the thrust force on a similar capacity H-Rotor VAWT becomes approximately 10% lower. Reductions in the thrust force, associated lever arm and therefore overturning moment and the centre of turbine mass combine to give a structure for the 10MW and 15MW H-Rotors that have reduced overturning loads than a similar capacity HAWT.

Maintaining structure draft and pitch at the same levels for the H-Rotor and conventional HAWTs offers an approximate 31-35% saving on structure size (Table 5.5) when considering the steel hull tonnage and assumed heavy weight ballast materials. Considering the hull alone there is c16% saving in steel tonnage for the larger turbine sizes.

The reduced submerged volume for the H-Rotor VAWTs spars (smaller diameter for given draft) and reduced mass will also have a positive impact on reducing the consequent mooring loads and anchor sizing. The overall reduction has not been assessed within this study, moorings are a magnitude smaller cost item than the hulls and any small reduction in loading will not have significant impact on the overall costings. However, it also provides an opportunity to maintain a like for like mooring system / chain size with a comparable HAWT with the reduced loading allowing less utilised components improving resilience and fatigue performance for VAWT in comparison with the HAWT.

Table 5.5 Structure Mass Reductions HAWT vs H-Rotor VAWT – Spar

Turbine Capacity (MW)	Steel Mass Reduction	Heavy Weight Ballast Mass Reduction	Total Mass Reduction
5	+5%	-9%	-7%
10	-16%	-38%	-35%
15	-16%	-34%	-31%

5.4.2 Semi-Submersible Optimisation

For semi-submersible optimisation, initial buoyancy calculations for column diameter and associated water ballast requirements are performed for a nominal quayside draft of 10m. In this condition the hull must provide sufficient buoyancy to maintain a shallow quayside draft whilst supporting:

- the hull structural mass,
- the mass of the turbine equipment to be integrated comprising the full tower, nacelle, and blade system and,
- an equivalent water ballast in each of the other two columns to ensure stability, assuming the tower is located above one column. Without this water ballast counterweight the tower assembly induces a static pitch/roll of the structure that compromises tower integration and quayside working.

The shallow draft quayside condition is found to be a driver for overall column sizing in order to ensure sufficient buoyancy to bring the hull alongside at the required draft.

The quayside optimised structure is then adopted for operational simulations and additional water ballast required for each system to achieve a nominal operational draft of 20m is determined. For comparative assessment, the columns are assumed to have a uniform diameter over their length. This is a conservative approach as any buoyant heave plate structure at the base of the columns (larger diameter cylinder) will help offset some of the relative diameter differences between turbine systems.

The floating structure's stability against overturning for the semi-submersible design is primarily a function of the spacing of the columns and their diameter at the water area as opposed to a ballast counterweight in the spars. It is akin to a person's ability to resist being pushed over with their feet apart (semi-submersible) as opposed to with their feet together (spar).

The finding from the overturning calculations is that the overall spacing for static stability is not a driving metric between concepts with only incremental differences in bracing lengths (hence mass) required compared to the column sizing for initial stability. For example, sizing to maintain a nominal target pitch angle of 5° for the 15MW HAWT which has a c.70% increase in overturning moment compared to the 15MW H-Rotor VAWT, requires an overall column centre to centre length only 21% greater. This can be offset further through active ballasting of columns to neutralise mean pitch angles from wind loading. Therefore, it is concluded, on a like for like basis there is minimal differential expected in overall structure extent in plan dimensions between HAWT and VAWT, with the prime differential driven by pontoon sizing to achieve ballast requirements for quayside integration. Dynamic stability assessments may realise a greater differential in plan form extent with the oscillating tower mass at significantly greater elevation for the HAWT systems. This is outwith the scope of this conceptual study.

The refined semi-submersible structures are presented in Table 5.6. The optimised structure masses are presented relative to turbine size in Figure 5.3 for total structure tonnage (including water ballast) and Figure 5.4 for the hull mass alone.

Table 5.6 Statically Optimised Structures – Semi-Submersible

Parameter	NREL	Siemens	Vestas	Darrieus			H-Rotor		
Turbine Type	HAWT	HAWT	HAWT	VAWT	VAWT	VAWT	VAWT	VAWT	VAWT
Turbine Size (MW)	5	10	15	3	9	11	5	10	15
Turbine Mass (Te)	697	1092	1372	677	1420	1774	543	880	1065
Quayside Draft (m)	10	10	10	10	10	10	10	10	10
Operational Draft (m)	20	20	20	20	20	20	20	20	20
Column Diameter (m)	14.1	16.9	18.4	13.8	18.2	19.8	13.0	15.4	16.7
Centre to Centre Length (m)	42	66	75	39	55	58	42	52	62
Steel Mass (Te)	2688	3597	4041	2587	3755	4153	2440	3103	3503
Quayside Water Ballast (Te)	2091	3276	4116	2031	4260	5322	1629	2640	3195
Operational Water Ballast (Te)	6177	9058	10904	5974	10860	13047	5155	7503	8838
Quayside Structure Mass (Te)	4779	6873	8157	4618	8015	9475	4069	5743	6698
Operational Structure Mass (Te)	8865	12655	14945	8561	14615	17200	7595	10606	12341
Pitch Angle (°)	5	5	5	5	5	5	5	5	5

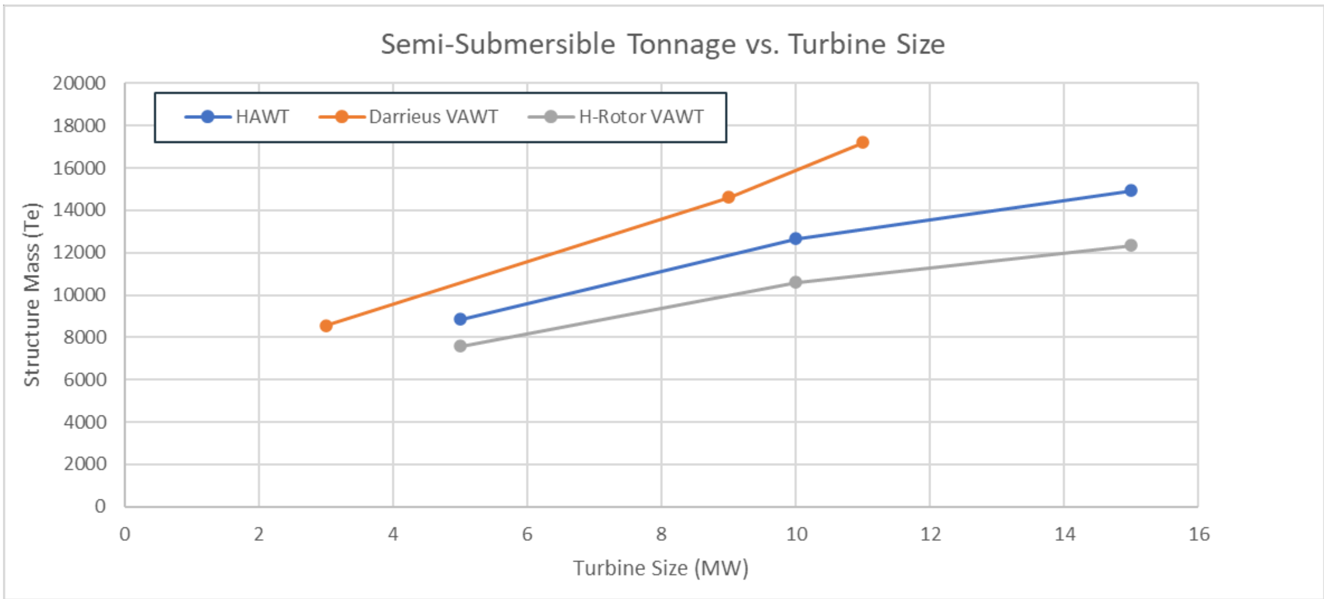

Figure 5.3 Optimised Structure Mass vs. Turbine Rating – Semi-Submersible

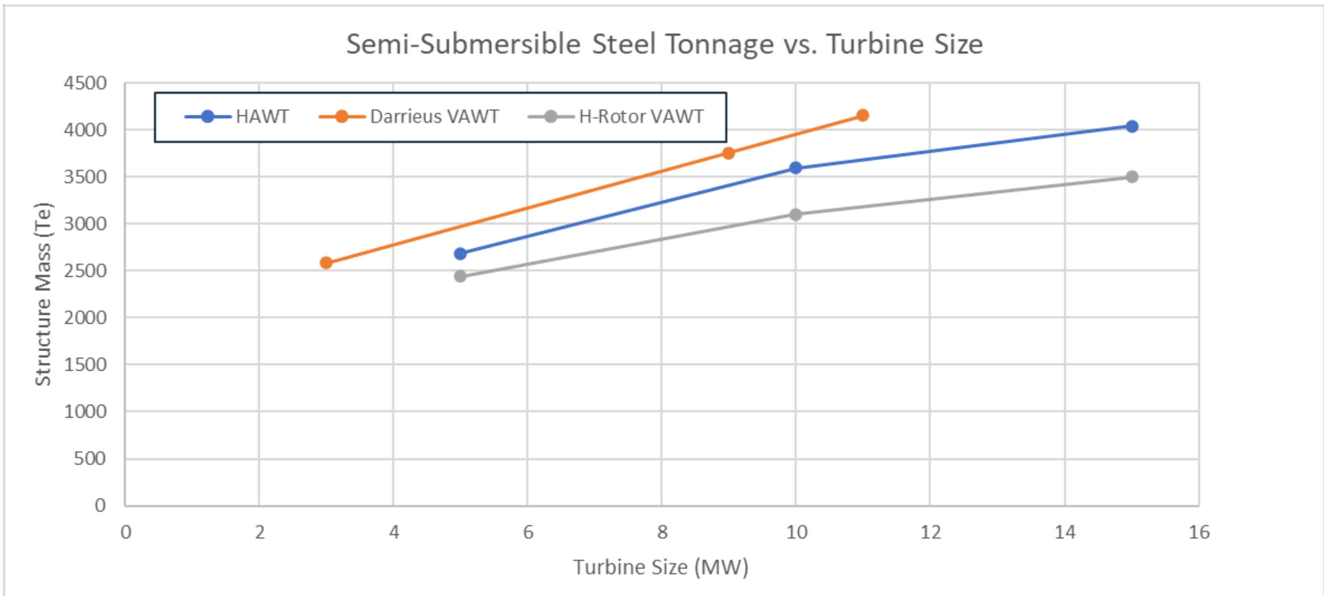

Figure 5.4 Optimised Structure Steel Mass vs. Turbine Rating – Semi-Submersible

There is a clear synergy between the projected structure mass and the overall mass of the tower assembly including tower, nacelle, and blades. This is the principal driver for the differences between structures, driving the column sizing to support the nacelle weight. Overall column separation is not projected to be a significantly driver for relative structure weights.

The H-Rotor VAWT offers an approximate 9-14% saving on structure size (Table 5.7) compared to the HAWTs when considering the steel hull tonnage. Ballast volumes are not considered a comparable metric unlike for the spar solutions. Although some water ballast may be swapped for structural mass the majority of ballast will require to be variable to cover scenarios for hull levelling quayside post tower integration and to subsequently achieve the deeper operational draft at site, hence ability to pump in/out water ballast as required.

The reduced submerged volume for the H-Rotor VAWTs semi-submersible columns (smaller diameter for given draft) and reduced mass will also have a positive impact on reducing the consequent mooring loads and anchor sizing. The overall reduction has not been assessed within this study, moorings are a magnitude smaller cost item than the hulls and any small reduction in loading will not have significant impact on the overall costings. However, it also provides an opportunity to maintain a like for like mooring system / chain size with a comparable HAWT with the reduced loading allowing less utilised components improving resilience and fatigue performance for VAWT in comparison with the HAWT.

Table 5.7 Structure Mass Reductions HAWT vs H-Rotor VAWT – Semi-Submersible

Turbine Capacity (MW)	Steel Mass Reduction	Water Ballast Mass Reduction	Total Mass Reduction
5	-9%	-17%	-14%
10	-14%	-17%	-16%
15	-13%	-19%	-17%

6.0 Lifecycle Cost Differentiators

6.1 Structure Sizing, Mooring and Anchoring

Previous cost modelling by Wood has found structure material and fabrication costs to be one of the largest cost shares for a FOW project, making up almost 20% of total expenditure. This modelling considered a 495MW wind farm made up of 33x 15MW wind turbines, 100km from shore in 100m water depth, with structural manufacturing performed in the UK. Therefore, reducing the mass of steel and ballast materials required for each structure has a positive impact on the LCOE of FOW projects.

Mooring, anchoring and infield cabling material and fabrication costs are a lower magnitude of cost for an offshore windfarm at around 5-6%. The bulk of this share of the cost is mooring related. For VAWTs there is the potential to condense the geographical footprint of the overall wind farm as there is less downstream wake turbulence. This provides a means to further reduce development costs with shorter cabling infrastructure. The mooring systems, albeit expected to have reduced loading hence smaller mooring chain and anchor sizing than HAWTs is expected to be only a marginal consideration.

With respect to the spar comparative sizing assessment, the structural mass reduction predicted for the 15MW VAWT, using this model, provides an LCOE reduction of 4%. This LCOE reduction increases to 5% when estimates of mooring line size and turbine spacing reductions are included when considering the opportunity.

With respect to the semi-submersible comparative sizing assessment, the structural mass reduction predicted for the 15MW VAWT provides an LCOE reduction of 3%. This LCOE reduction increases to 4% when estimates of additional savings of mooring line size and turbine spacing reductions are included.

The LCOE results demonstrate a greater cost saving for the spar configurations than semi-submersible. However, consideration should be given to the potentially significantly greater opportunity for Scotland in fabrication and construction for FOW the semi-submersibles could provide from quayside integration unlike spars which are expected to continue to require highly specialised heavy lift vessels for offshore integration of the towers and hulls. Quayside integration of the turbine could also reduce turbine contract costs for semi-submersible developments compared with spar developments. Presently turbine purchase costs typically include costs for procurement, delivery, installation, and commissioning of the turbine. Cost reductions from integrating the turbine at the quayside could therefore be passed on to the developer from the OEMs.

6.2 Operations and Maintenance

Routine operations costs are commonly covered by service agreements with the wind turbine manufacturers. As such it is difficult to estimate the cost impact on these agreements from making the turbine nacelle more accessible for routine operations and maintenance. Therefore, although accessible and inherently less risk from working at height no specific savings have been attributed to VAWTs compared to HAWTs for operations and maintenance.

7.0 Roadmap to Technological Maturity

It is expected that the floating structure will not be the driving concern in maturing the technology. However, it will be key in scaling up overall systems through deployment of demonstrators proving the wider technology application, teasing out any system concerns for VAWTs in a hostile dynamic marine environment. This will be a requirement to prove the concepts to developers, investors, and insurers in order to achieve acceptance for commercial deployment.

Section 3.2.5 identifies the low TRL level for VAWTs on floating structures with only two small scale protypes based on spar concepts deployed. This is a narrow window and in order to progress TRL levels. Additional hull typologies should be demonstrated at scale, particularly with a view to opportunities for structures that can be fabricated in Scotland and integrated at the quayside e.g. semi-submersible or barge concepts. The minimum additional hull type should be a semi-submersible solution given that this and spar concepts have the highest TRL levels for HAWT systems at larger turbine sizes.

Specific to developing the floating structure technological maturity will be proving the overall system performance with a view to demonstrating performance of reduced hull sizes compared to HAWT, alongside proving greater operating windows than HAWTs and potential for greater energy density through reduced array separation. This should encompass a range of hull typologies for small scale demonstrators in order to support benchmarking of the overall technical solution to identify the viable solution(s) with greatest economic impact for Scottish supply chains that should progress to a full-scale demonstrator.

Structure, mooring and anchoring requirements over and above HAWT systems that require to be investigated are developing further understanding of the torsional loading from VAWTs into the structure and the capacity of mooring systems for different hull typologies to address this loading regime for survival and operational conditions.

In summary, the high-level steps towards technological maturity required for VAWT FOW developments are:

1. Develop combined system models to address VAWT torsional loading and identify the associated mooring system solutions and/or technology gaps to be addressed.
2. Broaden the base of scale VAWT demonstrator projects to other hull typologies which as a minimum must include a semi-submersible solution.
3. Deploy full scale VAWT demonstrators informed by the scale VAWT demonstrators.
4. Commercial scale VAWT developments.

8.0 Conclusions and Recommendations

8.1 Conclusions

Wood in consortia with the National Subsea Research Institute and the University of Strathclyde have performed a technical and economic aspect of vertical axis wind turbines for FOW. Wood is the consortia participant leading work package Tec2, with support provided by the University of Strathclyde, with the remit to perform technical assessment of VAWT structures and associated subsystems.

