State-of-the-Art

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In this chapter, a review of some of the prototype FOWT devices that have been deployed to-date is presented. The technologies overviewed throughout the chapter are: Principle Power's semisubmersible WindFloat device; the Hywind spar under development by Statoil; the Goto Island project in Japan and the SWAY system.

Information presented for each technology includes: a brief description of the device; the concept development pathway; information on the prototype testing campaigns, including key achievements, milestone and measured data; and finally the commercialisation route planned for the technology. When applicable, relevant data is presented from initial operations, in an effort to document the experience and lessons learnt from these developments.

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1 WindFloat

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1.1 Device Description

The WindFloatis a three-legged semi-submersible offshore platform fitted with water-entrapment (or heave) plates at the base of the columns and a large wind turbine mounted asymmetrically on one of the columns. The holistic approach to this optimised design presents innovative and economically attractive solutions to the offshore wind industry with respect to turbine installation methodology and offshore operations. The structure's inherent stability permits most turbine assembly and commissioning activities to be performed at the quayside, in a sheltered environment. The methodology eliminates the need for specialised heavy-lifting offshore equipment and specialised operations such as a floating-to-floating lifting operations.

The WindFloat's innovative water-entrapment plates increase the hydrodynamic added-mass of the platform and add significant viscous damping, resulting in reduced platform motion in waves. An added benefit of the water entrapment plates is the reduced structural weight of the hull, when compared to larger structures with similar motion performance, ultimately resulting in a reduction of the overall levelised cost of energy (LCOE). Similar benefits have been observed in the oil and gas industry, where truss spars have replaced classic spars. A truss spar has a shorter cylindrical section, but adds vertically staggered heave plates under the structure.

The hull is also fitted with a closed-loop and actively controlled hull-trim system, which moves water between ballast tanks in each column to compensate for changes in average wind velocity and direction. This system enables the mean position of the tower to remain vertical, which improves the turbine's efficiency and allows for structural optimisations.

WindFloat Key Features

The design philosophy of the WindFloat structure, as shown in Figs. 1 and 2, focuses on the reduction of the structural weight and the optimisation of the power to weight ratio of the overall system. However, the lightest structure may not necessarily be the most cost effective solution, as the simplicity of other operations such as fabrication difficulty and installation may have more significant economic benefits. The primary design driver of the WindFloat emphasises the overall cost reduction by simplifying the primary structure, while still ensuring ease of fabrication. In particular, the WindFloat key features include.

Fig. 1 WindFloat key features

Shallow Draft

When compared to other floating concepts, such as a spar type platform, the WindFloat's transit and operational drafts are minimal. This permits transit from typical commercial offshore yards. Once out of the harbour, the hull is ballasted to its operational draft through a fully reversible ballasting operation.

Turbine Agnostic

The WindFloat is designed as a turbine agnostic system. Turbine loads, both static and dynamic, are design variables which come from the choice of the turbine and its manufacturer. Principle Power has been at the forefront of developing fully-coupled dynamic simulation tools and was one of the first groups to develop a hydro-aero-servo-elastic code (Cermelli et al. 2010). It is important to note that the WindFloat (turbine and hull) is modelled as an integrated system throughout the structural design and analysis.

Fig. 2 WF1 prototype operating at rated wind speed in Aguçadoura (Portugal)

Quayside Final Assembly and Commissioning

Final assembly, erection and commissioning of the wind turbine is completed onshore at the quayside, where the wave environment is not a constraint. This methodology provides significant cost savings opportunities, due to lower labour costs onshore, reduced time needed to complete the installation process, and usage of existing shore-side infrastructure such as shipyards or harbours.

There are no requirements for offshore upending of the hull, a floating-to-floating lifting operation to install the turbine, or complex mooring connection operations whilst offshore. This methodology significantly reduces the offshore contracting risks which is an issue constraining the industry today.

Large Correctives

All installation operations (ballast, mooring and cable hookup, etc.) are fully reversible, allowing for the hull and turbine to be towed back to the shore-side for major repairs to the turbine. This provides an opportunity to reduce OPEX while improving overall production and capacity factors, as the wait on both vessels and weather is suppressed and repair operations can be planned and optimised.

Inherently Stable in Transit

Eliminating transportation challenges for offshore wind turbines provides cost-savings opportunities. The WindFloat's stability in transit is a result of the same design parameters that make it fully stable offshore. The WindFloat is capable of supporting a fully-assembled and commissioned wind turbine in a wet tow configuration. The entire system can be towed at any draft to the project site without the requirement for transport barges or other ancillary marine equipment.

Conventional Mooring

Conventional mooring components are inexpensive, available globally and simple to install. The mooring configuration employed by the WindFloat includes drag embedment anchors, offshore grade chains and cables. The drag embedment anchors permit installation in various soil conditions including mud, clay and sand with simplified consent requirements (when compared to bottom-fixed structures). Drag embedment anchors offer the most economical installed solution and have proven experience in the oil and gas industry, including for permanently moored structures.

Further, the incremental cost increase associated with a WindFloat mooring in a wide range of water depth (e.g. >40 m) is negligible. This permits greater flexibility to developers and utilities.

Installation of the mooring requires only the use of surface vessels. A single anchor handling and tug supply vessel (AHTSV) can accomplish the mooring pre-lay in a very short time and relatively large (H_s = 2–4 m) waves. It is important to consider the moorings as an integral part of the system and recognise the significant engineering effort inherent to the WindFloat mooring design. Failure of a mooring component would be analogous to structural failure of a fixed structure, albeit with less severe consequences. The WindFloat mooring design is based on safety factors provided in the API RP 2SK (2005) recommended practice. A coupled hydrodynamic model is developed using Orcaflex/OrcaFast (FASTlink) software. Time-domain simulations of the platform and mooring dynamics are obtained based on the specified input environment (wind, waves and current). Coupling between the aerodynamics of the turbine and hydrodynamic forces are also taken into account fully.

These tools and knowhow enabled Principle Power to design, fabricate and install their first prototype within three years of a feasibility study with the Portuguese utility, Energias de Portugal (EDP).

1.2 Concept Development

The apparition of the semi-submersible platform fitted with heave plates dates back to 2004, when it was investigated as a means to provide a low cost floating hull with excellent motion characteristics applicable to various offshore industries (Cermelli et al. 2004). Following a few years of development, the hull was fitted with three wind turbines and a feasibility study was conducted (Zambrano et al. 2006). The result from the feasibility study was conclusive, and the concept was optimised with a single larger turbine (more power) and a lighter hull (lower CAPEX). The WindFloat, in its original form, was presented in 2009 (Roddier et al. 2009; Cermelli et al. 2009; Aubault et al. 2009). These publications summarise the first WindFloat feasibility study and include discussions on design requirements, numerical modelling, hydrodynamics and preliminary structural work. The study was later refined and synthesised in Roddier et al. (2010), with initial coupled hull-turbine modelling described in Cermelli et al. (2010).

Model Tests

Two model test campaigns were conducted at the UC Berkeley ship-model testing facility (a 60 m long towing tank outfitted with wave and wind generation) to validate numerical analysis tools. Scale models of the platform were fabricated out of acrylic, as shown in Fig. 3.

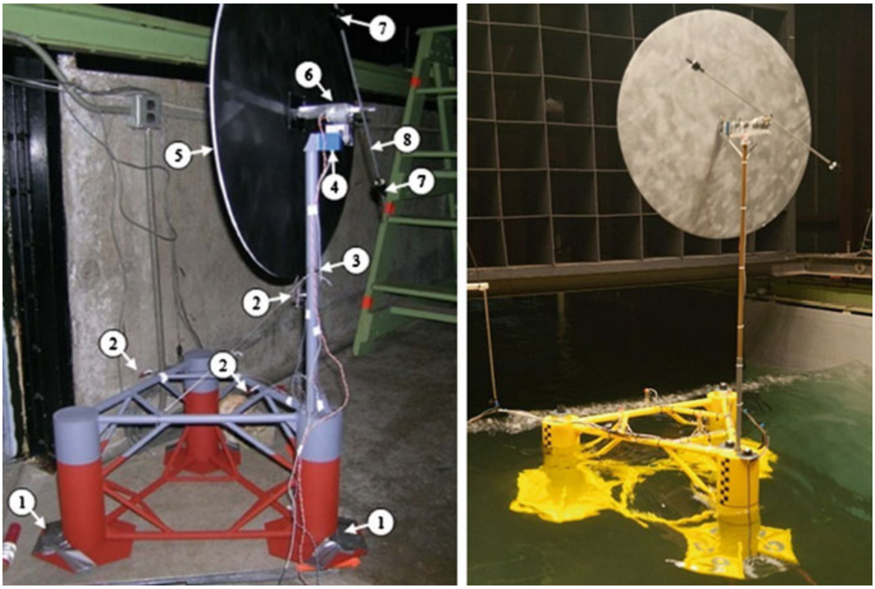


Fig. 3 WindFloat model tests—(*left*) model used in the 1st set of scale tests, (*right*) model used in the 2nd set of scale tests

Lead weights were placed inside the columns and on the water-entrapment plates to adjust the center of gravity to its target position (1). The platform motion was measured using a digital video camera using light emitting diodes (LEDs) placed on the model (2). The system provides 3 degree-of-freedom (DOF) measurements of the motion in the plane of the camera. The tower (3) was made of a thin (not-to-scale) 2.5 mm outer diameter (OD) acrylic pipe (Fig. 3—left) or copper tube (Fig. 3—right). The second scale model used in follow-on model tests (Fig. 3—right), employed a tower with correctly scaled stiffness.