The conclusions from the assessment of FOW system's structures and associated subsystems for VAWT applications are summarised below.

1. Floating offshore wind hull typologies for HAWT are not fully field proven (TRL9) to-date.
    a. HAWTs have been deployed commercially such as Hywind Scotland, WindFloat Atlantic and Kincardine Offshore Wind Farm, however given the relatively short period for which they have been operational it cannot be concluded they are fully field proven and are considered TRL8. However, there is no reason to doubt that they will achieve field proven status.
    b. Spar and semi-submersible hull forms are the leading TRL options (TRL8), followed by barges (TRL7). Tension leg platform hull forms have not been operationally deployed and are at a considerably lower technology level (TRL6).
2. The technological maturity of VAWTs is lower than for the well-established HAWTs. The ease of availability of HAWTs from the OEMs and field experience from existing demonstrators and pilot projects drives the developers along the selection route for HAWTs to reduce project risk and attract finance and insurers. To consider a VAWT it is likely that a proven demonstrator will be required to support project investment, this is expected to make projects uncompetitive in licencing round auctions.
    a. Only limited small scale spar demonstrators have been trialled and the TRL levels reflects this, being generally 2-3 levels below HAWTs. However, there is no fundamental reason the structure hull form, mooring and anchoring solutions from HAWTs cannot be directly transferrable to VAWTs.
3. Comparative hull sizing between VAWTs and HAWTs concludes that VAWTs, due to their lower mass and reduced thrust elevations hence overturning moment, for similar power output could realise up to a 16% reduction in structural steel mass with consequent reduction in costs. Reduced hull sizing for VAWT floating structures will translate also into reduced mooring and anchor loadings with further potential reduction in costs, albeit lower magnitude savings than for the overall hull sizing.
4. As turbine capacity scales up further, the swept areas of the turbines must also increase. VAWTs can do this by increasing either increasing diameter or blade height, the former mitigates against increasing the thrust force lever arm. However, HAWTs only have the option of getting taller with an ever-increasing overturning lever arm for the thrust force. This in turn requires larger floating structures to resist the increasing overturning moment. Therefore, for larger capacity turbines in the future the advantages of VAWTs structure sizing compared to HAWTs will further increase.
5. Floating structure costs are one of the largest cost shares for a FOW project, making up almost 20% of total expenditure. Reducing the mass of steel and ballast materials required for each structure has a positive impact on the LCOE of FOW projects of up to 5%.
6. The mooring systems, albeit expected to have reduced loading hence smaller mooring chain and anchor sizing than HAWTs is expected to be only a marginal consideration.

7. The overall density of turbine numbers across a development's footprint is governed by wake turbulence effects and maximising the power from each individual turbine. VAWTs have a reduced wake field such that hull density for a given area can be increased with reduced spacing between hulls. This reduced separation will reduce the length of cables between turbines, this will provide a cumulatively saving across a full development (included for in the LCOE reduction above).
8. The LCOE results demonstrate a greater cost saving for the spar configurations than semi-submersible. However, consideration should be given to the potentially significantly greater opportunity for Scotland in fabrication and construction for FOW the semi-submersibles could provide from quayside integration unlike spars which are expected to continue to require highly specialised heavy lift vessels for offshore integration of the towers and hulls. Quayside integration could also reduce the cost of turbine contracts through reduced installation costs for OEMs.
9. Routine operations costs are commonly covered by service agreements with the wind turbine manufacturers. As such it is difficult to estimate the cost impact on these agreements from making the turbine nacelle more accessible for routine operations and maintenance. Therefore, although accessible and inherently less risk from working at height no specific savings have been attributed to VAWTs compared to HAWTs for operations and maintenance.
10. Offshore wind has been beset by challenging accident statistics. Working at height provides inherent risk, requires additional training and extended time to perform operations. Furthermore, change out of components may require expensive specialised vessels to provide crane lift height capability. VAWTs provide the potential for developments to have key equipment such as generators and gearboxes on or near the deck providing a positive cost and safety benefit for the operation and maintenance of floating wind developments. Having equipment more accessible reduces operations time and removes the need for working at height and potentially expensive specialised vessel support.

8.2 Recommendations

Recommendations to progress VAWT technologies are outlined below.

1. The structural optimisation works for static stability performed in this comparative assessment should be extended to full dynamic modelling to fully capture the benefits of the reduced thrust force elevation and centre of turbine mass above the deck compared to HAWTs with a view to confirming the potential for reduced structure sizing identified above. This could also form the structure for future demonstrator testing.
2. Aero-elastic modelling of the VAWTs for torque loading should be performed and the output determined in a coupled finite element analysis incorporating the aero-elastic loading, floating hull and mooring system to identify any challenges and potential solutions for the mooring system in providing a restoring moment countering this yaw force on the hull.
3. The technical maturity of VAWT concepts needs to be developed, VAWT small scale demonstrators to-date have been limited to spar solutions. The opportunity arising from this is to prove the concept via a demonstrator that has been developed from a local supply chain, as far as possible, from the outset which could provide local and export opportunities. In summary, the high-level steps towards technological maturity required for VAWT FOW developments are:
    a. Broaden the base of scale VAWT demonstrator projects to other hull typologies which as a minimum must include a semi-submersible solution.
    b. Deploy full scale VAWT demonstrators informed by the scale VAWT demonstrators.
    c. Commercial scale VAWT developments.
4. Operations and maintenance for HAWT turbine blades is well understood and methodologies and techniques established. For VAWTs there will be new challenges to overcome, particular with H-type systems and the horizontal offset of the blades from the tower will impact on personnel access. However, with inspection technologies via drones progressing at pace this is not seen as a significant challenge.

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Appendix 6.3

6.3 Subsea UK/NSRI: Vertical Axis Wind Turbine: Economic Impact Assessment: GVA Report

Appendix 3

VAWT Economic Impact Assessment: GVA Analysis

Prepared on Subsea UK and NSRI on behalf of Scottish Enterprise

April 2021

INTRODUCTION

This paper sets out the assessment of impact that could arise from the economic activity associated with the set up and operations of a vertical access wind turbine (VAWT) manufacturing and servicing hub and related VAWT centre of excellence in Scotland. Developing such capability and related know-how in Scotland would support the development of the offshore wind sector across the UK and establish Scotland's reputation internationally as a centre for floating offshore wind.

The section sets out all core assumptions and models potential impact under low, medium and high growth scenario's using forecast developed by the Offshore Renewable Energy Catapult (OREC) for the offshore wind in the UK out to 2050, namely 75GW, 100GW and 150GW. The forecast for the penetration of vertical axis turbine technology assumes that a new turbine manufacturer will at mid-case capture no greater than an equal share of the market as the three strongest incumbent HAWT manufacturers (e.g. 25%).

The assessment of potential gross value add (GVA) to the Scottish economy is based on an approach approved for use by Scottish Enterprise and is developed from H.M. Treasury Green Book principles. Subsea UK / NSRI would like to acknowledge the support and input provided by Scottish Enterprise in the development of the model.

It should be noted the GVA impacts reported are based on a core set of assumptions developed by Subsea UK / NSRI concerning what *could be* achieved rather than what *will be* achieved. The results should, therefore, be used to inform decision making and be treated as indicative rather than definitive.

METHODOLOGY

The methodology adopts an income-driven approach, combining projected turnover derived from the activities associated with the manufacturing, assembly and resulting in-service maintenance of a quantity of VAWTs installed as a proportion of the projected installed floating offshore wind capacity in the UK from the period 2035-2050.

The logic and assumptions behind the model are as follows:

- the model includes potential low, medium and high case installed flowing wind capacity scenarios in the UK
  See pages 4 and 5 for all scenarios and growth assumptions.

- establishment of a VAWT sector in Scotland is additional to any planned offshore wind development in the UK over the period 2035-50
    - there is currently no offshore wind turbine manufacturing facilities being carried out in Scotland
    - there is currently no plans to develop any floating wind capacity using VAWT in Scotland.
- development of the cost / turnover model is based on:
    - a proportion of the activity associated with manufacture and assembly of the VAWT being carried out in Scotland
    - a proportion of the turbine substructure being manufacture in Scotland
    - a proportion of the in-service VAWT repairs and maintenance being carried out in Scotland.

    see page 6 for detailed turnover / revenue assumptions

- development of the VAWT market share is based on a gradual increasing penetration of the overall floating wind farm market:
    - as production capacity is scaled
    - as projects are sanctioned, consented and contracted
    - climate change targets / considerations grow the need for a greater (or lesser share) of installed floating offshore wind capacity to meet the demands of clean energy globally (the model includes potential low, medium and high case installed capacity improved recovery scenarios.

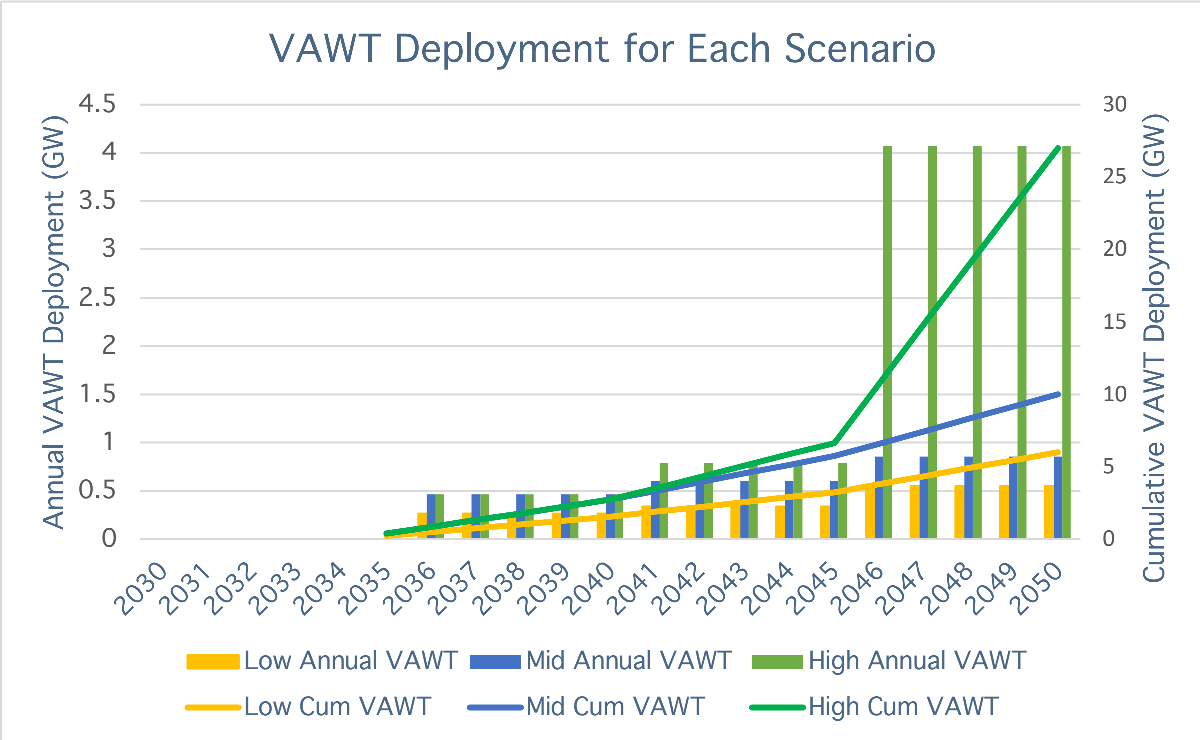


Figure 1: VAWT Deployment for Each Scenario Source: Subsea UK / NSRI

- base case costs / turnover are derived from projected costs developed by OREC for projects being installed in 2029 at full commercial scale i.e. using 15MW turbines at a 500MW farm scale[1].

See page 5 for detailed cost / turnover data

- revenue per turbine will decrease as installed capacity increases (five-yearly % reduction in costs is allowed for)
- any requirement to make adjustments for displacement, substitution and leakage (the extent to which project benefits are offset by the replacement, reductions of output elsewhere, or outside the intended geographic area) is not considered to be required for the purposes of the GVA calculation
- results are presented as net **economic impact to investment ratios** at milestone years 5, 10 and 15 (for transparency of growth profiles over time) and incorporate H.M. Treasury discount rates[2].

The Impact Model

The impact model captures the potential economic impact that *could* arise from activity associated with the development of a VAWT sector in Scotland serving into a UK and global. Income is derived via the calculation of annual turnover per VAWT turbine manufacture over the period 2035-2050 and associated in-service maintenance over the same period which is converted to annual GVA (the ultimate assessment of contribution to the economy).

GVA is estimated via the application of GVA % turnover and multiplier ratios.

The percentage of GVA applied uses the five-year average over the period 2014-2018 adapted from the Scottish Government's Annual Business Statistics (2020) [3] for the SIC codes 25, 27, 28 and 42 – more specially relating to the 5 digit codes:

25300 - Manufacture of steam generators, except central heating hot water boilers
25620 - Machining
27120 - Manufacture of electricity distribution and control apparatus
28110 - Manufacture of engines and turbines, except aircraft, vehicle and cycle engines
28990 - Manufacture of other special-purpose machinery not elsewhere classified
42220 - Construction of utility projects for electricity and telecommunications

This results in an estimated 41 pence of GVA for every £1 of income in 2020 (compared to £0.38 for Scottish manufacturing as a whole in the same period).

The model uses the average from what we consider to be the relevant GVA multiplier(s) to account for indirect and induced impacts i.e. "Type II Multipliers" [4] from codes 25, 28, 32, 33 and 41-43:

25 – Fabricated metal
28 – Machinery and equipment
32 – Other manufacturing
33 – Repair and maintenance
41-43 – Construction

This results in a GVA multiplier of 1.9 being applied to the GVA turnover.

Offshore wind and floating offshore wind deployment assumptions and scenario's use the Offshore Renewables Energy Catapult reference point for UK market growth deployment scenario's from 2030 – 2050[5].

These provide a low, mid and high case for the number of GW deployed.

UK OW Capacity		2030 (GW)	2040 (GW)	2050 (GW)		
Low (GW)		40	52	75		
Mid (GW)		40	64	100		
High (GW)		40	64	150		
Source: OREC 2021						
Floating Offshore Wind (OW) as % Share of OW		**2030**	**2035**	**2040**	**2045**	**2050**
Low		3%	10%	20%	30%	40%
Mid		5%	15%	25%	35%	40%
High		5%	15%	25%	35%	60%
Source: OREC 2021						
VAWT Share of FOW		**2030**	**2035**	**2040**	**2045**	**2050**
Low		0%	5%	15%	17%	20%
Mid		0%	5%	17%	20%	25%
High		0%	5%	17%	25%	30%
Source: Subsea UK / NSRI – based on having a minimum of three incumbent offshore turbine manufacturers (e.g. MHI Vestas, Siemens Gamesa and GE) we have modelled that a new entrant to the market at mid-case has the potential to capture an equal share of the market by 2050. The low and high case so a slightly lesser and greater market share.						

Turnover / Revenue (Costs) Model

For economic return / turnover we have used as the basis for the model the cost data contained in a 2020 OREC Supply Chain Report - BENEFITS OF FLOATING OFFSHORE WIND TO WALES AND THE SOUTH WEST. This provides projected Capex, Opex and Decommissioning costs relative to a floating offshore wind farm of 500MW scale using 15MW turbines for projects commissioned in 2029. The model deliver a projected LCOE of £64 / MWh. As the OREC cost model uses 2020 prices for GVA purposes we have incorporated PV into the final GVA output. The diagram below shows the breakdown of the main components that make up both the Capex and Opex. In summary it forecasts that a 500WM farm will cost circa £1.55Bn i.e.

- Total Capex is £3,043 per kW/hr = £3.043m x 1000kW x 500MW = £1.521Bn
- Total Opex is £68 / kW / year = £68 X 1000kW x 500MW = £34m / year
- Decommissioning is £51 / kW = £51 x 1000kW x 500MW = £25m

Capex		Wave Hub	PDZ	300MW Site	500MW Site
Development and Consenting	£/kW	95	94	209	124
Substructure	£/kW	1,368	1,142	1,011	879
Wind turbine	£/kW	1,280	1,200	1,100	1,000
Anchors	£/kW	55	45	32	26
Mooring lines	£/kW	63	95	95	92
Array Cables	£/kW	21	227	22	19
Electrical infrastructure	£/kW	-	190	573	364
Ports & Logistics	£/kW	55	67	30	21
Vessels and subsea engineering	£/kW	379	928	251	198
Other Capex	£/kW	513	561	396	320
Total Capex	£/kW	**3,829**	**4,549**	**3,719**	**3,043**
Opex		**Wave Hub**	**PDZ**	**300MW Site**	**500MW Site**
O&M offshore activities	£/kW/year	45	31	27	23
O&M onshore activities	£/kW/year	30	11	5	3
Other Opex	£/kW/year	44	44	43	42
Total Opex	£/kW/year	**119**	**86**	**74**	**68**
Decommissioning		**Wave Hub**	**PDZ**	**300MW Site**	**500MW Site**
Decommissioning	£/kW	345	173	74	51

Table 3: Project costs

Levelised Cost of Energy		Wave Hub	PDZ	300MW Site	500MW Site
LCOE (2012 real pre-tax)	(£/MWh)	123	120	80	64

Table 4: Levelised Cost of Energy

Source: OREC - Supply Chain Report - BENEFITS OF FLOATING OFFSHORE WIND TO WALES AND THE SOUTH WEST. *(2020)*

GVA Turnover Contribution Assumptions

We have made certain assumptions around the turnover that could be attributed to the Scottish economy based on the manufacture and installation of key turbine elements and related structure and balance of plant / Capex activities and Opex. These are:

Capex

- 100% of blade manufacturing will be carried out in Scotland
- 50% of other turbine related manufacturing activity (drive train, controls, assembly) will be carried out in Scotland
- 25% of the value of substructures will be manufactured / built in Scotland
- 10% of the remainder of Capex activity will be carried out in Scotland

Opex

- 75% of turbine maintenance value will be carried out in Scotland (this component has 25% of the value of total O&M activity).

The results in gross turnover contributions being:

Turbine turnover pa (assume 33 turbines / 15 MW / 500 MW farm)				
Capex £1.55Bn				
	% to GVA	Number (£m)	Contribution to GVA total field	Contribution per turbine
Blades	100	125	125	3.8
Other turbine	50	375	187.5	5.7
Structure	25	450	112.5	3.4
BOP	10	600	60	1.8
			485	**14.7**
Opex £34m pa				
Turbine maintenance	0.75	8.5	6.375	0.19
Other maintenance	0	25.5	0	0
				0.19

A factor was then allowed for cost reduction (productivity and efficiency gains) over five year cycles over the period 2035-2050. This resulted in final per unit contribution costs of:

Capex /VAWT Turbine (£M)				Opex /VAWT Turbine in service (£M/yr.)		
2035-2040		14.7		2035-2040		0.19
2041-2045		14.0		2041-2045		0.18
2046-2050		13.3		2046-2050		0.17
Source: OREC 2020 / Subsea UK / NSRI assumptions						

Schedule 1 sets out the detail modelling of the turnover income for each growth scenario, GVA and NPV calculations.

NB The impact assessment factors in costs over time (base year costs 2020) and profiles impacts annually for the period 2035-2050. Both are discounted per annum based on standard discount rates outlined in the HM Treasury Green Book.

VAWT GVA Summary

A summary of GVA (PV) output for each scenario is outlined below:

Low Growth Scenario – 75GW OW / 30 GW FOW BY 2050

The low scenario is based on a potential installed capacity for 6 GW of VAWTs over the period 2035-50. This contribution could lead to **£2.11 Billion** of net additional GVA (PV) by 2050. A breakdown of the cumulative GVA in five-year increments is outlined below:

	Turnover	GVA (PV)
Year 5 (2039)	£1,597,000,000	£571,000,000
Year 10 (2044)	£3,335,000,000	£1,179,000,000
Year 15 (2049)	£6,089,000,000	£2,115,000,000

Medium Growth Scenario – 100 GW OW / 40 GW FOW BY 2050

The low scenario is based on a potential installed capacity for 10 GW of VAWTs over the period 2035-50. This contribution could lead to **£3.57 Billion** of net additional GVA (PV) by 2050. A breakdown of the cumulative GVA in five-year increments is outlined below:

	Turnover	GVA (PV)
Year 5 (2039)	£2,785,000,000	£994,000,000
Year 10(2044)	£5,905,000,000	£2,081,000,000
Year 15(2049)	£11,119,000,000	£3,567,000,000

High Growth Scenario – 150 GW OW / 90 GW FOW BY 2050

The low scenario is based on a potential installed capacity for 27 GW of VAWTs over the period 2035-50. This contribution could lead to **£8.34 Billion** of net additional GVA (PV) by 2050. A breakdown of the cumulative GVA in five-year increments is outlined below:

	Turnover	GVA (PV)
Year 5 (2039)	£2,785,000,000	£994,000,000
Year 10 (2044)	£6,794,000,000	£2,335,000,000
Year 15 (2049)	£26,081,000,000	£8,334,000,000

Figure 2 below shows the cumulative build- up of each scenario over the period 2035-50.

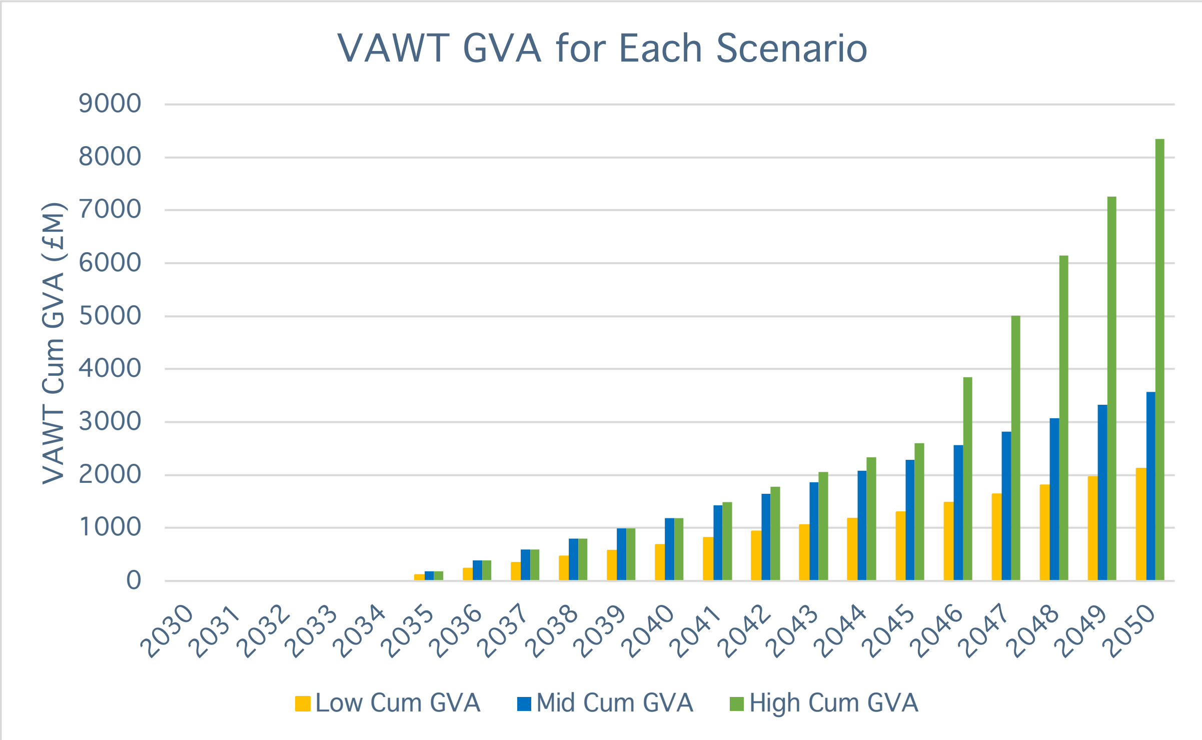


Figure 2: VAWT GVA for Each Scenario (Source Subsea UK / NSRI)

CONCLUSION

Based on the assumptions presented in this report the potential GVA (PV) that could arise from the economic activity associated with the set up and operation of a manufacturing and servicing hub, and the creation of an internationally recognised centre of excellence for VAWT over 15 years 2035-2050 is the range of £2billion - £8billion.

Note:

Globally OREC has one scenario for offshore floating wind, being 9 GW deployed by 2030 and 71 GW deployed by 2040. Quest Offshore projects upwards of 180 GW of floating offshore wind to be deployed by 2050. Taking a low case 20% market share of this for VAWT this would mean a total of 30 GW (excluding UK 6 GW) of additional VAWT being installed by 2050. Assuming the Scottish supply chain associated with the development of a centre of excellence in VAWT based floating offshore wind captured 20% of this using the same turnover assumptions, that could deliver the equivalent GVA (PA) of £2billion as the UK low case scenario.

References

1. https://ore.catapult.org.uk/?orecatapultreports=benefits-of-floating-offshore-wind-to-wales-and-the-south-west-supply-chain-report (2020)
2. Page 131 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/938046/The_Green_Book_2020.pd
3. https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2020/06/scottish-annual-business-statistics-2018/documents/sabs-2018-tables/sabs-2018-tables/govscot%3Adocument/SABS%2B2018%2B-%2BTables.xlsx?forceDownload=true
4. https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2019/08/input-output-latest/documents/all-tables-all-years/all-tables-all-years/govscot%3Adocument/SUT-98-17.xlsx?forceDownload=true
5. https://ore.catapult.org.uk/wp-content/uploads/2021/01/FOW-Cost-Reduction-Pathways-to-Subsidy-Free-report-.pdf (2021)

Schedule 1 – VAWT GVA Model

See separate worksheet

Appendix 6.4

6.4 UK Defence Solutions Centre: Interactive Analysis Toolset: Vertical Axis Wind turbine Supply Chain Development

UKDSC – Wind Turbines

30/03/2021

HARAJAN DEUSI, HEAD OF DATA AND INNOVATION

DANNY WELLS, SIMULATION MANAGER

Official: Commercial in Confidence

The information provided in this report has been sourced through the UK Defence Solutions Centre's Interactive Analysis Toolset (IAT). The IAT draws on over 170 different information sources across the world but should not be taken as all-inclusive. All analysis performed is subject to the following copyright notice, and should be used to direct further research activities requiring additional due diligence.

In developing this analysis, data has been extracted from subscription-based databases, working with various information providers and drawing information from multiple sources, including companies house, supplemented with analysis provided by in-house research teams. The information provided through the IAT is subject to change and reflects the latest data available from each of our data sources listed below:

- Beauhurst
- PitchBook Data, Inc
- Crunchbase
- Derwent
- Orbis (Bureau Van Dijk)
- Companies House

UKDSC – Commercial in Confidence

UK-Patent trends using Derwent

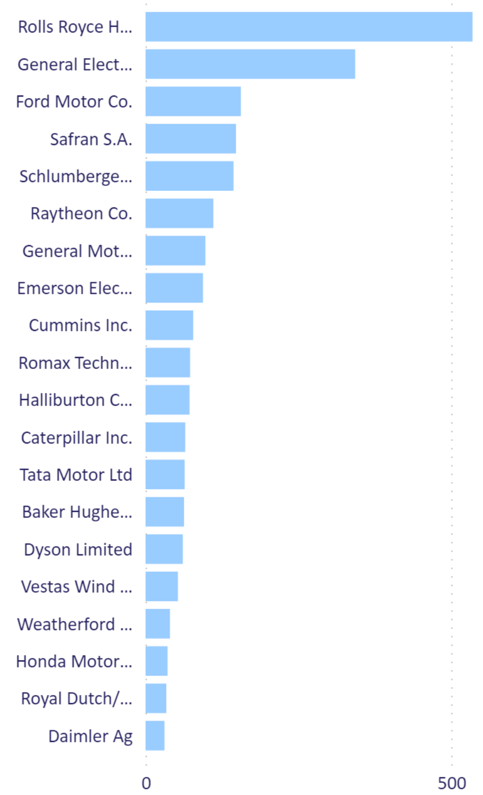
Keyword

All

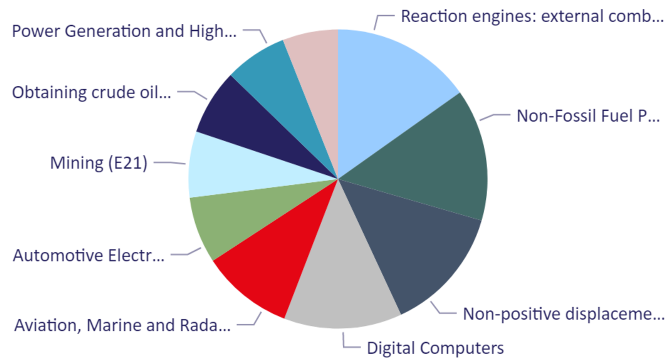
4400	10K	4684
Patents	Inventors	Assignees