The turbine model device was connected to the top of the tower and onto a load cell (4) (see Fig. 3), which measured the axial force perpendicular to the tower. A large disk (5), made of foam board, was placed on the model to induce wind loads at the tower base corresponding to the design wind forces. No attempts were made to match the atmospheric turbulence. The wind maker (visible in Fig. 3), produced some level of unsteady flow and the wind fluctuations were absorbed by the large disk. In the end, the wind force was measured and the turbulence level compared to variations in the aerodynamic forces generated by a prototype wind turbine. The disk diameter was a third of the total area covered by the rotor. The drag coefficient on the disk was estimated to be 1.2. An electrical motor (6) was placed at the top of the tower to model the gyroscopic effect. This well-known mechanical force arises when a rotor spinning around a certain axis undergoes a rotation around a different axis. For instance, platform pitch and yaw would lead to gyroscopic forces applied on the tower. These forces are a significant design issue for wind turbine blades and the drive shaft/bearings, but may also have a contribution to the global response of the floater. The motor was adjusted to spin at the Froude-scaled turbine speed, and the inertia of the blades was approximately modelled with two weights (7) positioned on an aluminum rod (8).

The effect of the active hull-trim system was modelled by shifting lead ballast manually on the model to compensate for the mean wind overturning moment.

The second model test was performed in a similar manner, and was part of a front end engineering and design (FEED) study for the WindFloat 1 (WF1) Prototype Project.

Even though recent advances (Robertson et al. 2013; de Ridder et al. 2014) focus on modelling a spinning turbine in tank tests, adhering to basic engineering principles and Froude scaling ensures sound results from model testing, and provides sufficient information to be used during engineering design (see also Sect. 6 of Chapter “Modelling of Floating Offshore Wind Technologies”).

WindFloat WF1 Prototype Model

The WF1 unit was commissioned and instrumented with a comprehensive array of sensors, both on the hull, as well as the turbine. The hull instrumentation included accelerometers, inclinometers, gyrometers, multiple pressure sensors and strain gauges, wave radars and multiple GPS in order to obtain 6-DOF measurements during the operational phase of the project. Figure 4 presents a diagram of instrumentation installed on the WF1 hull.

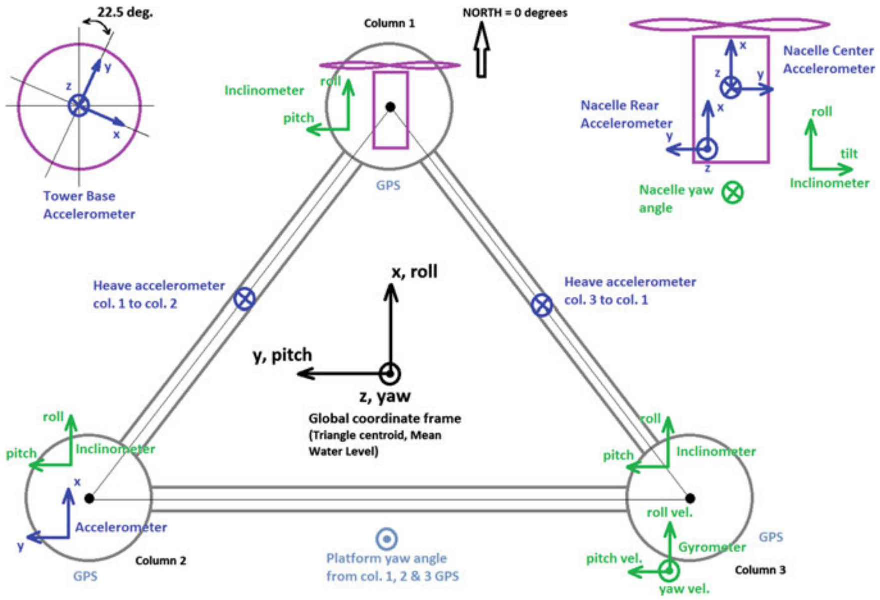


Fig. 4 Sketch of the initial instrumentation of the platform

In addition to the hull instrumentation, the wind turbine generator (WTG) included its own instrumentation package and supervisory control and data acquisition (SCADA) system capable of contributing real-time power production and wind information to the measurement campaign. Some additional instruments were outfitted to the WTG outside of the *standard* Vestas V-80 instrumentation package. These included inclinometers added on the nacelle to control the turbine and strain gauges added in the tower and blades to assess the system performance.

The WF1 data is still undergoing analysis at the time of release of this book and will be used to update and validate current and future versions of the tools used by the engineering team. This dataset is invaluable to the design team as it assists in the forthcoming challenges of making the WindFloat a commercially viable offshore wind technology.

1.3 Prototype Testing

The WF1 (Fig. 5) was installed 5 km offshore of Aguçadoura, Portugal, on October 22nd, 2011. The floating hull supports an off-the-shelf offshore Vestas V-80 turbine, fitted with a Class-I tower. The project and key learnings are described in detail in Cermelli et al. (2012). By July 2015, the WF1 had produced in excess of 15 GWh of renewable wind energy delivered to the Portuguese grid (Fig. 6).

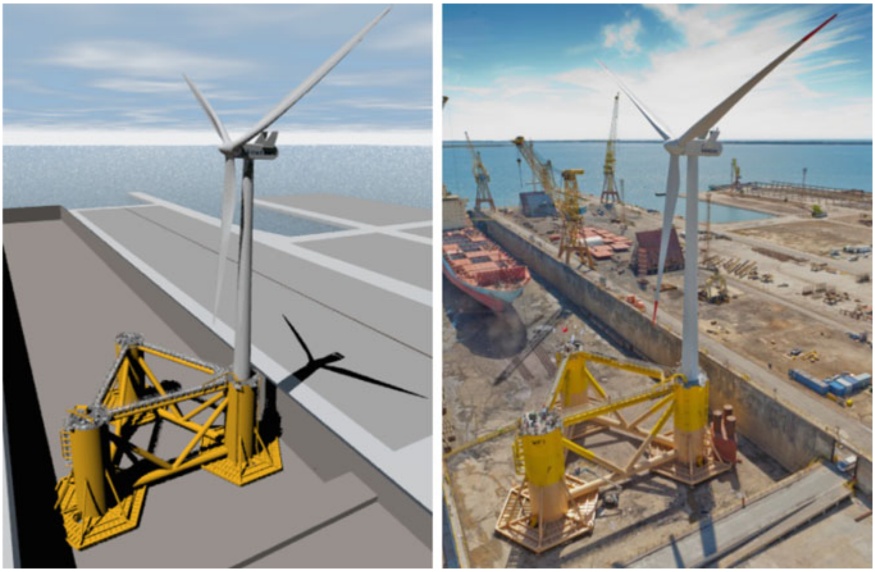


Fig. 5 WF 1: from CAD drawing to fabricated hull

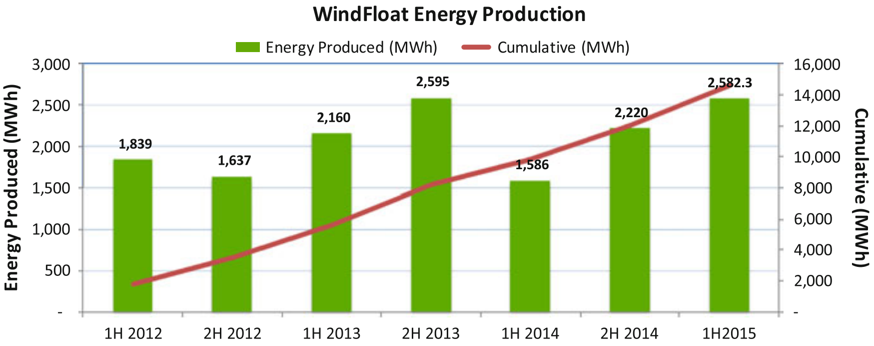


Fig. 6 WindFloat 1 electricity production

The WF1 represented a project of many *firsts* both for the Portuguese energy industry as well as the global offshore wind industry as a whole. The major achievements are listed below:

- First offshore full-scale wind turbine to be installed using a semi-submersible floating foundation worldwide;
- First offshore wind turbine to be installed without the use of any heavy-lift jack-up vessels or floating cranes;
- First offshore wind turbine to be installed at the quayside and towed fully commissioned to site;

- First offshore wind turbine to be installed in open Atlantic waters;
- First offshore structure to be built to oil and gas standards in Portugal.