1975 2020

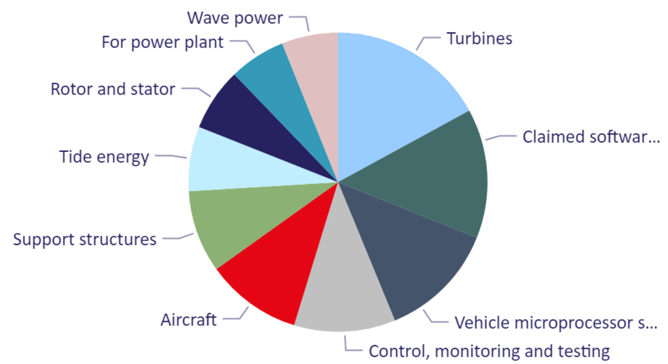
No. Patents by Ultimate Parent



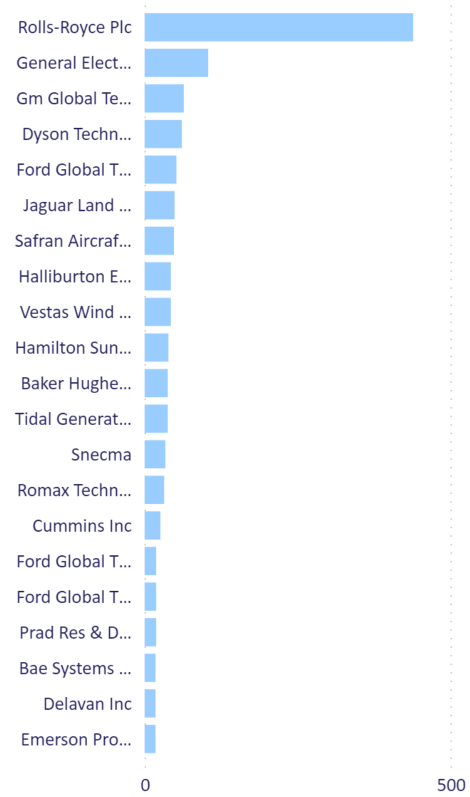
No. Patents by Class



No. Patents by Manual Code



No. Patents by Assignee



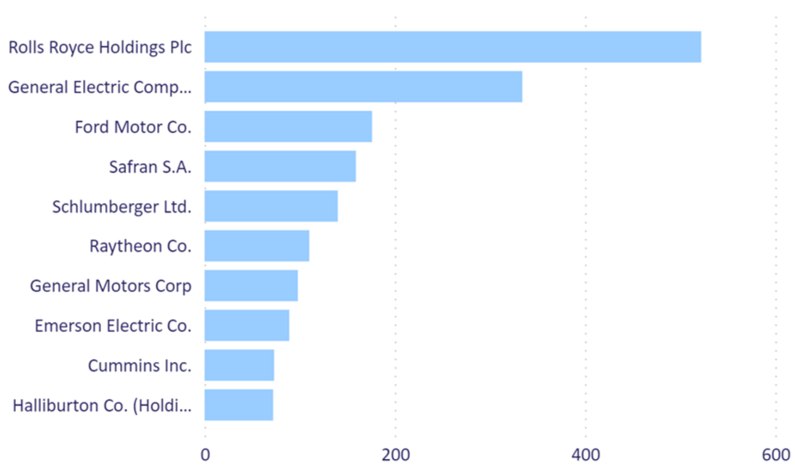
UKDSC – Commercial in Confidence

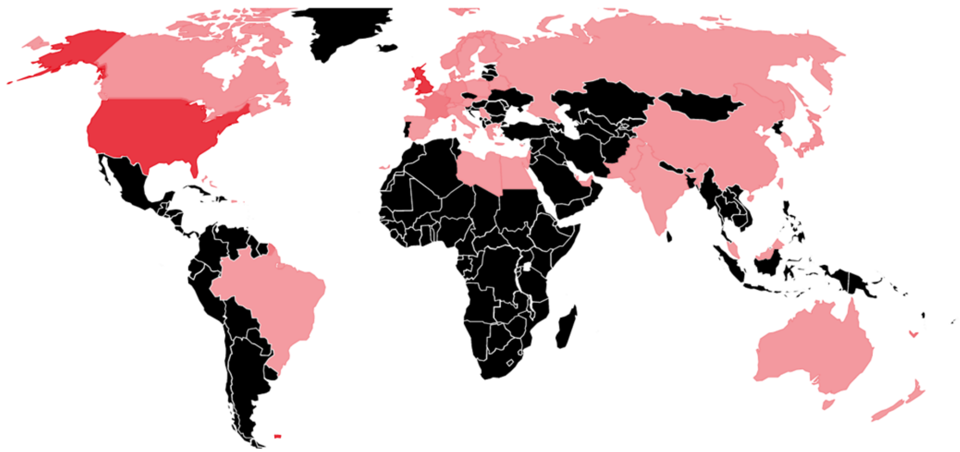
UK-Patent trends using Derwent

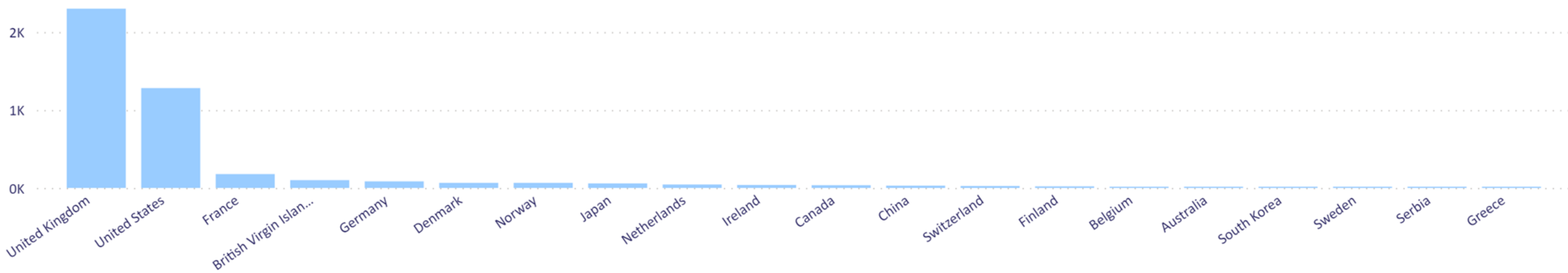
Keyword

All

1975 2020



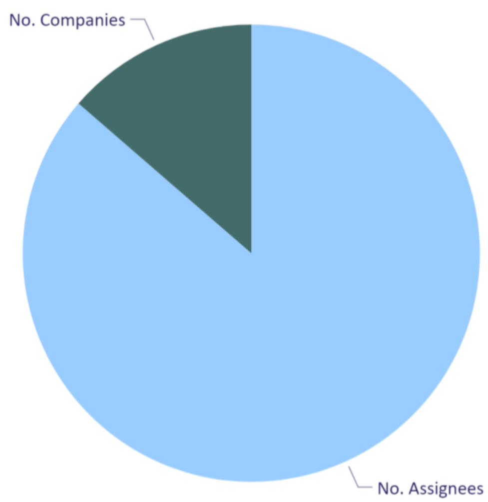


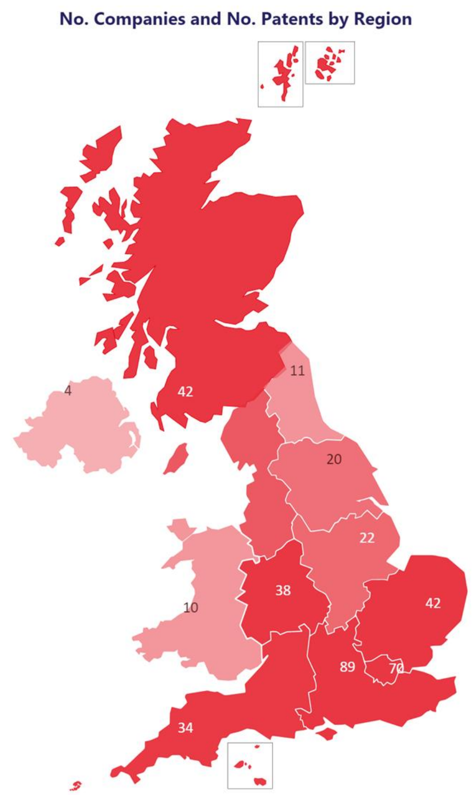


UK-Patent trends using Derwent

Region	No. Patents	No. Companies
London	672	68
South East	237	88
West Midlands	154	37
South West	151	33
East of England	122	42
North West	82	26
Scotland	75	42
Yorkshire and the Humber	53	20
East Midlands	33	22
Wales	20	10
North East	16	10
Northern Ireland	6	4
Total	**1621**	**402**

To link the patents to region, we found the companies listed as assignees. If the assignee was a person for example, this cannot be captured. Only 409 companies were returned, compared to the 2500 UK base assignees. Therefore location information on over 2000 assignees is missing.





UK High Growth Market

Wind Turbines:

High Growth Market Overview (2016-2020)

Data Source: All

Most Recent Turnover Threshold: All

85 Companies	£2.9bn Reported Turnover	25 Scaleups	5 Academic Spinouts	9 Accelerator Attendances

The Most Common Sectors Are:

Clean energy generation & **Clean energy generation**

The Top Buzzwords Are:

Drones & **Artificial Intelligence**

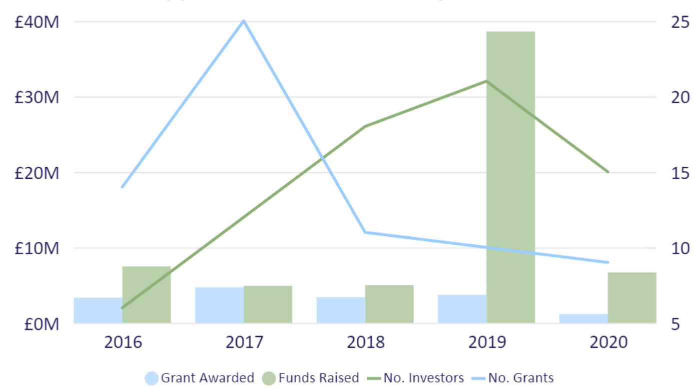
Company HQ's Tend To Be Located In:

North West & **Scotland**

Most Common Stages of Evolution Are:

Seed & **Established**

Approximate Investment by Investors



52 Fundraisings	£63.0M Raised	71 Grants Received	£16.4M Grant Amount Received	21 High Growth List Appearences

UK High Growth Market

Wind Turbines - Buzzword Breakdown

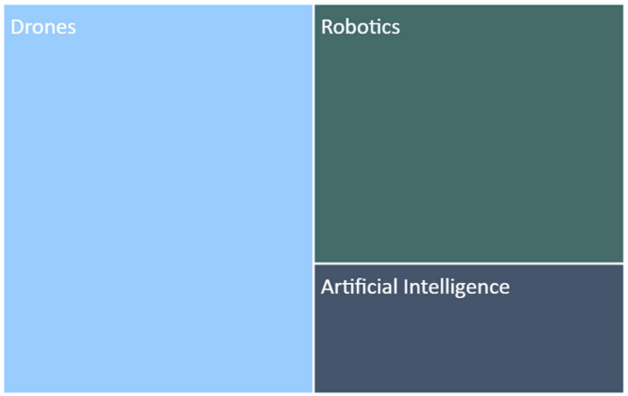
Data Source: All

Most Recent Turnover Threshold: All

Buzzwords: All

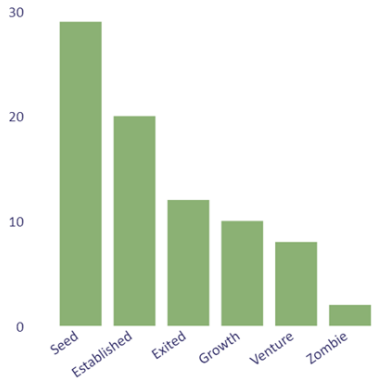
Regional Investment

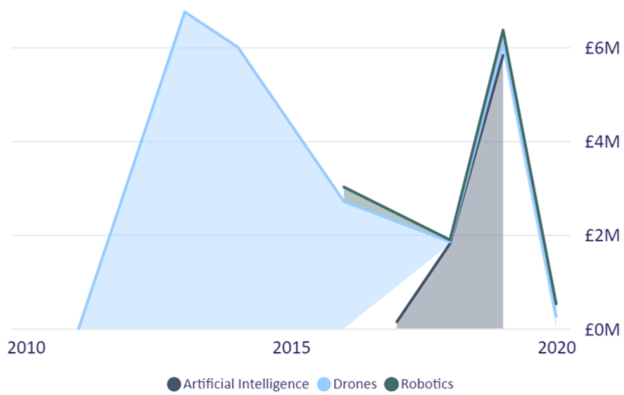
Top Buzzwords (Technologies)



Company Name	Buzzwords	Amount Invested	Region	Current Stage of Evolution	Turnover
Aveillant	Drones	£15,150,016	East of England	Exited	£0
Rovco	Artificial Intelligence	£7,780,180	South West	Venture	£0
Perceptual Robotics	Drones	£877,994	South West	Seed	£0
Perceptual Robotics	Robotics	£877,994	South West	Seed	£0
BB Stratus	Drones		South West		£0
Bladebug	Robotics		London	Seed	£0

Current Stage of Evolution Breakdown



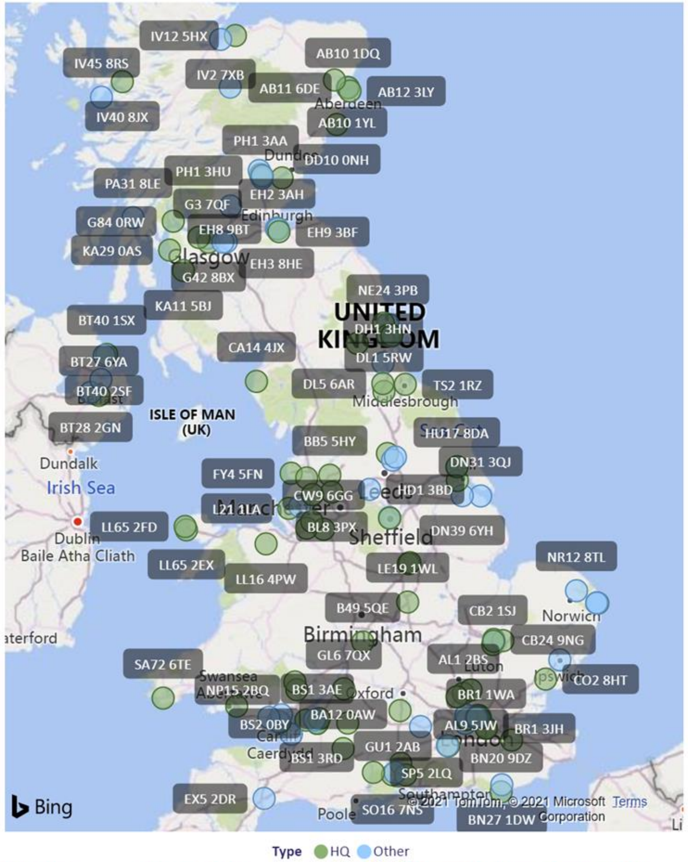


Official: Commercial in Confidence

UK High Growth Market

Wind Turbines - Location Breakdown

Data Source	Region	No. Offices	Buzzwords
All	All	All	All



Official: Commercial in Confidence

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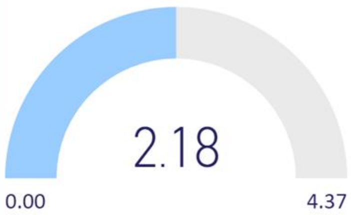
Most Common Office Region:

Scotland

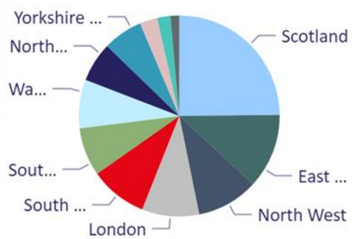
Average No. Employees:

77.02

Average of No. Offices



No. Offices per Region



Company Name	No. Offices	Grant Amount Recieved	Amount Invested	Buzzwords
3sun Group	5		£10,000,000	
I&H Brown	5			
RES	5			
Aveillant	3	£304,000	£15,150,016	Drones
Bostonair Group	3			
Community Windpower	3			
insitU	3		£30,001	
James Ingram & Associates	3			
Oldbaum Services	3	£262,000		
Rigmar Services	3			
Smart Component Technologies	3	£2,395,800	£200,010	
Trident Energy	3	£445,000	£440,000	
Advance Windpower	2	£100,000		
Attollo Offshore	2			
Australis Energy	2		£500,000	
Bitbloom	2	£126,000		
Blade Dynamics	2	£1,400,000	£13,207,826	
Bladebug	2	£651,500		Robotics
Chillwind	2			
CTruk	2	£1,000,000	£7,300,000	
Earthmill	2		£5,350,000	
Ecodyn	2	£100,000		
ERSG	2		£24,000	
G.F. Job	2			
Grampian Continental	2			
LMAT	2	£272,600		
Mar-Train Heavy Haulage	2			
Miller Research	2			
Oceanflow Energy	2	£764,900	£999,800	
Osbit	2	£632,700		
Peel Ports Great Yarmouth	2			
ProPlanEn	2	£138,000		
Renewable Parts	2		£356,014	

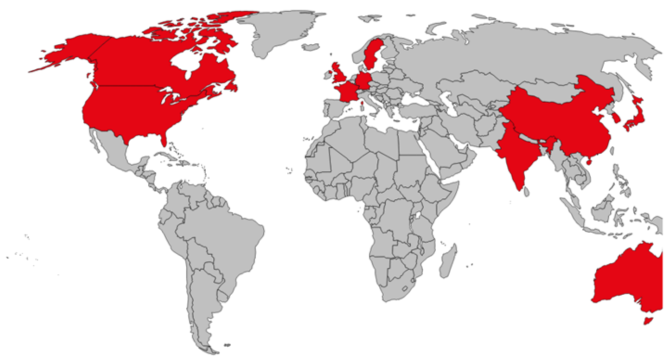
Global Investment Market

Wind Turbines - Overview (2015-2019)