Post-installation, the WF1 underwent a series of commissioning tests including a phased ramp-up to full power production. During this trial period, several parameters including motions, loads and vibrations were analysed in real-time while the team gained confidence in the WF1's operational performance and the defined performance envelope. The unit was fully commissioned and operating autonomously by March 2012.

Power production analysis has shown that the WTG installed on WF1 has not been affected by the *floating* nature of the system. Throughout a wide range of wind and wave conditions, power production has consistently been on par to that exhibited by the reference system on a fixed foundation. The data has been compared against a certified power curve from Vestas (Fig. 7).

Operation of the platform has provided the project team with invaluable hands-on experience with regards to the performance of all WF1 systems and a keen understanding on the required system specifications for future builds. In addition, such areas as access and implementation of health, safety and environment (HS&E) procedures will inform future WindFloat design efforts.

Over the past four years of operation, the initial objectives of the project have been met. These objectives were driven by the need to demonstrate the following:

- Fabricate, commission at the quayside and install fully-assembled WindFloat;
- Produce power in all weather conditions up to the one-year storm;
- Survive large winter storms;
- Withstand wave- and wind-induced fatigue;
- Perform O&M activities on the platform;
- Operate the active ballast system, other systems and equipment;
- Predict the important responses of the system with numerical tools.

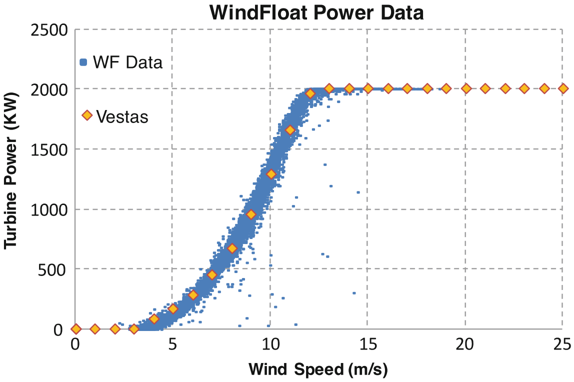


Fig. 7 WindFloat 1 power curve

Figure 8 shows a snapshot of a wave run-up event on column three during a large winter storm on Christmas Day, 2013. The WindFloat turbine resumed operations shortly after the picture was taken. Throughout the four winters of operation to date, WF1 has not sustained any structural damages. The turbine has operated in sea states greater than $H_s = 6$ m ($H_{max} = 12$ m), and the structure survived storms of $H_s > 10$ m ($H_{max} = 20$ m).

The platform measurements have been compared to numerical simulation outputs for various observed conditions. The collected full-scale data set is very valuable as it has allowed direct calibration and validation of numerical models, such as hydrodynamic and structural damping coefficients. This ensures that all relevant physics are properly captured in the numerical simulations during engineering design.

The WF1 test and validation campaign, inspections, and adherence to HS&E practices will continue throughout the operational phase of the project. Operation of this system in the harsh North Atlantic offshore environment is challenging. Wave loads, humidity, corrosion, marine growth, and access are examples of obstacles that are challenging the project team daily.

Health and safety has been a primary focus throughout the operational phase of the WF1 project. Through diligence and adherence to HS&E best practices, the project has been able to maintain a zero lost time incident record due to injuries. A summary of the HS&E statistics for the project to date is included in Table 1.

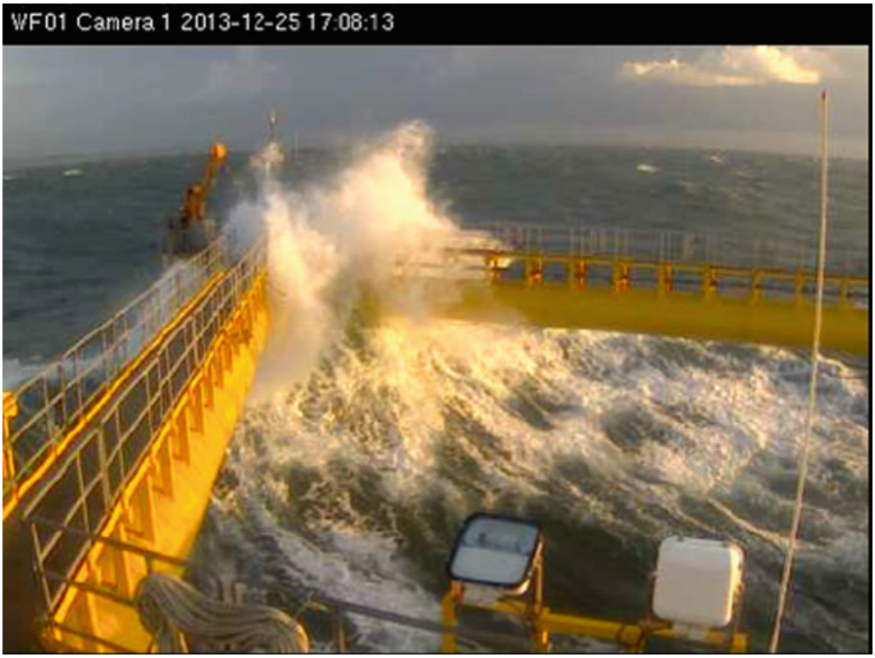


Fig. 8 WindFloat, steady in storms

Table 1 WF1 HS&E project statistics

Summary 2011–2014	
Training actions	14
Persons involved	15
Time spent (h)	204
Safety briefings	33
Toolbox talks	105
Audits	3
Lost time incidents (LTI)	0
On-duty accidents/minor cuts and bruises	2
Emergency drills	2
Recycled waste:	
• Principle power (kg) • Contractors (kg) • Vestas (kg)	643 24 27

1.4 Commercialisation Pathway

The WindFloat technology roadmap is summarised in Fig. 9. In addition to the technical objectives discussed earlier, the demonstrator project (WF1) was deployed in an effort to:

- Prove the technology, inclusive of the method of fabrication and deployment,
- Convince the interested parties that the power produced was not being penalised by the floating foundation. The demo unit was not chartered to target LCOE cost

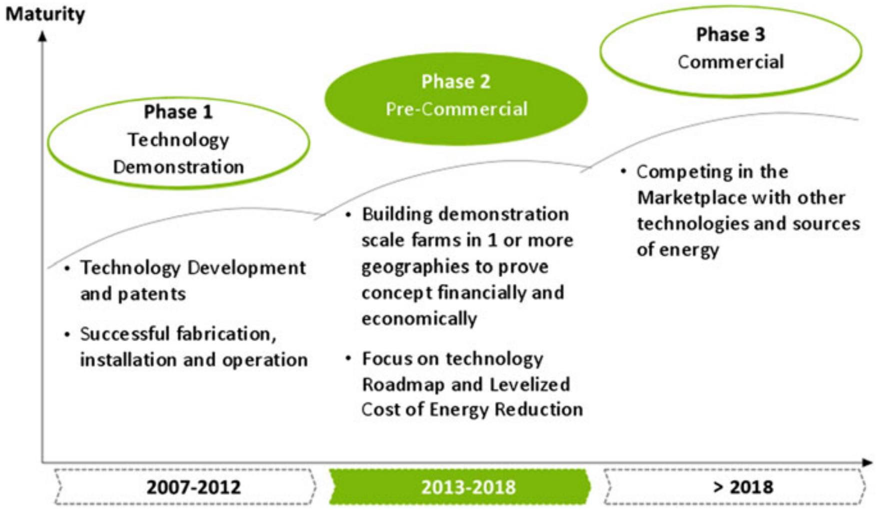


Fig. 9 Technology development roadmap

reduction, but the minimisation of both CAPEX and OPEX is still addressed inherently in the WindFloat design philosophy.

Follow-on, pre-commercial projects are intended to build upon the experience of the WF1 prototype. Lessons learned workshops were performed after the prototype deployment and learnings were captured to be explicitly applied to follow-on projects. In addition to the incorporation of lessons learned, focus on LCOE reduction is an area of particular scrutiny in new design decisions.

Currently, Principle Power is working on the FEED engineering phase of two pre-commercial farms of ~25 MW capacity with 6–8 MW turbines (nearly a four-fold increase in turbine power from the WF1). These pre-commercial projects are as follows:

- The WindFloat Atlantic Project, a 25 MW farm in the north of Portugal, was recently the awardee of European Commission NER300 funding, EDP Renováveis (EDPR) is the project developer.
- The WindFloat Pacific Project, awardee of the Department of Energy (DOE) Offshore Wind Advanced Technology Demonstration Projects funding, is located in Oregon and, when constructed, will be the first offshore wind farm in the US west coast.

These two pre-commercial projects represent a significant step towards commercial viability of an offshore floating wind farm. Additionally, for a project to be commercially financed, fabricated and commissioned by a project developer, without any government subsidies, the topic areas discussed below have been identified as being both necessary and achievable.

Structural Optimisation

Work is being performed to minimise steel weight in the hull structure. Even a 100-ton reduction in steel weight, per unit, would be significant to the overall project economics.

Larger Turbines

Potential for economies of scale are quite substantial with larger turbines. The primary sizing for the hull is driven both by the offshore environment and by the thrust force exerted by the turbine. For a given environment, only the latter part of the loading increases. The ratio of hull weight to turbine power is significantly advantageous to the larger hulls and turbines.

Down-Time Minimisation

A direct learning from the WF1 prototype was gained in relation to access. Boarding the platform is a critical operation that can only be done in times of low sea states. Increasing access windows, reducing equipment failures through improving reliability and planned maintenance, minimising time on-board and simplifying operation and maintenance (O&M) tasks are key topics of current R&D activities.

Fabrication in Series

Serial fabrication and learning curve advantages can impact LCOE and are expected to play a role in Principle Power's near-term pre-commercial projects. Various fabrication alternatives are being studied to measure their respective impact on cost savings.

As an example, we consider here an industrialised build of fifty WindFloat units per year. The primary pre-requisites that need to be considered when selecting suitable locations for an industrialised build are:

- Sufficient shoreside area to build multiple WindFloat units concurrently,
- Access to quayside water depth of approximately 10 m deep (dependent on sail-away draft), together with a means of loading out the WindFloat units.

For efficiency and cost saving opportunities, building multiple units should not be done in series, a single WindFloat at the time. Instead, the fabrication schedule must make use of parallel processes and maximise the use of pre-fabricated modules. Ultimately, the goal is to limit assembly outside the workshops to completed modules (already outfitted, coated and prepped for assembly).

In order to achieve an optimised, fully industrialised build, which takes advantage of as many process efficiencies as possible, it has been determined that a purpose built yard, or modification to an existing yard fit for purpose, could be required to minimise overall fabrication costs (which is not possible in pre-commercial projects where flexibility in fabrication methodology is more favourable). The requirements for a fully integrated industrialised facility have been looked at in detail. A few highlights of these requirements are summarised in Table 2.

A graphical depiction of an *ideal* facility is provided in Fig. 10. A rendered version of this facility is depicted in Fig. 11.

WindFloat LCOE Targets

LCOE is defined herein as the net present value of electricity amortised over the lifetime of the generating asset. The inputs for LCOE analysis include (among others) the CAPEX of a project, the OPEX, the net annual energy generation and a discount rate. The aforementioned technology development focus areas (e.g. structural optimisation, larger turbines, downtime minimisation etc.) play a crucial role in the determination the project CAPEX, OPEX and revenue of a given project. In the specific case of WindFloat projects, due to the maturity level of the technology and of the industry, there exist a significant potential for greatly reduced

Table 2 Requirements of a fit-for-purpose yard

Area description	Required space (m^2)
Covered fabrication shops	52,000
Covered painting shop	10,100
Covered column assembly building	36,600
External final assembly and load-out	51,000
Stockyard	32,000

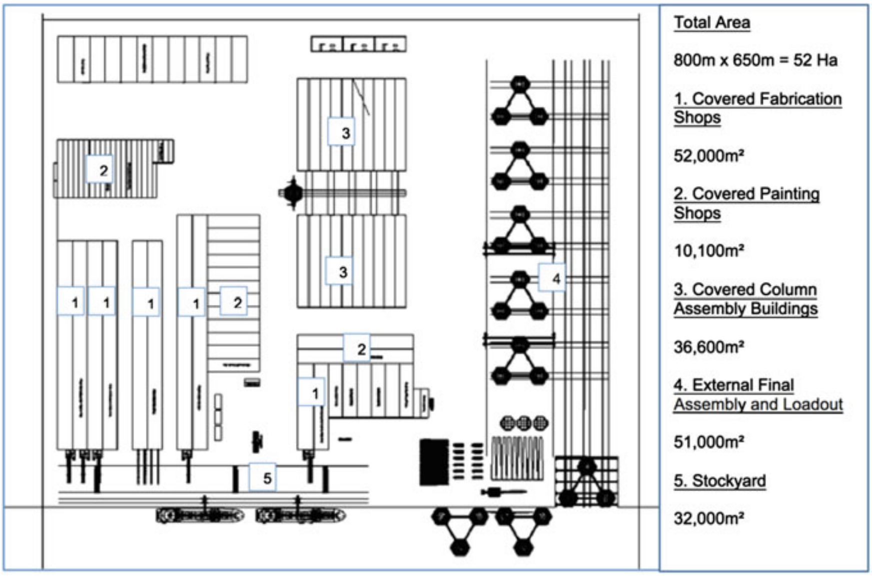


Fig. 10 Top-view of fully integrated industrialised WindFloat build facility

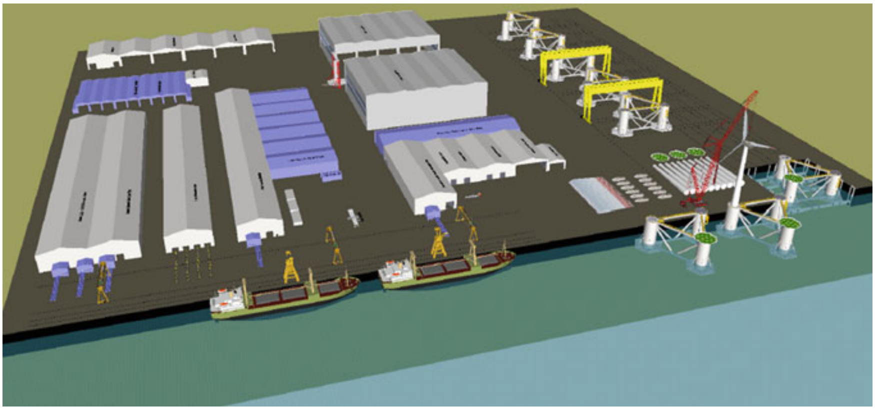


Fig. 11 Rendered view of a fully integrated industrialised WindFloat build facility

LCOE and ultimately greater profitability for the customer. As part of the technology development effort, detailed LCOE analyses are performed both by Principle Power and third parties to ensure design decisions are informed and LCOE prediction monitored accordingly. Future successful commercial offshore wind projects will have to offer project owners LCOE cost levels below €100/kWh. Current forward-looking models for the WindFloat are on par with this prediction.

2 Hywind

Eirik Byklum and Mairéad Atcheson

Over the last decade Statoil ASA has developed the Hywind floating offshore wind concept. The Hywind concept combines known offshore technologies in a completely new application and opens up the possibility for capturing wind energy in deep-water environments.

2.1 Device Description

Based on Statoil's background in and experience with design, installation and operation of floating offshore oil and gas platforms, Hywind has been designed as a slender cylindrical structure, under the classification of a spar-type platform. The substructure is the lower part of the unit, indicated in yellow in Fig. 12. The wind turbine generator (WTG) is the remaining part in white, consisting of tower, nacelle and rotor. The nacelle and rotor is supplied by a WTG supplier, while the tower is usually separately manufactured by a specialist tower fabricator.

The Hywind structure is ballast-stabilised and anchored to the seabed. The mooring system consists of three mooring lines attached to anchors suited to the seabed conditions on site. In the unlikely event of a mooring line failure, the two remaining lines have adequate reserve strength to prevent the structure from breaking free and drifting off. The electrical cables can be designed to have expansion loops on the seabed to prevent damage in this event.

The substructure design is a ring stiffened tapered cylinder with a larger diameter for the majority of the submerged part, which tapers to a smaller diameter at the waterline to minimise wave actions. The substructure is divided into two compartments; an upper water tight deck close to top of the substructure and a water tight deck between the bottom plate and upper deck. The bottom deck is a traditional plate stiffened structure with stiffeners and girders. The flat bottom plate and water tight decks are stiffened with t-shape girders. The mooring connection points are located close to the top of the lower cylindrical section. The overall size of the structure is a result of several analyses and optimisations with respect to wind turbine generated loads, environmental loads at the specific site, mooring line loads, and requirements related to stability and WTG motion and accelerations.