Data Source: All

Country: All

359	Companies
£117.0bn	Revenue
27	Mergers & Acquisitions
62.9%	Average of % Acquired
12	Accelerator/Incubator

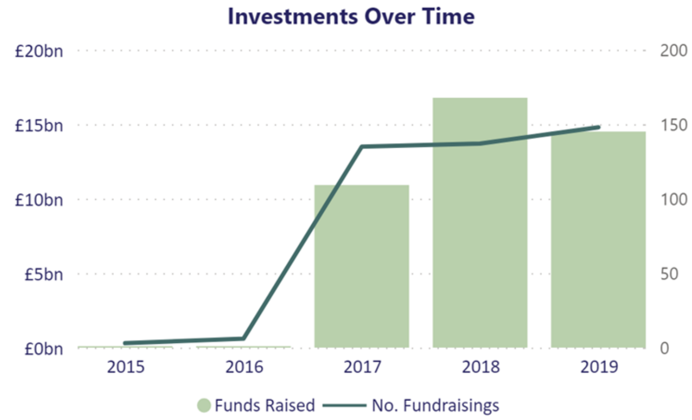


United Kingdom — Most Common Country

Buildings and Property — Most Common Industry

CleanTech — Most Common Vertical

Most Common City



429	Deals
£42.2bn	Capital Invested
14	No. Grants
£13.1M	Grant Invested
341	Investors

Global Investment Market

Wind Turbines - Market Breakdown

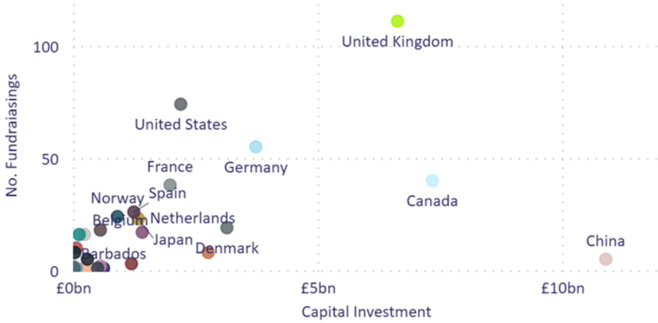
Data Source: All

2006 – 2021

Country	Sector, Group	Industries	Verticals	Keywords
All	All	All	All	All

Deals by Country

Capital Invested by Country



482
Companies

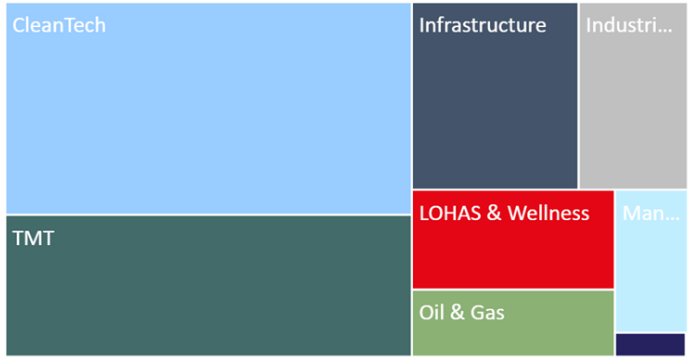
£57.8bn
Capital Invested

£143.6bn
Revenue

Energy Production
Most Common Industry

CleanTech
Most Common Vertical

Amount Investment by Vertical



Capital Invested by Year

SIC 28110 Comparison

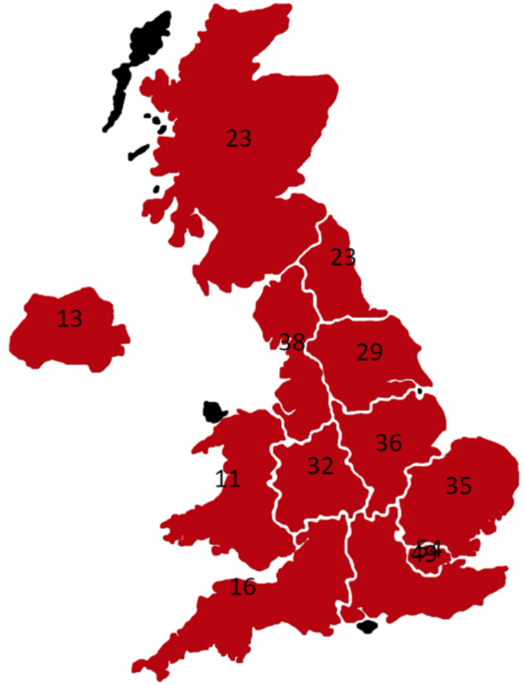
Wind Turbines: SIC 28110 Comparison

331
Companies

£77.4M
2020 Turnover

Region	Number of employees 2020	No. Companies	Average Number of employees 2020
East Midlands	167	36	18.56
East of England	62	35	12.40
London	2	54	1.00
North East	3	23	1.50
North West	20	38	2.50
Northern Ireland	19	13	3.80
Scotland	57	23	19.00
South East	111	49	13.88
South West	61	16	30.50
Wales	3	11	3.00
West Midlands	2	32	1.00
Yorkshire and the Humber	64	29	10.67
Total	**571**	**331**	**10.77**

Regional Breakdown



SIC 281921 Comparison

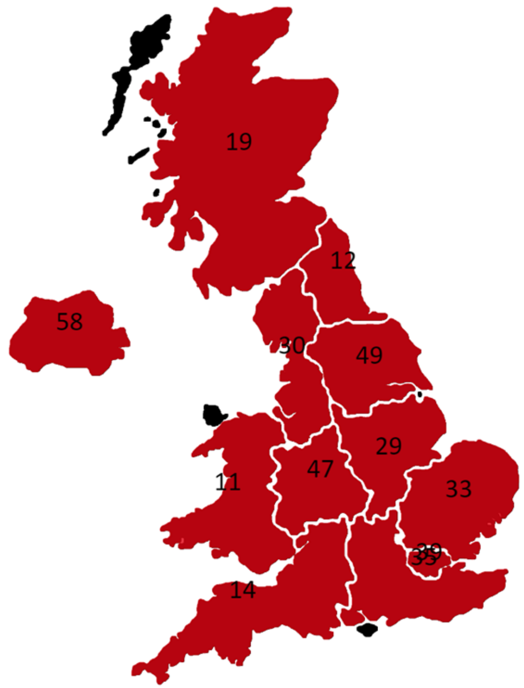
Wind Turbines: SIC 28921 Comparison

357
Companies

£953.8M
Turnover 2020

Regional Breakdown

Region	Number of employees 2020	No. Employees	Average Number of employees 2020
East Midlands	65	29	7.22
East of England	218	33	11.47
London	189	39	17.18
North East	75	12	18.75
North West	223	30	13.94
Northern Ireland	126	58	14.00
Scotland	61	19	5.08
South East	907	35	64.79
South West	86	14	9.56
Wales	16	11	3.20
West Midlands	167	47	12.85
Yorkshire and the Humber	318	49	14.45
Total	**2451**	**357**	**17.14**



Appendix 6.5

6.5 TechnipFMC: Expert Opinion on Installation Challenges for Floating Offshore Wind

Technical Note:	Constructability Opportunities for VAWT in Floating Offshore Wind
Date:	12th March 2021
Issued By	Gordon Tough

Following a discussion with NSRI on the development of Vertical Axis Wind Turbines (VAWT), this note summarises challenges identified in the construction and installation of floating offshore wind foundations with Horizontal Axis Wind Turbines (HAWT). Although at a lower level of technical maturity, it is considered that VAWT could address these challenges and improve project economics.

TechnipFMC have established construction and installation methods for the installation of floating offshore wind turbines. This work has been based on large scale arrays and next generation HAWT's. While these methods are credible and will be competitive with FOW in general, the route to economic parity with fixed bottom wind will be difficult without a rethink on the technology employed. VAWT may be a technology that provides this opportunity.

Constructability challenges that VAWT may address are as follows:

- Floating foundations specified for HAWT are large in both footprint and mass, 50m radius and 1000 Te/MW mass (for concrete foundations) are typical requirements. It is anticipated the stabilising moments required for VAWT will be lower than for HAWT and will reduce the footprint and mass.
- Smaller foundations would use less material, reducing the cost of the foundation and the environmental impact related to material consumption.
- Smaller foundations may allow increased multiples to be fabricated simultaneously in a dry dock. Construction of FOWT at large scale requires a high production rate to align with offshore construction windows.
- For an onshore lift, the nacelle lift for a HAWT defines the crane capacity. Smaller foundations and a nacelle located at deck level will significantly increase the lifting options that are currently limited.
- Infield and inshore operations and maintenance benefits are also anticipated with having the nacelle at deck level. Referring again to onshore crane capacity, while large ring

cranes may be mobilised for the construction phase, it is unlikely to be feasible to retain this craneage for future maintenance (e.g., replacement of heavy nacelle components).

- There is published literature suggesting a high spatial energy density can be achieved with VAWT. This may provide lower cost infrastructure.
- The mooring system for HAWT will have a significant cost for supply and installation. It should be investigated if lower loads and closer spacing for VAWT can introduce cost savings.

Floating wind's route to cost parity with fixed bottom is largely premised on increasing scale. While that will be successful to a point, the onshore infrastructure needed to construct the largest turbines and arrays may become impractical. VAWT could provide the paradigm shift needed if this scale cannot be achieved. Our established construction and commercial models for floating offshore wind with horizontal axis turbines could be applied to this VAWT to support this development.

Appendix 6.6

6.6 European Offshore Wind Developer and Turbine Manufacturer: Supply Chain Review

Wind Turbine

Companies	Operating?	HQ Location	Scotland/UK Presence	Catapult Category
GE Renewable Energy	Y	Paris France	Langhope Rig wind farm 2014	T Wind turbine
MHI Vestas Offshore Wind	Y	Aarhus Denmark	Seagreen project	
Siemens Gamesa Renewable Energy	Y	Bilbao Spain	NnG offshore wind project in Scotland	
Doosan Babcock	Y	Crawley England	Office in Scotland	
Envision	Y	Shanghai China	?	
Goldwind	Y	Urumqi China		
Hitachi	Y	Tokyo Japan	Scotland office	
Ming Yang	Y	Guangdong China	?	
Sinovel	Y	Beijing China		
Eisengiesserei Torgelow	Y	Torgelow Germany	?	T.1.1 Bedplate
MGH GussTec	Y	Hirrlingen Germany		
Metso	Y	Helsinki Finland		
MeuselWitz	Y	Meuselwitz Germany		
Siempelkamp	Y	Alzenau Germany		
Liebherr	Y	Bulle Switzerland	Office in Scotland	T.1.2 Main bearing
Schaeffler	Y	Herzogenaurach Germany	Offices in UK	
SKF	Y	Gothenburg Sweden	?	
thyssenkrupp	Y	Essen Germany		
Bruck	Y	Duren Germany	?	T.1.3 Main shaft
Skoda	Y	Mlada Boleslav Czechia		
thyssenkrup	[redacted]			
Bosch Rexroth	Y	Lohr a. Main Germany	Office in Scotland	T.1.4 Gearbox
Eickhoff	Y	Bochum Germany	?	
Hansen	Y	Horsholm Denmark	Offices in UK	
Moventas	Y	Jyvaskyla Finland	Office in UK	
Renk	Y	Augsburg Germany	Global presence	
ABB	Y	Zurich Switzerland	Offices in UK	T.1.5 Generator
GE	Y	Boston MA USA	Global presence	
Ingeteam	Y	Milwaukee WI USA	Global presence	
Leroy Somer	Y	Angouleme France	Offices in UK	
VEM	Y	Wernigerode Germany	Office in UK	
Bachmann	Y	Philadelphia USA	Global presence	T.1.7 Control system
DEIF	Y	Skive Denmark	Global presence	
KK-Electronic	Y	Middelsex England		

Mita Teknik	Y	Rodkaersbro	Global presence	

ABB	[redacted]			T.1.8 Yaw system
Bonfiglioli	Y	Lippo di Calderara di Reno Italy	Office in UK	
Bosch Rexroth	[redacted]			
VEM	[redacted]			

IMO	Y	London England	Global presence	T.1.9 Yaw bearing
Liebherr	[redacted]			
thyssenkrupp	[redacted]			

Siegerland	N			T.1.10 Nacelle auxilliary systems
Stromag	N			
Svendborg	Y	Vejstrup Denmark	Global presence	
Hydac	Y	Sulzbaach Germany	?	
Windsyn	N			
Cotes	Y	Aarhus Denmark	Global presence	
FT Technologies	Y	Teddington England	Global presence	
Gill Instruments	Y	Lymington UK	Global presence	
Kipp and Zonen	Y	Delft Netherlands	?	
NRG Systems	Y	Hinesburg VT USA		
Orga	N			
Thies	N			
Vaisala	Y	Vantaa Finland	Global presence	
Vector Instruments	Y	Stuttgart Germany	?	
Wood	Y	Aberdeen Scotland	Global presence	
ZX Lidars	Y	Ledbury England	UK presence	
Danfoss	Y	Nordborg Denmark	UK and Ireland	
Firetrace	Y	Scottsdale AZ USA	?	
Minimax	Y	Bad Oldesloe Germany	Global presence	
AKI Power Systems	Y	Gross-Zimmern Germany	?	
Effer	Y	Bologna Italy	Effer and Hiab the same company since 2018	
Hiab	Y	Malmo Sweden		
Liftra	Y	Aalborg SV Denmark	Global presence	
Palfinger Marine	Y	Salzburg Austria	Global presence	

August Friedberg	Y	Gelsenkirchen Germany	?	T.1.13 Structural fasteners
Cooper and Turner	Y	Sheffield England	Offices across UK	
Fuchs and Sanders	Y	Lotte Germany	?	
Gexpro Services	Y	Irving TX USA	Global presence	
Multifix	Y	Maidstone England	UK based	

3A Composites	Y	Sins Switzerland	Global presence	
Airtech	Y	Huntington Beach CA USA	Presence in Europe	

Diab	Y	Helsingborg Sweden	Global presence	T.2.1.1 Structural composite materials
Gurit	Y	Wattwil Switzerland	Global presence	
Hexcel	Y	Stamford USA	Global presence	
Owens Corning	Y	Toledo USA	Global presence	
PPG	Y	Pittsburgh USA	UK offices	
SGL	Y	Wiesbaden Germany	Global presence	
Zoltek	Y	St. Louis USA	Global presence	
Eisengiesserei Torgelow	[redacted]			T.2.2 Hub casting
Gusstec	[redacted]			
Metso	[redacted]			
MeuselWitz	[redacted]			
Rolls Royce	Y	London England	Global presence	
Sakana	N			
Siempelkamp	[redacted]			
Vestas	[redacted]			
IMO	[redacted]			T.2.3 Blade bearings
Liebherr	[redacted]			
Rollix	N			
SKF	[redacted]			
thyssenkrup	[redacted]			
Bosch Rexroth	[redacted]			T.2.4.1 Hydraulic pitch system
Fritz Schur	N			
Hydratech Industries	Y	Vra Denmark	Global presence	
MOOG	Y	Elma USA	Global Presence	T.2.4.2 Electric pitch system
SSB Wind Systems	Y	Salzbergen Germany	Global presence	

Appendix 6.7

6.7 Oxford Brookes University: Numerical modelling and optimisation of vertical axis wind turbine pairs - a scaled up approach

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Numerical modelling and optimization of vertical axis wind turbine pairs: A scale up approach

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ABSTRACT

The performance augmentation of pairs of vertical axis wind turbines (VAWTs) is known to be dependent on incident wind direction, turbine spacing and direction of rotation. Yet, there is a lack of robust numerical models investigating the impact of these parameters. In this study two-dimensional CFD simulations of an isolated VAWT and of co- and counter-rotating pairs of VAWTs were performed with the aim to determine turbine layouts that can increase the power output of VAWT farms. More than 11,500 h of simulations were conducted at a turbine diameter Reynolds number of $1.35 \cdot 10^7$. A mesh convergence study was conducted, investigating the influence of mesh size, domain size, azimuth increment, number of iterations per time step, and domain cell density. Results showed that mesh size, domain size, and azimuth increment proved to have the biggest impact on the converged results. For the configurations analysed, pairs of VAWTs exhibited a 15% increase in power output compared to operating in isolation, when the second rotor was spaced three turbine diameters downstream and at an angle of 60° to the wind direction. Furthermore, when three turbines were positioned in series, the power output was greater than a pair by an additional 3%.

1. Introduction

The UK's wind capacity is expected to almost double by 2030 [1]. So far, all large scale wind farms (>40 turbines) are utilising horizontal axis wind turbines (HAWTs), and these are continuously becoming more efficient and larger in size [2] in order to maximise the energy extracted from the given site. Yet, turbulent wakes created by the first row decrease the power output of the turbines behind by up to 40% [3]. Vertical axis wind turbines (VAWTs) could solve this problem since research [4,5] has shown that this type of turbine exhibits the opposite behaviour when composed in wind farms and apparently they enhance each other's performance. Furthermore, maintenance costs are lower due to fewer moving parts, which also makes them easier to install, and, opposite to HAWTs, they can be installed at sites with varying flow conditions (i.e. varying wind direction) [6,7]. Their primary disadvantages are the lower efficiency, reaching 35%–40% in isolation compared to HAWT's that is near to 50% [8], and the low starting torque for some designs – i.e. external power is required to accelerate the turbine at small angular velocities up to its optimal tip speed ratio, λ. In summary, harnessing wind power coming from any direction to create energy using VAWT is an attractive option and despite the intensive research in the field, the underlying performance parameters of VAWTs are not well understood. To develop wind farms that can meet future energy demands, performance optimization of VAWT farms is required.

There are studies in literature [2,9–13] investigating optimal VAWT blade designs and geometric properties, with the primary tool being Computational Fluid Dynamics (CFD) and/or wind tunnel experiments. One of the few studies that investigated performance augmentations of VAWT farms was that of Dabiri [5], where experiments in a desert with six 10 m tall times 1.2 m diameter VAWTs were conducted. The experiments investigated the effects of turbine spacing and direction of rotation. It was observed that while HAWTs experienced an overall decrease in power by 20%–50% when placed in close proximity to each other (1.65 turbine diameter separation), the VAWTs enhanced the overall performance by 5–10%. Furthermore, when the spacing was 4*D* (*D* = turbine diameter) for the VAWTs, the downstream rotor exhibited a 5% lower deviation from its isolated performance. This held true for other tip-speed ratios too. Results were also in

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contrast to HAWTs where a turbine spacing of 15D-20D downwind to fully recover the wake was required [5].

Parneix et al. [14] is an example of another study, where two side-by-side VAWTs were analysed; the CFD model used an in-house code based on vortex methods to estimate power co-efficients. The two-dimensional simulations showed that for a turbine spacing of 1.2D, the power coefficient was 15% higher for both turbines. Additionally, the three-dimensional simulations found an increase of at least 8%.