A full-scale prototype Hywind device (Hywind Demo) was designed and installed in 2009, and has since then completed a comprehensive demonstration programme. By the end of 2015, the unit is still in operation and delivering power to the grid. The demonstration unit was the world's first full-scale grid-connected

Fig. 12 Hywind deep spar concept (courtesy of Statoil)

floating wind turbine and for this reason a conservative design approach was chosen. The Hywind design has since been further developed. By up-scaling to a larger WTG size, and optimising the substructure design, the cost efficiency has been improved for the commercial-size Hywind unit planned for the Hywind Scotland Pilot Park. A description of Hywind Demo and the subsequent modifications made for the Hywind Scotland Pilot Park are presented in the following sub-sections.

Hywind Demo

Hywind Demo consists of a standard Siemens 2.3 MW offshore WTG unit mounted on a ballasted vertical steel cylinder anchored to the seabed. The deep spar platform prototype was designed for extreme North Sea conditions and was deployed in a water depth of approximately 200 m off the Norwegian coast in 2009 (see Fig. 18). The device rotor diameter is 82.4 m and the rotor nacelle assemble unit weighs 138 t. The Hywind Demo substructure is essentially an 8.3 m diameter tapered cylinder, ballasted with gravel and water, which extends 100 m below the water surface. The substructure has a smaller diameter of 6 m at the waterline to minimise wave action on the structure. The substructure of the Hywind Demo was produced in steel, but a concrete substructure is also considered for future projects.

The Hywind Demo device attaches to the seabed using a three-point spread mooring system, using drag embedded anchors. At approximately half the draft of the hull, the mooring lines are split using a crow-foot configuration to form a y-shaped arrangement of lines that connect to either side of the support structure. The crow-foot configuration acts to increases the yaw stiffness of the overall mooring system (Nielsen et al. 2006a, b). The mooring lines are designed using chain and wire, as well as clump weights to achieve the required mooring line force displacement characteristics (Skaare et al. 2015). A buoyant cable support system is used to support the power cable from underneath the spar.

Hywind Scotland Pilot Project

The full-scale measurements and experience gained from the Hywind Demo project provided the basis for further developments of the Hywind concept to form the basis for a pilot park. The Hywind units for the pilot park will be equipped with a higher rated wind turbine of 6 MW, with a rotor diameter of 154 m, operating at a hub height of approximately 100 m. The device substructure is modified from the original prototype to a shorter, but larger diameter hull. The reduced draft will extend to approximately 78 m below the water surface, with the submerged structural diameter increasing to approximately 14 m, with a diameter of approximately 10 m at the waterline. An example of the Hywind unit due to be deployed in the Hywind Scotland pilot park is illustrated in Fig. 13.

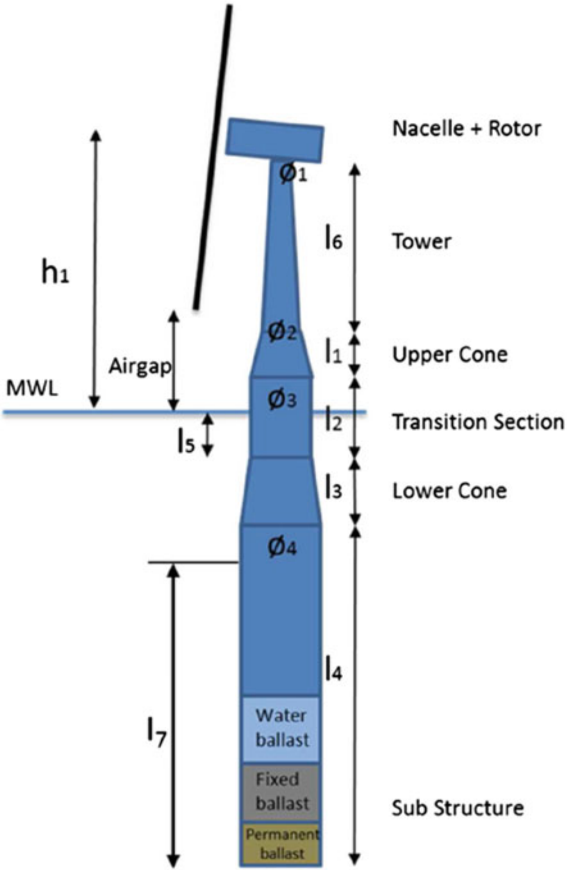
Summary of Hywind Unit Specifications

Table 3 presents the specification for both versions of the device. Figure 14 illustrates the original Hywind Demo and the modified Hywind design for the Hywind Scotland pilot project side-by-side.

2.2 Concept Development

The Hywind technology was first conceptualised in 2001, a scale model was used to test the concept in 2005 and the world's first floating full-scale wind turbine Hywind Demo was installed in 2009. Figure 15 illustrates the initial stages of development of the Hywind concept. Since 2010, the conceptual design for Hywind has been developed further to form the basis for a pilot park considering Hywind solutions up to 6 MW turbines (see Sect. 2.4).

Fig. 13 Hywind substructure with WTG unit (courtesy of Statoil)



A fundamental factor in the development of the Hywind concept has been the capacity to predict the dynamic behaviour of the system. The dynamic behaviour of a floating offshore wind turbine is a function of several processes (i.e. waves, wind, mooring tension, as well as control functions of the wind turbine) occurring simultaneously and interacting with one another. Throughout the Hywind concept development process, numerical models have been used to simulate the device under different environmental and operating conditions. Results from the numerical models have been compared with experimental data from Hywind model experimental campaigns to validate the results (Nielsen et al. 2006a, b; Hanson et al. 2011). The initial development stages of the Hywind concept, including model scale experiments and numerical model developments, are described in the following sub-sections.

Model Scale Experiments

In 2005, experimental model scale tests were carried out at the Ocean Basin Laboratory run by MARINTEK in Trondheim. The ocean basin simulates wind and

Table 3 Hywind specification approximate figures

Description	Hywind Demo (demonstration unit)	Hywind 6 MW (Hywind Scotland pilot project)
Turbine nameplate capacity	2.3 MW	6 MW
Annual production per unit	7.6–10.1 GWh (actual)	25–30 GWh (predicted)
Hub height	65 m	Approx. 100 m above MSL
Rotor diameter	82 m	154 m
Operational draft	100 m	Approx. 78 m
Top head mass (rotor and nacelle)	138 t	Approx. 420 t
Displacement	5300 m^3	Approx. 12,000 m^3
Water depth at site	200 m	95–120 m
Air gap (MSL to blade tip)	24 m	22 m
Substructure diameter at waterline	6 m	Approx. 10 m
Substructure diameter submerged	8.3 m	Approx. 14.5 m
Mooring lines—radius from centre	Approx. 800 m	Approx. 700 m

Fig. 14 Hywind 6 MW design (*left*) and Hywind Demo (*right*) (courtesy of Statoil)

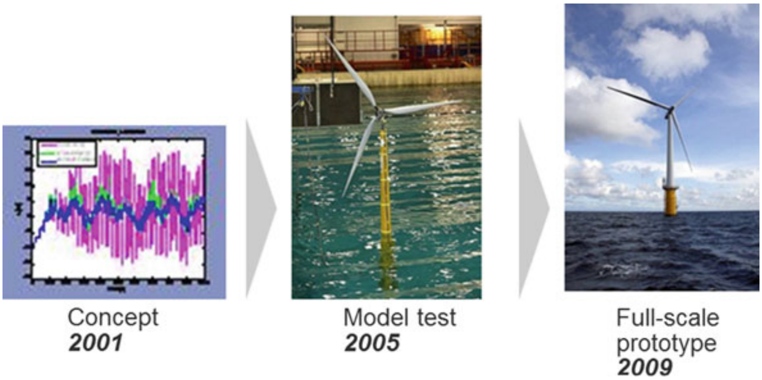


Fig. 15 Initial development stages of the Hywind concept (courtesy of Statoil)

wave conditions at sea. The tests were conducted at 1:47 model scale of a 5 MW Hywind concept. The Hywind model was equipped with a variety of sensors to measure the platform motions and loading on the device. Parameters measured during the tests included: tower motions in 6-DOF; axial acceleration at nacelle level; shear force between the nacelle and tower; rotational speed of the rotor and blade pitch angle. Two DC motors were used to control the rotational speed of the model rotor and the blade pitch angle, based on estimates of the relative velocity between the incoming wind and the turbine.

One of the key design challenges during the development of the Hywind concept has been to avoid resonant pitch motions of the tower during the operation of the wind turbine above rated speed, which required the investigation into control strategies for Hywind (Skaare et al. 2007a). The model tests showed that when the wind velocities were above the rated wind speed, the implementation of a conventional blade pitch control algorithm introduced negative damping of the tower motion. This results in the excitation of the natural frequency of the tower in pitch, which could potentially cause unacceptable tower motions (Nielsen et al. 2006a). A control algorithm for the active damping of resonant wind induced tower motions was implemented to mitigate large tower motions.