Finally, Brownstein et al. [4] conducted experiments of a pair of 5-bladed VAWTs in an open circuit, subsonic wind tunnel. The rotor diameter (D) was 0.20 m, and the blades had a NACA 6415 aerofoil shape. The study investigated the rotor performances for varying; array angle (β) between −90° and 90°, direction of rotation, and turbine spacing between 1.25D to 3D. The Reynolds number was $7.3 \cdot 10^4$ for all experiments, and this is more than a factor of 100 lower than what a larger VAWT would experience offshore. Three distinct regions in β were found, and for $\beta \gtrsim 30°$, both turbines exhibited performance augmentations between 1.1% and 12.5%. In this regime, a turbine spacing of 1.25D displayed the best improvements.

In this study, the power improvements of a pair of VAWTs configured in two-dimensional CFD simulations for varying; array angle, direction of rotation, and turbine spacing were investigated. To the authors' best knowledge, this is the first attempt at numerically investigating the efficiency augmentations of VAWTs for more than 20 different layouts. The results were compared using a dimensionless parameter and validated against experimental data in literature [4].

2. Methodology

A frequently applied method for analysing VAWTs is CFD simulations, and in this work, the software package Simcenter STAR-CCM+ 2019.2.1 was used. Three-dimensional CFD simulations are computationally expensive and Bianchini et al. [2] concluded that two-dimensional VAWT studies give accurate results if reasonable mesh, timestep, and geometry settings are applied; thus, it was decided to perform two-dimensional URANS CFD simulations. The CFD simulations were transient, because of the rotational motion, and the implicit method was applied since it was more numerically stable. Balduzzi et al. [9] used a coupled algorithm, however, there were negligible affects when using a segregated solver for small time increments. Coupled flow requires 1.5–2 times more memory, thus, it was decided to use the segregated flow algorithm to develop a computationally efficient model. When wind blows over a VAWT, it occurs at very low Mach numbers and therefore the compressibility effects are minimal to null. As a result, it can be assumed that the air has constant density and is incompressible. k-ε is the most frequently applied turbulence model for analysing VAWTs [9], however, recent papers within the field of VAWTs [9,15] recommended applying the SST model instead of the k-ε model as it gives results that are closer to the experimental data. Hence, in this study the SST (Menter) k-ω (SSTKO) turbulence model was applied, and the model differentiated from the standard k-ω model (SKO) in the formulation of the production terms P_k and P_ω in the two transport equations (Eqs. (1) and (2)):

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho k \overline{\mathbf{v}}) = \nabla \cdot [(\mu + \sigma_k \mu_t)\nabla k] + P_k - \rho \beta^* f_{\beta^*}(\omega k - \omega_0 k_0) + S_k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \nabla \cdot (\rho \omega \overline{\mathbf{v}}) = \nabla \cdot [(\mu + \sigma_\omega \mu_t)\nabla \omega] + P_\omega - \rho \beta f_\beta \left(\omega^2 - \omega_0^2\right) + S_\omega \quad (2)$$

For P_k, an additional non-linear production term (Eq. (3)) is added in the SSTKO model, and for P_ω, a cross-diffusion term (Eq. (4)) is included [16].

$$\nabla \cdot \overline{\mathbf{v}} : (T_{RANS,NL}) \quad (3)$$

$$2\rho(1 - F_1)\sigma_{\omega 2}\frac{1}{\omega}\nabla k \cdot \nabla \omega \quad (4)$$

The time step of 0.003155 s was derived from a sensitivity analysis during the mesh convergence study, and further information can be found in supplementary material S.4. The optimal setup parameters within the range investigated balancing accuracy and solving time, are stated in Table 1. The mesh convergence study was solved by using the supercomputer at Oxford Advanced Research Computing for a total of 2458 h. The layout simulations were done on the pooled computers at Oxford Brookes University, and the total simulation time was >9000 h.

2.1. Rotor geometry

VAWTs can either be comprised of asymmetric or symmetric aerofoils. The classic NACA four-digit symmetric aerofoils have been used by many researchers, because they have been thoroughly tested. Islam [17] performed a numerical study of a wide range of asymmetric aerofoils and compared them to a symmetric NACA0015 profile. The results showed that the asymmetric aerofoils exhibited the highest power coefficients at low tip speed ratios ($\lambda < 3$), whereas the NACA0015 had a higher efficiency at greater tip speed ratios ($\lambda > 3$). Brusca et al. [18] concluded that a NACA 0018 was the most efficient aerofoil, and its optimal tip speed ratio occurred around 3.5. Fig. 1 shows the three-bladed design and its geometric dimensions applied in this study.

2.2. Domain geometry

The flow must be fully developed over the length L, and the width W must be enough to avoid the boundary effects near the walls affecting the flow in the middle [19]. A domain size that is too small, does not allow the flow to fully develop. Balduzzi et al. [9] concluded that the domain size had to be greater than $W = 60D \times L = 90D$ to replicate open-field-like boundaries (Fig. 2). Furthermore, the first rotor (R1) was positioned $L_1 = 20D$ from the inlet,

Table 1
Properties of CFD model.

	Parameter	Value
Physics Continuum	Space	Two Dimensional
	Time	Implicit Unsteady
	Material	Air
	Density	1.18415 kg/m^3
	Dynamic viscosity	1.85508E-5 Pa-s
	Flow	Segregated flow
	Equation of state	Constant Density
	Viscous Regime	Turbulent
	Reynolds-Averaged Turbulence	SST (Menter) K-Omega
	Transition	Gamma Transition
	Order of accuracy	Second-order
	Solvers: Time-Step	0.003155 s
	Maximum Inner Iterations	15

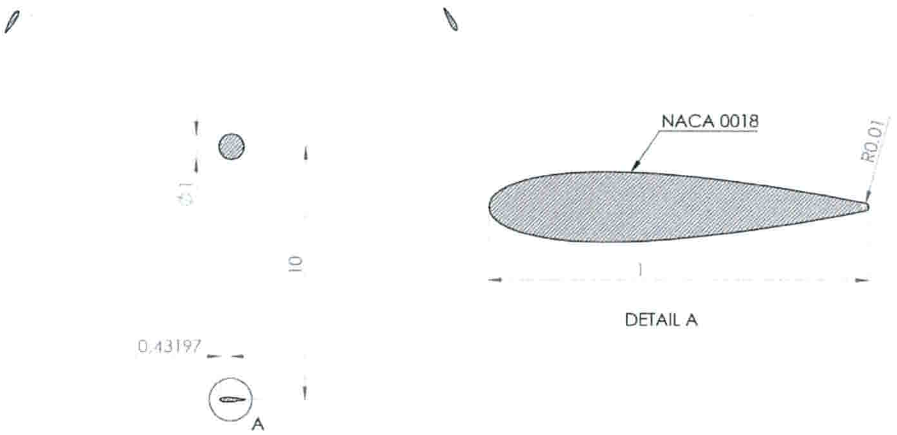

Fig. 1. Rotor geometry. Dimensions are given in meters.

because the wake was the most important feature and it stretched longer than what occurred in front of the turbine.

2.3. Boundary conditions

The rotors were positioned in a rotating region within a larger rectangular domain with stationary walls top and bottom, a velocity inlet, and a zero-gauge pressure outlet (Fig. 3). The rotating regions had a diameter, D_{RR}, of 1.5*D*. An overset mesh was created between the rotating region and domain using STAR CCM+, and a slip-condition was applied to the walls to avoid blockage effects. Verified by data from Bockstigen offshore wind farm, Gotland, Sweden the inlet velocity, U_0, was 10 m/s and the turbulence intensity was 1% [20]. Angular velocities, ω, were set at 3.5 rad/s according to Ref. [18]; thus, the turbine diameter Reynolds number was $1.35 \cdot 10^7$. 25 different layouts were analysed and evaluated with 24 being with two rotors and 1 layout with three rotors. Three variables were investigated; the turbine spacing, *dist*, the array angle, β, and the direction of rotation of R2 with R1 always rotating in a counter-clockwise direction.

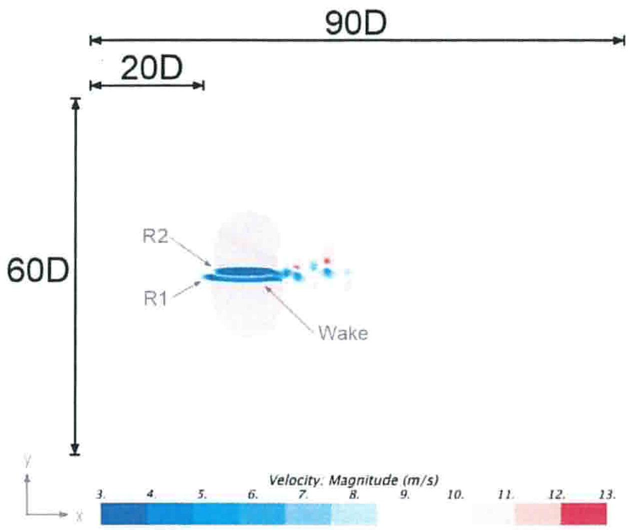

Fig. 2. The domain geometry was big enough to avoid boundary effects.

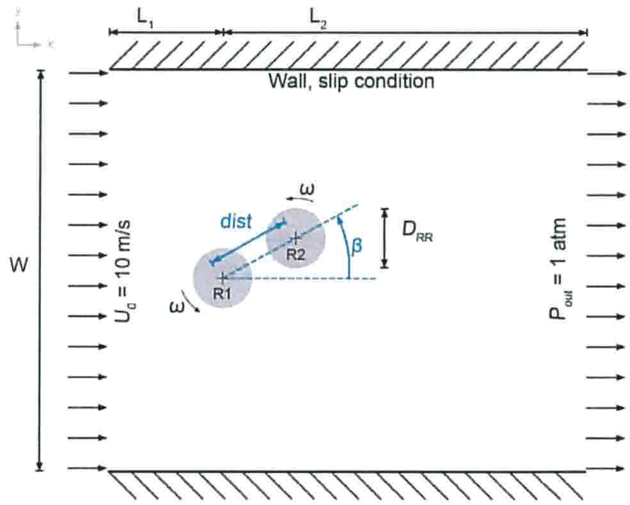

Fig. 3. Boundary conditions. R1 was always rotating in counter-clockwise direction, but the direction of rotation of R2 varied depending on whether the pair was co- or counter-rotating. dist was the turbine spacing, and β was the array angle.

2.4. Meshing strategy

A mesh convergence study was conducted using the supercomputer at Oxford Advanced Research Computing for a total of 2458 h. The final mesh predicted moment coefficients that deviated 2.1% from the finest mesh, however, it solved 32 times quicker. Fig. 4 illustrates the final mesh with (a) structured hexahedral cells in the domain including refinement boxes around the wakes derived from the findings and recommendations of [9,21]. Circular rotating regions with triangular cells (b), and tall, dense prism layers near the aerofoils (c) to accurately resolve the boundary layer. The grid convergence study concluded the mesh properties to be 150 prism layers with a first layer height of $5.41 \cdot 10^{-2}$ mm and prism stretching factor of 1.03. Surface curvature of the blades was set to be 1000 points/circle, and the base size of the rotating region was 0.16 m. The base size of the; domain was 16 m, largest refinement box was 1.6 m, and smallest refinement boxes were 0.2 m. The surface growth rates, 1.05 in the rotating regions and 1.25 in the domain, were kept low to ensure a smooth transition from near the walls to the freestream regions. There were approximately 340,000 cells in each of the rotating regions, and

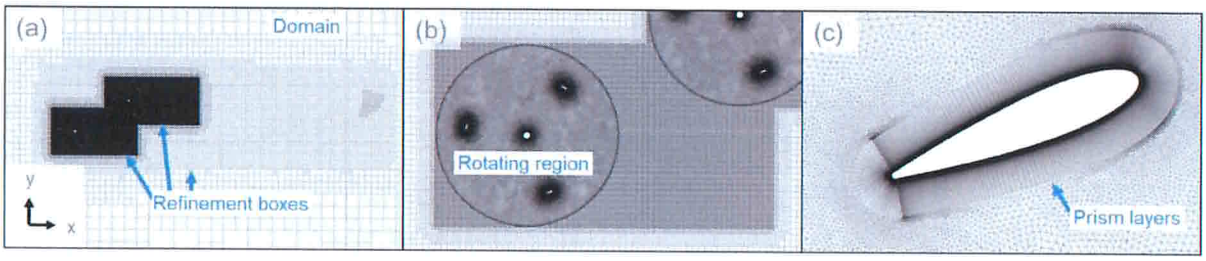

Fig. 4. Final mesh: (a) structured hexahedral cells in the domain including refinement boxes around the wakes, (b) rotating regions with triangular cells and (c) tall, dense prism layer near the aerofoils.

220,000 cells in the domain, i.e. a total of ~900,000 cells. Finally, the high number of prism layers meant the wall y^+-values did not exceed 6.05 even in extreme flow conditions (e.g. in wakes etc.) as seen in Fig. 5.

2.5. Convergence

The averaged moment coefficients over one revolution lowered as more revolutions were solved. Previous studies were typically concerned with the percentage change between the moment coefficients of two consecutive revolutions, and the most stringent criterion in literature was the one suggested by Balduzzi et al. [9], who concluded a simulation to be converged when the difference was below 0.1%. All results showed that R2 took the longest to converge, hence why studies regarding convergence criterion for a VAWT in isolation were not strictly applicable to a pair in all instances.

It was found that performing regression analysis using a rational function with degrees between 1 and 15 gave the best results at predicting the moment coefficient. The rational function describing the average moment coefficient, M_{avg}, as a function of number of revolutions solved, was:

$$M_{avg}(N_R) = \frac{\sum_{i=1}^{m} \psi_i \cdot (N_R)^i}{\sum_{i=1}^{k} \zeta_i \cdot (N_R)^i} \quad (5)$$

where N_R was the revolution number, m and k indicated the degree of the polynomials in the numerator and denominator respectively, and ψ and ζ were coefficients. The best fitting functions occurred for $m = k$. The mathematical software Maple 2019 was utilised to determine the fitting equations. As initial revolutions have minimum effect on the final convergence, the first 10 revolutions were not taken into account, when using the fitting equations. Simulations were solved for an average of 56 revolutions, and the data points were smoothened for three consecutive revolutions.

The weighted mean square error was applied to evaluate the applicability of each fitting equation. The weighting was derived from the number of revolutions, so that the last revolutions had a greater importance than the initial values. The weighted mean square error, *WSME*, was calculated as:

$$WMSE = \frac{\sum_{i=1}^{n} (N_R)_n \cdot \left(M_n - \widehat{M_n}\right)^2}{\left(\sum_{i=1}^{n} (N_R)_n\right) \cdot |n|} \quad (6)$$

Where M_n was the average moment coefficient for the n'th revolution, $\widehat{M_n}$ was the moment coefficient predicted by the fitting equation at the n'th revolution, and $|n|$ was the cardinality of set n.

2.6. Performance indicator

The parameters most frequently used to evaluate the performance characteristics of VAWTs are; the instantaneous moment coefficient (C_m) – indicating the torque generated by the blades – and the coefficient of power (C_P) – indicating the energy efficiency of a turbine. The instantaneous moment coefficient is defined as;

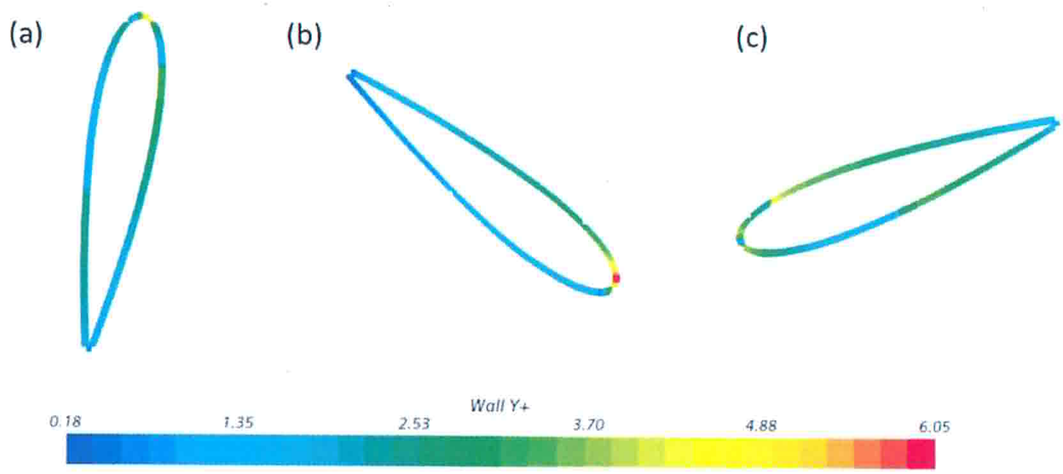

Fig. 5. Wall y + values for R1 operating in isolation at three different positions.

$$C_m = \frac{M}{\frac{1}{2}\cdot\rho\cdot A\cdot R\cdot U_0^2} \quad (7)$$

where M is the instantaneous moment, ρ is the air density, A is the cross-sectional area, R is the turbine radius, and U_0 is the freestream velocity. The power coefficient is

$$C_P = \frac{P}{\frac{1}{2}\cdot\rho\cdot A\cdot U_0^3} \quad (8)$$

where P is the power of the turbine, and it is defined as

$$P = M\cdot\omega \quad (9)$$

Combining Eqs. (7)–(9), one will obtain [22].

$$C_P = \frac{C_m\cdot R\cdot\omega}{U_0} = C_m\cdot\lambda \quad (10)$$

This expression (Eq. (10)) thereby correlates the three most important parameters (tip speed ratio and coefficients of power and moment) in the simplest manner. In this project, all rotors had equal angular speed, and since one was interested in the performance augmentations, the following performance indicator (Ω) was defined by Eq. (11):

$$\Omega = \frac{\sum_{i=1}^{n} C_{P_i}}{n\cdot C_{P_{iso}}} \quad (11)$$

where C_{P_i} was the coefficient of power of each rotor, C_{P_iso} was the performance of a single rotor in isolation, and n was the number of turbines in the layout. Therefore, if $\Omega > 1$, the configuration exhibited a higher power output than if the two turbines were operating on their own.

3. Results

3.1. Rotor orientation

The average performance of co-rotating and counter-rotating pairs for a turbine spacing of 2D, are plotted in Fig. 6 against the array angle β. For both directions of rotation, the efficiency was greatest for $45° \leq |\beta| \leq 90°$, but all compositions except for $\beta = 0°$ (R2 behind R1) had an efficiency above 1. Therefore, two VAWTs increase each other's efficiencies when positioned in specific layouts controlled by beta. Counter-rotating turbines showed to

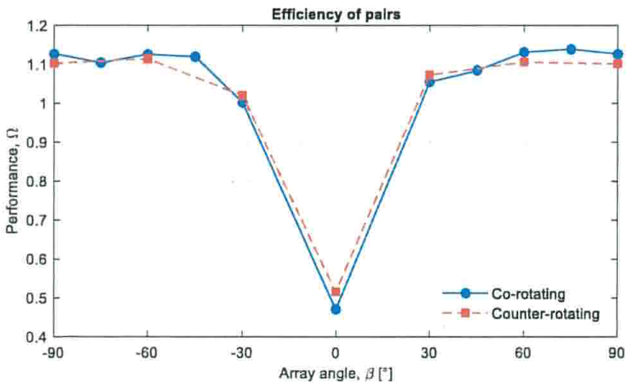

Fig. 6. Average performance of the two turbines in the pair against varying array angle, β, for the layouts with a distance of 2D. If Ω > 1 the pair exhibited a greater power output than if the two turbines were individually operating in isolation.

produce greater power than co-rotating at smaller ($|\beta| \leq 30°$) and the opposite at larger ($|\beta| > 30°$) angles of β. Finally, whether the second rotor was positioned above, $\beta > 0$, or below, $\beta < 0$, only had a marginal impact on the performance when $|\beta| \geq 45°$.

Velocity diagrams of ten layouts are illustrated in Fig. 7. When R2 was located in the wake of R1, (b) and (h), R2 did not experience the same kinetic energy of the wind compared to in isolation, hence there was a drop in performance. This occurs for HAWTs in wind farms too [3,5], however, their wake is more persistent (i.e. longer) and therefore the turbines must be spaced further apart. It can also be observed that the blades in (h) were only shadowed for half of their revolution, and as a result, the performance was nearly a factor of 2 greater in comparison to (b), which was fully covered by R1's wake.

Fig. 7 (f) and (g) show that if R2 was at the periphery of R1's wake, then R2 bended the wake of R1 causing a greater power output of R2, and a lower power output of R1. This is also seen later in Fig. 8 for the co-rotating plot that the performance of R1 at 30° (R2 at the border of R1's wake) was lower than at 0° (R2 did not lie on R1's wake boundary) before increased performance augmentations again at $|\beta| > 30°$ (R2 was away from R1).

For larger angles of β; R2 was not in R1's wake – see Fig. 7 (c), (d), (e), and (j); and the pair experienced augmentations. Fig. 7 (c) indicates the distorted flow field around the turbines too. For example, the red regions outside the wake had a higher velocity than the freestream region. Thus, the turbine caused the flow to accelerate.

It was not only the second rotor that was affected; the first rotor also experienced either an increase or decrease in power output. Fig. 8 shows the normalised performance values for the first and second turbines. R1 experienced a greater efficiency as β approached 90°; yet, R2 reached a peak at $|\beta| \approx 60°$. However, as shown previously in Fig. 6, the optimal layout for a pair as a unit occurred at $\beta = 75°$. Co- and counter-rotating configurations gave similar results, and the co-rotating configurations exhibited the greatest performance for its R2 at −60°, where the performance augmentation was 1.231. Similarly, the smallest value occurred at 0°, giving a performance of −0.024, i.e. power was required to rotate the turbine.

Fig. 8 also shows a spike for R2 at $-90° \leq \beta \leq -30°$, whereas at $30° \leq \beta \leq 90°$ the performance indicator Ω curve is flatter (it is clearest to see for the co-rotating layout). A hypothesis is that R1 was always rotating in the CCW-direction, and similar to an aerofoil generating lift by redirecting flow momentum downwards and away, then R1 acted in a similar way. This phenomenon is illustrated in Fig. 9. As R1's wake was directed towards the bottom right corner, then it affected the results, because R2 was now closer to the border of R1's wake at −30° than at 30°. Therefore, the performance augmentation Ω was greater at 30°. Even though, the performance was greater at $\beta = -45°$ than for 45°, then this is likely to be due to simulation tolerances.

3.2. Validation of numerical model

The results from Fig. 8 were compared to Brownstein et al. [4] experimental data as shown in Fig. 10. At this point it should be noted that in Ref. [4] the parameters do not exactly match the conditions of the numerical study such as number of blades and Reynolds number, however this was the closest available to our model study that can be used for validation. The average deviation was 5.1% and 7.8% for respectively R1 and R2, when only considering the results obtained for $|\beta| > 30°$. The deviation was greater if all angles were considered (R1: 7.1% and R2: 24.7%), however, these are not of interest when looking for the optimal position due to poor performance. The larger deviation for small angles of β, is

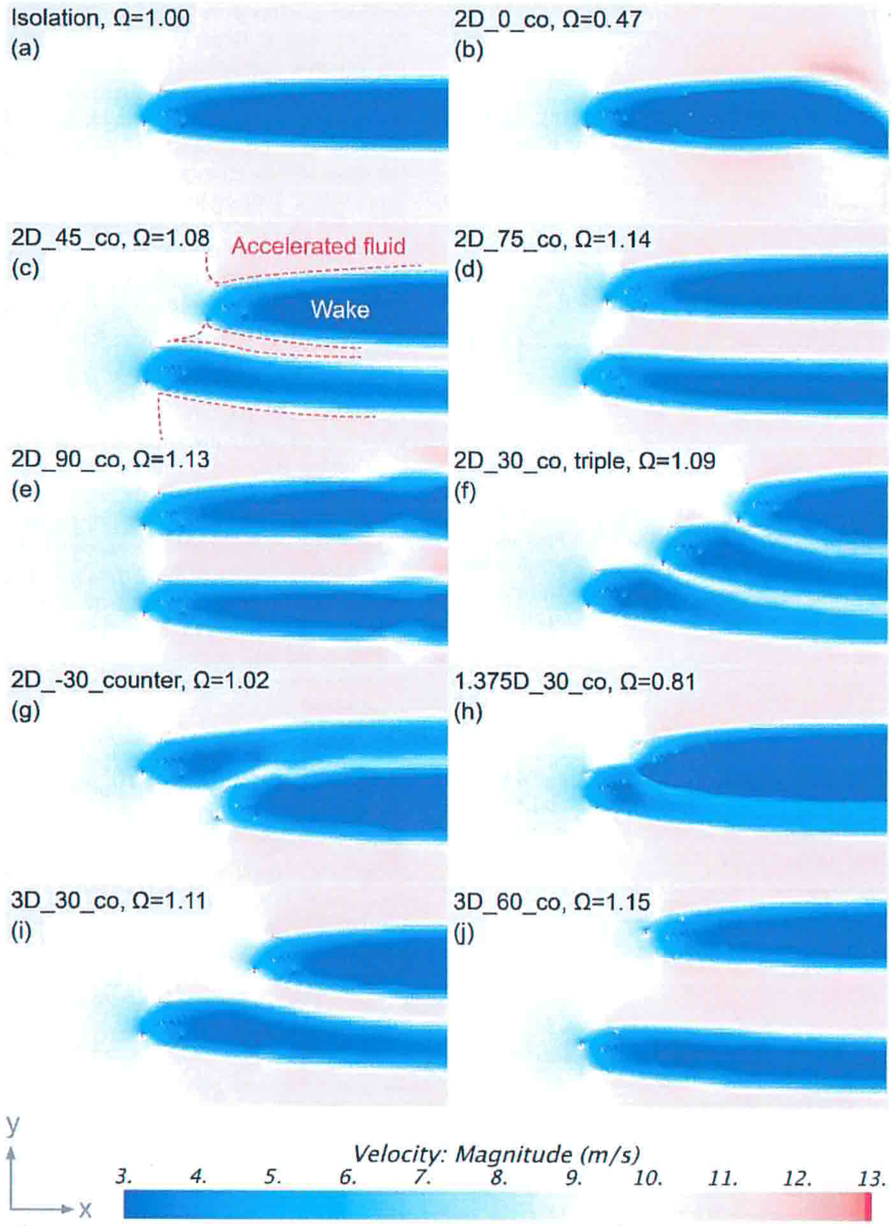

Fig. 7. Velocity diagrams of several layouts. The blue regions have a lower and the red regions a higher velocity than the freestream velocity at the inlet.

hypothesized to be due to three-dimensional effects not being included in the two-dimensional CFD-simulations; e.g. how wind from above may travel to lower altitudes to recover the wake quicker. Furthermore, the asymmetry of the upstream turbine was not as dominant as the one found by Ref. [4], however, the wind tunnel experiment in Ref. [4] with a 5-bladed VAWT design was conducted at a Reynolds number that was a factor of 185 times lower than the one of this work. Nevertheless, two-dimensional CFD simulations are applicable at predicting the performance augmentations experienced by pairs of VAWTs for $|\beta| > 30°$. Finally, results were in a very good agreement with [4] where the experimental results showed a spike at $\beta \approx -40°$, and a flatter curve for $\beta \geq 30°$.

As described in section 3.1 *Rotor orientation*, the shift in the performance indicator Ω was due to the wake being directed downwards. A possible reason to why the numerical results did not show a significant shift was that [4]'s 5-bladed turbine pushed more fluid downwards. Furthermore, the wind speed was nearly a factor 2 (as more representative values monitored by Larsen, G. C. and Hansen, K. S [20]. replicating real working conditions were deployed) lower than this CFD study, and therefore the air had less momentum to 'straighten' the wake. Although, there was a mean 6.5% error in values, then the overall trend of the performance behaviour was captured very well by this methodology.

3.3. Turbine spacing

Fig. 11 shows that turbine spacing also proved to influence the performance. The power enhancement increased as R2 was positioned further away from R1. Furthermore, near-all configurations

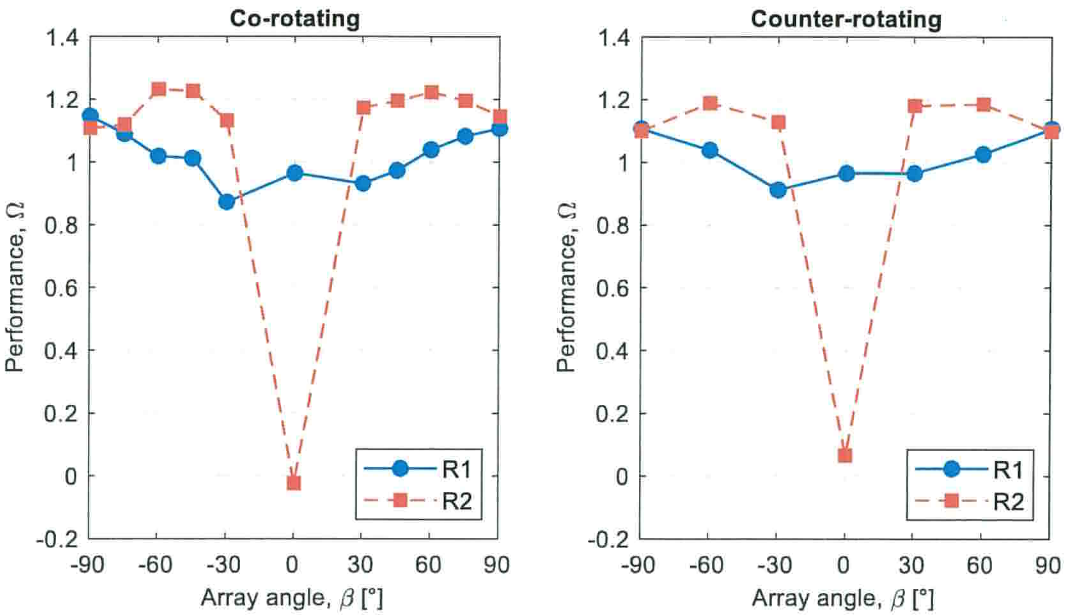

Fig. 8. Shows the individual performance of Rotor 1 (R1) and Rotor 2 (R2) varied as a function of array angle β.

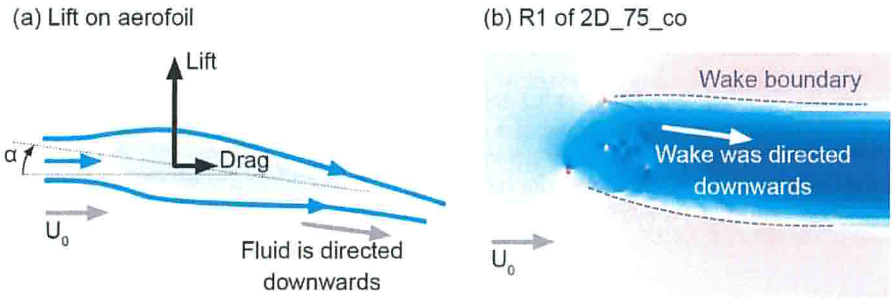

Fig. 9. (A) Illustration of lift acting on an aerofoil and redirection of fluid momentum. (b) R1 of the 2D_75_co layout shows how the wake was naturally directed downwards.

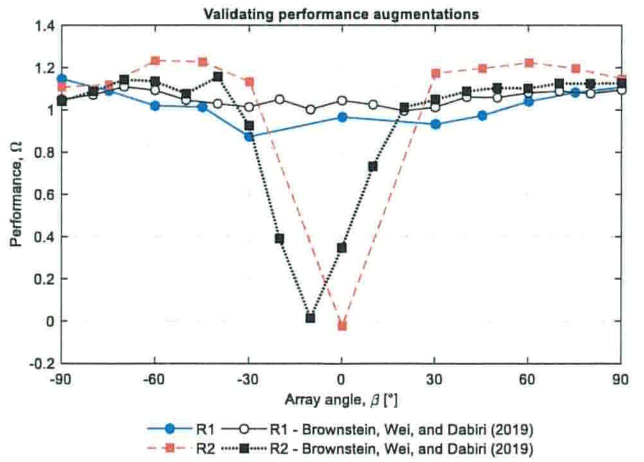

Fig. 10. Comparing results of project to the experimental data obtained by Brownstein, Wei, and Dabiri (2019). The rotors were co-rotating. The deviations of R1 and R2 for $|\beta| \geq 30°$ were respectively 5.1% and 7.8%.

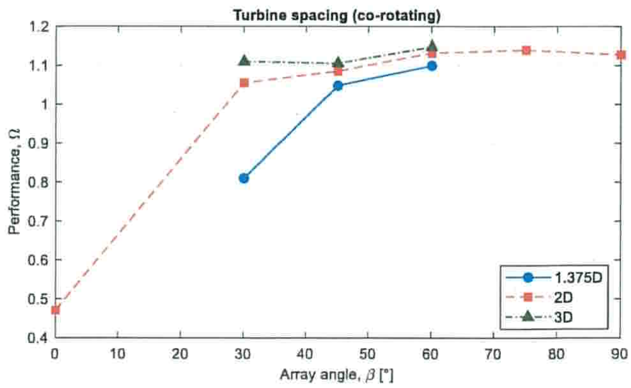

Fig. 11. Performance vs array angle for various turbine spacing (co-rotating). All configurations featured turbines rotating in co-direction. Turbine spacing are given in reference to the turbine diameter, D.

showed an increase in power as β approached 60°. It appears that the enhancement for increasing turbine spacing decayed as β approached 90°. This might indicate that theoretically the optimal distance between rotors was $\approx$3D. Nevertheless, the results argue that for larger angles of β, the turbines can be packed closer together without considerable loss in performance. Hence, for a turbine space of 2*D*, more turbines can fit within the same area and still generate power close to that of 3*D*.