The model tests investigated the dynamics of the Hywind concept under a range of environmental and operational conditions, for example: the 100-year wave condition, wind velocities above rated wind speed and with the application of different control algorithms. Model test results also provided data for the verification and validation of numerical simulation results of the Hywind concept under the same test conditions.

Numerical Model Developments

The first numerical analyses for the dynamics of the Hywind concept, including comparisons with model tests, are presented in the publications of Nielsen et al. (2006a, b). These initial analyses were carried out using the HywindSim and

SIMO/RIFLEX computer programs. HywindSim is an in-house MATLAB/Simulink code developed specifically for the dynamic analyses and control of the Hywind concept. SIMO/RIFLEX is a code developed by MARINTEK, which simulates the dynamic response of marine structures and combines the SIMO and RIFLEX computer programs. A comparison between model scale tests and simulation results from both computer programs, under prescribed environmental conditions, confirmed the simulation results and showed that the wave-induced platform motions were similar between simulations and model tests.

Subsequent numerical analyses of the Hywind concept extended the capacity of the numerical code to include an aerodynamic modelling component, using the HAWC2/SIMO/RIFLEX (H2SR) code. The code developments incorporated two existing, independent, computer programs (SIMO/RIFLEX and HAWC2) as the basis for a new tool. The HAWC2 computer program is an aero-elastic code developed by the Risø National Laboratory used to simulate the response of fixed foundation wind turbines. The H2SR code allowed the dynamic response of floating wind turbines exposed to wind, waves and current loads to be simulated. Skaare et al. (2007b) provides details on the integration of the H2SR code and compares simulation results with the model tests carried out at MARINTEK in 2005. The results show good agreement, validating the accuracy of the coupled H2SR code and its capacity to simulate the dynamics of the Hywind model.

An example comparing experimental and simulation results, which also highlight the influence of the control algorithm on the tower motions, originally presented in Skaare et al. (2007b) are presented in Figs. 16 and 17. The square root of the power spectra of the nacelle motion in surge from simulations (H2SR program) and the model scale experiments are shown with and without active damping applied. Results are presented for identical model set-up and environment conditions (i.e. same significant wave height H_s, peak wave period T_p, mean wind velocity U_m and turbulence intensity T_i) and the turbine is operating at above the rated wind speed.

Fig. 16 Square root of the power spectrum of the nacelle surge motion. $\boldsymbol{H_s}$ = 5 m, $\boldsymbol{T_p}$ = 12 s, $\boldsymbol{U_m}$ = 16.44 m/s, $\boldsymbol{T_i}$ = 6.7 % and conventional control (Skaare et al. 2007b)

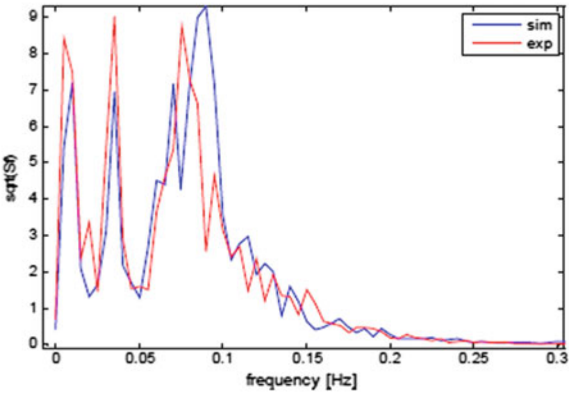
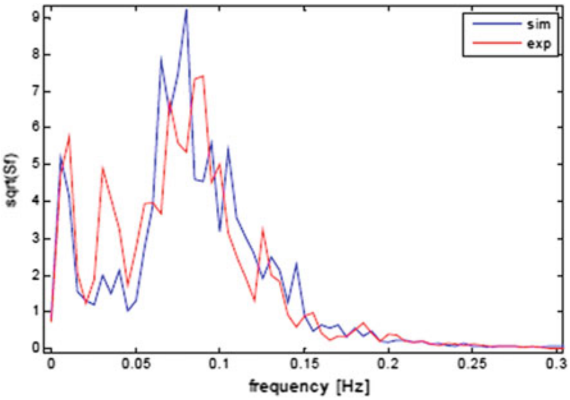


Fig. 17 Square root of the power spectrum of the nacelle surge motion. H_s = 5 m, T_p = 12 s, U_m = 16.44 m/s, T_i = 6.7 % and conventional control with active damping (Skaare et al. 2007b)



A good agreement between the simulation and experimental results was obtained, as illustrated in Figs. 16 and 17. Three peaks are clearly identifiable from the power spectra, these correspond with the following device motions: low frequency response in surge, the medium frequency is the tower pitch response and the higher frequency peak is attributed to the wave response. Figure 17 shows a significant decrease in the peak value recorded at the natural pitch frequency when the active damping term is introduced, highlighting the influence of the control strategy on the tower motions.

Most recently, the SIMO and RIFLEX programs have been included as part of the SIMA analysis tool, and the software has been extended to model offshore wind turbines (for further information on the SIMA tool see Ormberg et al. (2011) and Luxcey et al. (2011)). The dynamic analysis of the Hywind concept using the SIMA analysis tool, including comparisons of the simulation results with corresponding full-scale measurements by Hywind Demo, are presented in Skaare et al. (2015).

2.3 *Prototype Testing*

The Hywind Demo is currently the most advanced spar concept and was the first floating offshore wind turbine to have reached full-scale prototype testing. The Hywind Demo unit was installed near Karmøy, north of Stavanger and 10 km off the Norwegian coast at 200 m water depth. Figure 18 illustrates the installed Hywind Demo unit. The prototype was deployed in September 2009 and the test programme was initially planned for two years, but the device is still generating electricity and feeding it to the Norwegian grid by the end of 2015. Hywind Demo was equipped with a 2.3 MW standard offshore wind turbine model (SWT-2.3-82) from Siemens Wind Power. Table 4 presents some characteristic data for the SWT-2.3-82 wind turbine.

Fig. 18 Hywind Demo deployed off the Norwegian coast (courtesy of Statoil)

Table 4 Characteristic data for the SWT-2.3-83 wind turbine (based on information from Siemens Wind Power 2009)

Variable	Characteristic data
Rotor diameter	82.4 m
Rotor speed	6–18 RPM
Gearbox type	3-stage planetary-helical
Cut-in wind speed	3–5 m/s
Rated wind speed	13 m/s
Cut-out wind speed	25 m/s

The manufacturing and installation of the Hywind Demo unit was supported by the following major component contractors: Technip (offshore structure and installation), Siemens (wind turbine) and Nexans (offshore cabling). The spar structure was produced by Technip in Finland and towed to Stavanger, Norway, where it was up-ended by filling the cylindrical structure with water to raise it from a horizontal to a vertical position. This procedure, and the installation and commissioning of the nacelle and rotor assembly, were completed close to the shore in a relatively sheltered deep water fjord, where the depth was sufficient for the structure to be upended. Once assembled, the whole unit was towed to the installation site by tug boats, where anchors had been pre-installed. Figures 19, 20 and 21 illustrate the sequence of the towing, upending and assembly of the Hywind Demo unit.

During the initial months of operation, the turbine underwent a range of tests and was only operated during online monitoring from the Hywind Operations Room. Following this initial start-up phase, the Hywind Demo unit was switched to automatic operating mode for all wind speeds in January 2010.

Prototype Measurements

The Hywind Demo unit is equipped with more than two hundred sensors continuously logging measurements on aspects such as structural motions and loads, mooring line tension, metocean data and typical conventional wind turbine measurements (i.e. rotational speed, blade pitch angle and generator power).

The motions of the unit are recorded in 6-DOF by a motion reference unit (MRU) fixed to the prototype substructure. Strain gauges were located at four different levels along the tower and substructure. The strain gauge measurements are used to monitor the structural bending moments and axial forces on the structure. The tension in the mooring lines is measured with sensors in the six anchor pins placed in fairleads in the hull, one for each mooring delta line.

Fig. 19 Towing and upending of Hywind Demo (courtesy of Statoil)

Fig. 20 Assembly of Hywind Demo (courtesy of Statoil)

Fig. 21 Hywind Demo installation (courtesy of Statoil)

The wave climate is measured by a wave rider buoy located in close proximity (less than 100 m away) to the floater. The buoy measures the time history of the wave elevation and direction, as well as providing statistical values for other parameters, including current velocity and direction at different water depths.

A measurement of the distance between the Hywind Demo platform deck and the sea surface was estimated from two downward-looking wave radars. The undisturbed wave field at the Hywind Demo location was estimated based on a combination of the different wave field and motion measurements (for further details see Skaare et al. 2015). Wind speed and direction measurements were made on top of the nacelle behind the rotor.

Full-Scale Results

Results from the Hywind Demo project, including a comparison of full-scale measurements with the simulated responses from computer codes, have been presented in Hanson et al. (2011) and Skaare et al. (2015). Some examples of the results recorded by the Hywind Demo prototype are presented within this section.

The natural motion response periods of the device were identified using power spectra plots derived from measurements taken on the Hywind Demo and are presented in Table 5. Eigenmodes derived from simulations using the SIMA software program are also included in Table 5 for comparative purposes.

As previous Hywind studies have highlighted (see Sect. 2.2), a floating wind turbine operating above the rated wind speed experiences a negative damping contribution from the rotor thrust force in the platform pitch mode (Skaare et al. 2007a, 2011). If a conventional control system is used, the floater may become unstable. An active damping floater motion control system was incorporated within the Hywind Demo unit to minimise the platform pitch motion of the device. Figure 22 shows two measured responses of the tower pitch motion on Hywind Demo, one with, and one without the active damping floater motion control system activated. The two tests were run in quick succession of one another, so both tests were completed under similar environmental conditions. In the tests when the motion control was deactivated, the turbine was shut down after approximately 250 s due to large tower pitch angles (Skaare et al. 2015).

The results presented in Fig. 22 confirm that the tower pitch motions are considerably lower and more stable when the floater motion controller is activated. The simultaneous measurements of wind speed and device pitch motion time series data, taken from the Hywind Demo data acquisition software, is shown in Fig. 23. In this example, the wind speed gradually increases to a level above the rated wind speed of 13 m/s. During this period of strong wind speeds, the turbine is operating above

Table 5 Comparison between eigenmodes from simulations and Hywind Demo measurements (data from Skaare et al. 2015)

Mode of motion	Numerical analysis (s)	Hywind Demo measurements (s)
Surge	126.3	125.0
Heave	27.8	27.4
Pitch	24.2	23.9
Yaw (with clump weights)	23.4	23.8
Yaw (without clump weights)	7.5	6.2

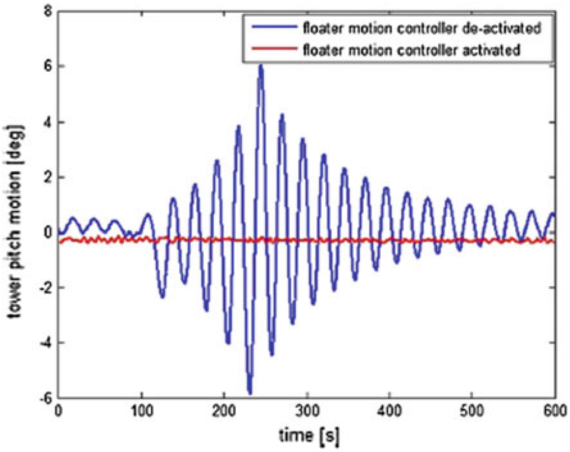


Fig. 22 Measured tower pitch angle on Hywind Demo with the floater motion controller deactivated (*blue*) and activated (*red*). Mean value removed (Skaare et al. 2011, 2015)

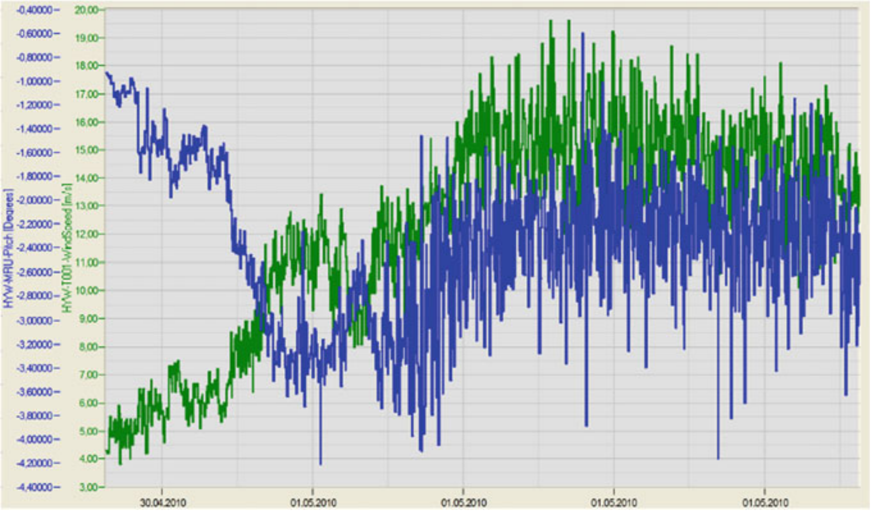


Fig. 23 Hywind Demo operation and monitoring software—wind speed and pitch behaviour of the prototype over a 30-h period, (wind speed (m/s)—*green line*; pitch motion (degrees) of the platform—*blue line*), (Keseric 2014)

the rated wind speed. When the turbine is operating above the rated wind speed, the active floater motion control system is activated to stabilise pitch motions. The stabilising influence of the active floater motion controller on the pitch behaviour can be observed in Fig. 23 during this period.

Power Production

Hywind Demo is the first floating offshore wind technology that has been verified through operational testing under harsh conditions for more than five years, and having produced approximately 41 GWh of electricity (per end October 2014). It performed beyond expectations, having a record year in 2011 with a capacity factor of over 50.1 % and produced 10.1 GWh. A screenshot of the Hywind Demo operating and monitoring software interface, including the Hywind Demo performance curve, with power generated as a function of wind speed is shown in Fig. 24.

Figure 25 shows an example of the power production trend measured by Hywind Demo in heavy seas over a 24-h period, wind speed and wave height measurements are also presented. The average wind speed for the results presented is 16 m/s, with a maximum wind speed of 28 m/s recorded. The wave height increases over the 24-h period, with an average significant wave height of 4.7 m and maximum value of 7.1 m. The results show that the Hywind Demo is capable of continued power production during heavy seas, with the device operating at 96.7 % of the rated power over the 24-h period presented. The Hywind Demo turbine has experienced several storms with maximal wave height of up to 19 m and wind speeds of 44 m/s without any consequence to the structure. Hywind operations have an excellent HS&E record without any major incidents during almost 6 year of operations.

There have been no observable negative effects on the WTG as a consequence of being installed on a floating substructure. The amount of unscheduled maintenance for the demonstration unit was the same as any other turbine of this model from the same manufacturer. The Hywind Demo project has proved that Statoil's floating

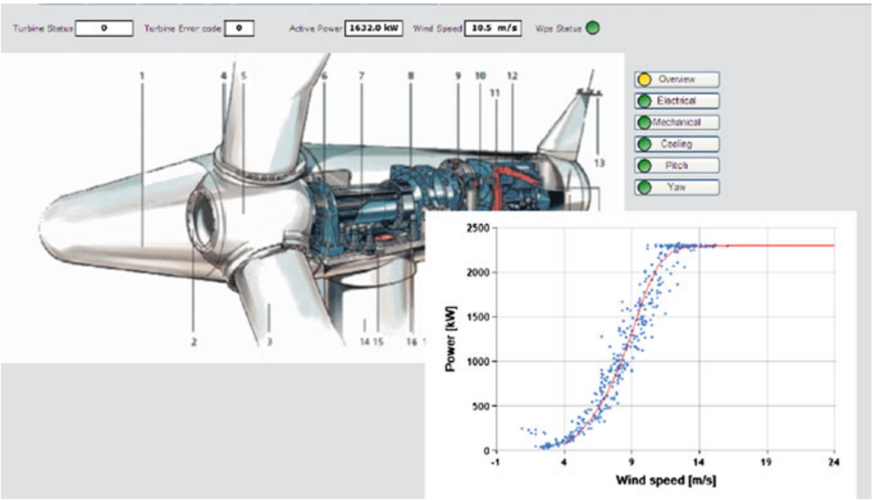
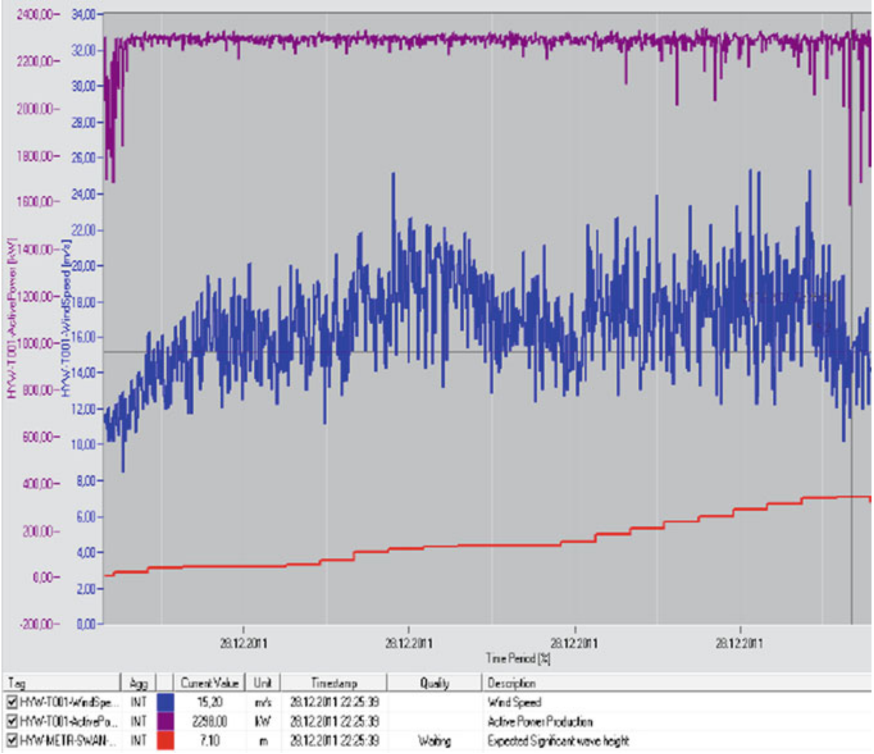