3.4. Effect of multiple turbines

If the number of rotors in series was increased to three turbines, the results showed that the efficiency for the whole system increased from 1.05 to 1.09, i.e. a further power improvement of 4% points. However, the R1 and R2 had a lower efficiency, yet, it was the high efficiency of R3 that generated a greater overall power output (Fig. 12). In other words, the average performance of R1 and R2 was 0.99, but R3 brought up the average performance to 1.09.

3.5. Torque profiles

In order to understand the fluid accelerations caused by R1, the blade torque profiles of the turbines over one revolution were compared (using the results of the last revolution in the simulation). The graphs for two of the layouts are shown in Fig. 13 and Fig. 14. These were particularly chosen because the first (Fig. 13) exhibited a low power output of $\Omega = 0.81$. R2 experienced higher torque for $0° \leq \theta \leq 100°$ compared to operating in isolation, thereafter the moment coefficient was significantly lower up until $\theta \approx 300°$. For R1, the torque was lower throughout the whole revolution. In summary, these lower torque-values caused the layout to perform a power output that was 20% lower compared to isolation.

In Fig. 14, the opposite was true with the turbine experiencing a power greater than isolation conditions, $\Omega = 1.10$. The performance augmentation was due to the moment coefficient of R2 being greater compared to the isolation case for near all angles of θ. For R1, the greater moment coefficient occurred primarily between $120° \leq \theta \leq 180°$ and $240° \leq \theta \leq 360°$. Hence, the performance enhancements occurred due to a higher torque during predominately the upwind stroke of the rotation, i.e. $0° \leq \theta \leq 180°$.

3.6. Velocity across rotor span

The presence of a second turbine generated changes to the mean flow velocity field. Fig. 15 shows the variation of velocity across the rotor span for varying array angle, β. The velocity was averaged across the vertical (y-direction) rotor diameter span in the middle. Moreover, the velocity magnitudes were averaged over one full revolution, U_{avg}, and then normalised by dividing by the results of a turbine in isolation, U_{iso}. The improvements/deficits in average velocity travelling through R1 and R2 were similar to the performance augmentations previously shown in Fig. 8. For example, the normalised average velocity was greater for R2 than R1 for both cases, and the trend that the incident flow speed on R1 increased as the array angle approached 90°.

The lower output of R1 and R2 was likely to be due to R3 negatively interfering with their wakes. Instead, if the triple-configuration utilised a larger turbine spacing and let $\beta \approx 75°$ (ref. Fig. 6), hypothetically, the wake interaction would be more beneficial, and the fluid would continue to accelerate for each rotor downstream. However, the curve must flatten out at some point, and the wind energy available at the site could potentially be the limiting factor in this case.

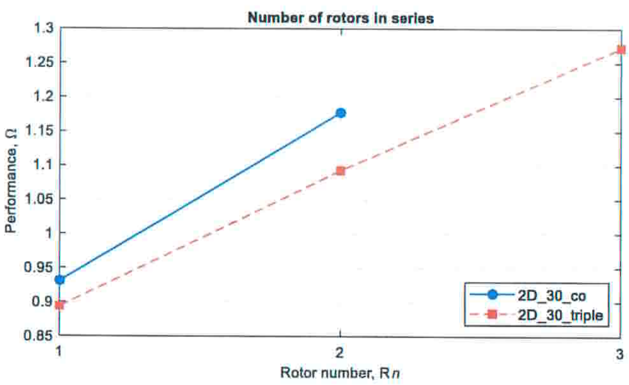

Fig. 12. The performance improvements of multiple turbines in series.

4. Discussion

Mesh sensitivity analyses were carried out for five different parameters (mesh size, time step increment, domain cell density, number of iterations per timestep, and domain size), and these showed that the domain size, mesh size, and time step increment were the values that had the biggest influence on the average moment coefficient within the ranges evaluated. Yet, mesh convergence studies for wind turbines are critical, but they do not imply universal applicability, due to factors such as leading edge erosion and changes in flow conditions.

Results confirmed the potential of VAWT farms, since close-to-all layouts experienced performance augmentations within turbine spacings that are not achievable with HAWTs. Interestingly, Fig. 6 indicated that the efficiency improvements in the range of 1.00–1.15 occurred for a broad range of angles, $30° \leq |\beta| \leq 90°$. In other words, this indicates that there should not be a significant decrease in power output if the wind direction changed from north to east. Of the 25 different layouts investigated, a turbine spacing of 3*D*, array angle of 60°, and both rotors spinning in the same direction exhibited the greatest improvement in efficiency by a 15% increase. This layout was at the limit of the scope, therefore, as evidenced by the other results, which exhibited an optimal angle around 75°, the augmentations are likely to be higher if the 3*D* layout had an array angle of 75°.

The layout being least prone to changes in wind direction would be ~83°, because if there was a slight change in wind direction, the pair would still exhibit performance augmentation. Fig. 16 depicts this argument, and in this diagram β was 90° (a) for illustrating purposes and added simplicity. In configuration (b) the wind direction changes by 15°, and therefore the effective array angle is 105°, which corresponds to the layout analysed with $\beta = -75°$. According to Fig. 6, this layout (turbine spacing of 2*D*) resulted in $\Omega = 1.10$, hence performance augmentations would occur. The same is true if the wind direction changed by −15°. Finally, an array angle of ~83° is least prone to changes in wind direction, due to the results indicating that the power enhancements were greater at 30° than −30°. Therefore, the interval in which $\Omega > 1.05$ happened from $30° \leq \beta \leq 90°$ and $-90° \leq \beta \leq -45°$, and the middle of this region is approximately 83°.

The aerofoil of a VAWT rotated with a higher speed than the fluid surrounding it, thus in the region where the blade was moving downstream, it accelerated the flow around it. On the other hand, when the blade was moving upstream it decelerated the surrounding fluid, and as a result, a distorted velocity field was established. As Fig. 7(c) indicates, there were red regions with accelerated flow and a wake, where the wind speeds were negligible. In the end, these fluid mechanical movements influenced the distribution of flow momentum in the vicinity of the turbines, which suggests that the power enhancements were caused by redirections of momentum near the rotors.

The improvements in incident flow speed lead to a discussion of the CFD setup. This work applied an equal constant angular speed

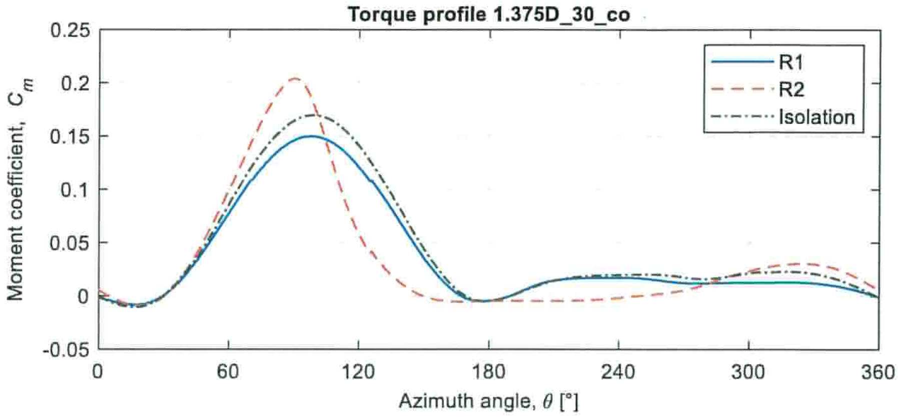

Fig. 13. Torque profile over one revolution for a turbine spacing of 1.375D, array angle of 30°, and the turbines were co-rotating. The performance of this layout was $\Omega = 0.81$.

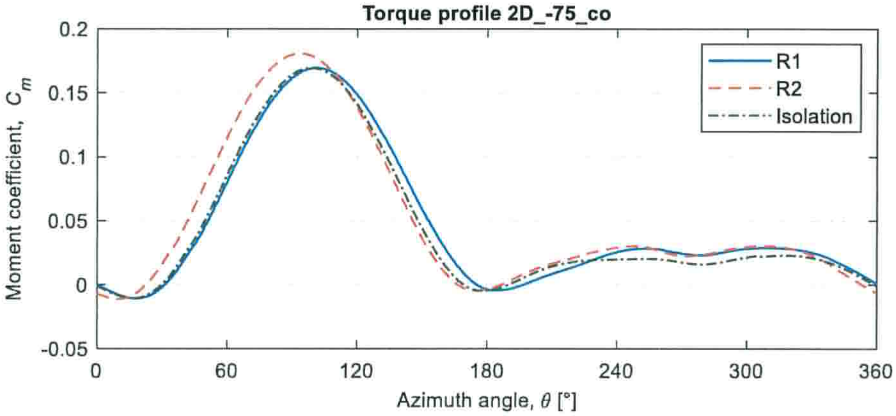

Fig. 14. Torque profile over one revolution for a turbine spacing of 2D, array angle of −75°, and the turbines were co-rotating. The performance was $\Omega = 1.10$.

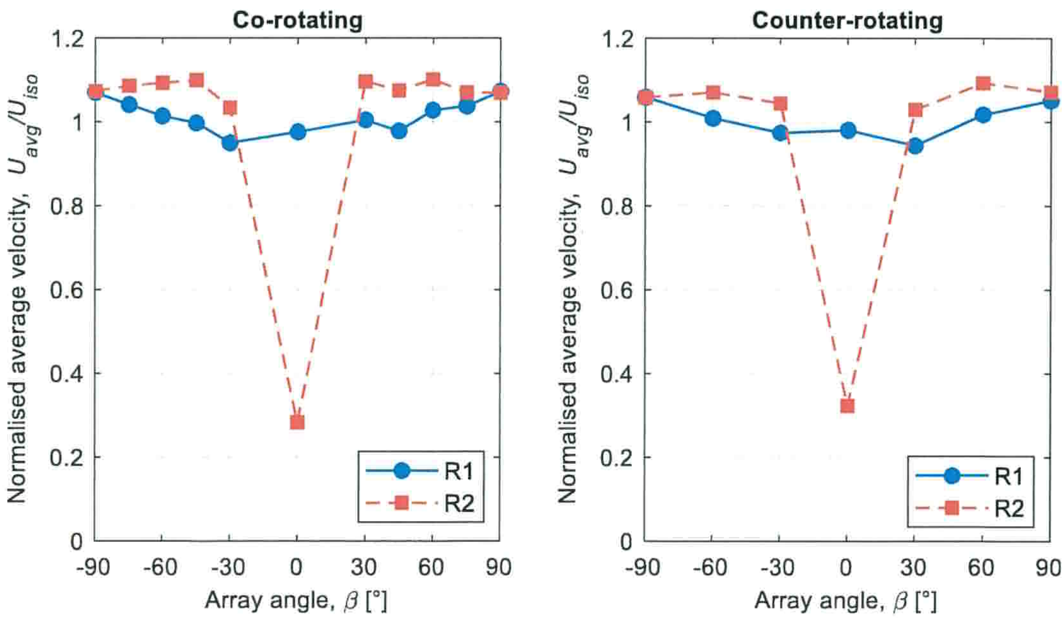

Fig. 15. Normalised average velocity across rotor span against array angle. U_{avg} was the average velocity over one full revolution for the given rotor, and U_{iso} was the velocity across turbine diameter for a turbine operating in isolation.

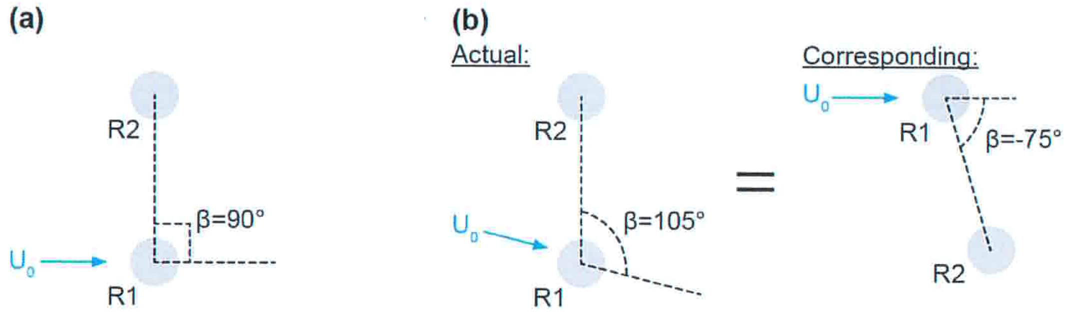

Fig. 16. (a) Array angle of 90° with wind direction at 0°. (b) Wind direction at 15° resulting in an array angle of 105° between R1 and R2. This corresponds to one of the layouts investigated with R1 as the upstream rotor, and an array angle of −75°.

to both rotors, and as previously stated, this was an assumption made to simplify the problem. Under real conditions, the angular speed will vary over one revolution, due to varying torque. Furthermore, as evidenced by this study, the varying mean flow field will further increase the variance in torque, and therefore one might question the assumption that rotors should rotate with a constant speed. One may say that the CFD simulation should be setup as an iterative procedure, i.e. the angular velocity of each rotor is changed for each time step to replicate realistic conditions. The tip-speed ratio will also not be equal for R1 and R2, because their incident velocity will be different. From the results, it can be derived that the turbines did not operate at their optimal tip-speed ratio, since a higher freestream across the rotor span of R2 at $|\beta| \geq 30°$ (Fig. 15) caused an improvement in power output (Fig. 8). All these measures increase the complexity of the problem, however, as evidenced by the similarity with the wind tunnel tests, CFD simulations still have validity, if setup correctly.

The CFD simulations demonstrated notable wake interactions. For larger wind farms, the suppressed wakes caused more energy to be available for the subsequent rows, thus maximising the power density. VAWT dynamics are strongly influenced by tip-speed ratio [4], and therefore the efficiency enhancements for a wide range of tip-speed ratios must be further investigated. The results obtained are strictly valid only for the given rotor geometry and boundary conditions simulated, since the quantitative properties are expected to depend on the Reynolds number regime [23].

In summary, it is generally accepted that the primary flow mechanism is proposed to be the flow acceleration around the upstream turbine (R1), which increases the incident wind speed on the downstream turbines (R2, R3). Additionally, the flow in the arrays is reenergised by the turbulent phenomena, and together, these mechanisms are proposed to be the reason why VAWTs exhibit improvements in power compared to operating in isolation [24].

5. Conclusions

In this paper 25 different layouts were investigated. Results show that VAWTs increase each other's performance by up to 15%, and this optimal layout was for a turbine spacing of three turbine diameters, an array angle, β, of 60°, and when the rotors were co-rotating. Yet, this layout was at the limit of the scope, and the other results indicated an optimal angle around 75°, hence the augmentations are likely to be higher for layouts in this region. Key findings of the study were:

a. As $|\beta|$ approached 90°, the performance of R1 increased.
b. R2 peaked in power augmentation at $|\beta| \approx 75°$
c. The total efficiency increased as the turbine spacing increased
d. Increasing the number of turbines further increased the overall efficiency.
e. Two-dimensional CFD simulations produced accurate results when compared to wind tunnel tests, since the values were within 6.5% of experimental data for the augmented layouts.
f. Greater performance of pairs was predominately due to a distorted flow field that was established in the vicinity of the VAWTs, and in these regions, fluid travelled with a greater speed than the freestream velocity.

In the future, the study has scope of expansion on bigger infrastructure by adding more turbines or going three-dimensional. Moreover, the rotor geometry was derived from numerical studies for boundary conditions and Reynolds numbers that were not exactly equal. Accordingly, there is great potential in conducting a design optimization study with the application of wind farms in mind to achieve further advances in performance. One might find that the optimal design for a turbine in isolation is not identical to the one optimised for wind farm configurations.

The potential applications for VAWTs are endless, because the turbines are cheaper and easier to manufacture and maintain. For example, remote villages and islands that primarily rely on electricity from diesel generators or off the coast of UK. The common factor is that VAWTs farm are likely to not be limited by the efficiency of the turbines, but by the wind energy available at the given site.

CRediT authorship contribution statement

Joachim Toftegaard Hansen: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Mahak Mahak:** Formal analysis, Writing – review & editing. **Iakovos Tzanakis:** Resources, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2021.03.001.

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