Turbine Status 0
Turbine Error code 0
Active Power 1632.0 kW
Wind Speed 10.5 m/s

Fig. 24 Hywind Demo operation and monitoring interface and characteristic power curve for Hywind Demo (Keseric 2014)



Tag	Agg		Current Value	Unit	Timestamp	Quality	Description
☑ HYW-T001-WindSpe...	INT	🟦	15,20	m/s	28.12.2011 22:25:39		Wind Speed
☑ HYW-T001-ActivePo...	INT	🟪	2298,00	KW	28.12.2011 22:25:39		Active Power Production
☑ HYW METR-SWAN-...	INT	🟥	7,10	m	28.12.2011 22:25:39	Waiting	Expected Significant wave height

Fig. 25 Power production trend of the Hywind Demo in heavy seas, wind speed and wave height measurements (wind speed (m/s)—*blue line*; active power production (kW)—*purple line*; expected significant wave height (m)—*red line*), (Keseric 2014)

wind concept is a suitable platform for conventional multi-MW turbines, and confirms Statoil's ambitions and objectives on bringing floating wind towards commercialisation.

2.4 Commercialisation Pathway

The feasibility of floating wind turbines has so far been demonstrated through analysis, model testing and prototype testing. Statoil now intends to scale up this technology to larger applications as shown in Fig. 26. The next step in the commercialisation plan of the Hywind concept is the installation of a pilot park to demonstrate improvements and cost reductions achieved by the modified Hywind device. The information in the following section is based on internal documents provided by Statoil (Byklum 2015).

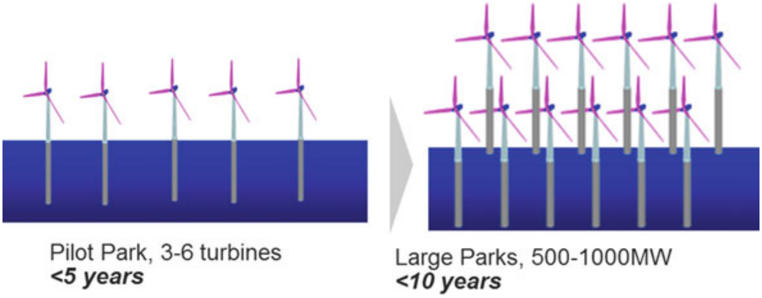


Fig. 26 Commercial development of Hywind (courtesy of Statoil)

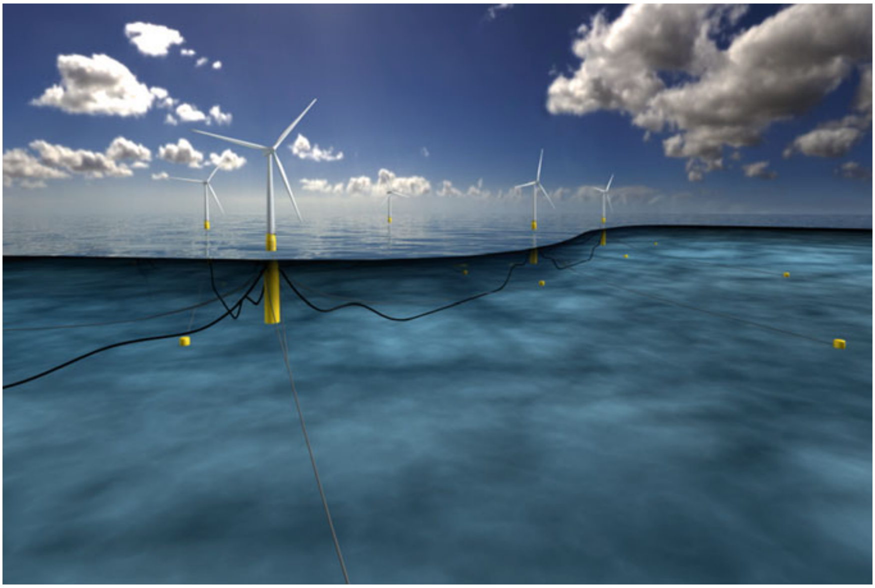


Fig. 27 Hywind Scotland pilot part overview (courtesy of Statoil)

The Hywind Scotland pilot park project is currently underway with plans to complete the final commissioning of the park by 2017. The pilot project will consist of five, 6 MW Hywind units, installed in water depths of 95–120 m (see Fig. 27). The park will be located near Buchan Deep, approximately 25–30 km off the coast of Peterhead in Aberdeenshire (UK).

Technology Development in Hywind Scotland Pilot Park

The Hywind Scotland pilot park project is intended to demonstrate the necessary reductions in both cost and risk from the prototype Hywind Demo to progress the technology toward medium and large scale wind park deployment. The pilot park will support the development of large scale parks through:

- *Technical innovation and validation*:
  - Utilise the Hywind Demo construction experience and operational performance data to develop and demonstrate a more optimised and cost efficient design, with a larger turbine and an optimised substructure. The Project design is being developed by use of a sophisticated coupled dynamic model, scalable to larger turbine units.
  - Furthermore, the project will study the effects of wake and turbulence on the floater motions for floating turbines in a park with multiple units, and demonstrate the concept and the motion controller for use in a park configuration. A critical part of the concept is the Statoil-developed pitch regulator, which has already been tested on Hywind Demo and will be adapted to the new design. Thus, the Hywind Scotland pilot park project will monitor the continued success of this advanced pitch regulator in a new environment.
  - The pilot park will also, to the extent possible/practical, be used to test out and demonstrate new technology which can be used to reduce costs for future large parks.
- *Risk reduction for large park development*: The Hywind Scotland pilot park project will advance the general base of knowledge for offshore floating wind, thereby reducing the risk for future large scale wind park development.
- *Cost reduction and market acceptance*:
  - Obtain validation of construction, installation and operating costs based on a multiple-turbine park. Demonstrating scalability of costs is viewed as a key step to building credibility in the market for the commercialisation of floating wind parks. The objective is to demonstrate the path for Statoil and other developers to achieve cost reduction and full-scale commercial viability.
  - The pilot project will demonstrate scale efficiency, and contribute to maturing the supply chain, in particular when it comes to substructure manufacturing and marine operations.

Due to the up-scaling of the substructure and turbine capacity, floater motion control and mooring system for the large Hywind units require particular attention. One new challenge related to turbines with larger rotor diameters is the effect of the increased wind loads on the yaw and roll motion of the floater, and the design of the mooring system to obtain the correct stiffness. Detailed analytical studies will be carried out to study these effects, but it will also be critical to demonstrate the performance of the concept in full-scale. It is also a continuous on-going effort to improve and optimise the floater motion controller for Hywind. Work is still on-going on Hywind Demo to test out the controller in different sea states to cover as many conditions as possible and analytical work is on-going to improve the controller to be able to control the motions also in yaw and roll, in addition to the pitch motion.

Motion response of a floating wind turbine in a park configuration with multiple units needs further investigation, both analytical and through full-scale demonstration. Wake effects on bottom-fixed structures have been studied extensively previously, but the focus has so far been on the wake loss when it comes to production. For floating WTG units, the critical aspect is rather the effect of the wake on the wind loads acting on the floating turbines in the wake, and how the non-uniform wind loads in the wake affect the floater motions. There is currently a lack of analytical tools to analyse this effect, but there is work on-going to develop tools which can be used. Nevertheless, since this is a new research topic, it will be essential to carry out full-scale measurements in the pilot park to verify the findings. For this reason, the park layout and turbine spacing for the pilot park will be chosen so that it is representative of the wake effects that will be present in a large park.

In the pilot project, a number of studies will be carried out to gain an improved understanding of these challenges and potential solutions. This includes for example advanced fully-coupled dynamic analyses to assess the effect of asymmetric load effects on floating WTGs with large rotors, assessment of asymmetric wake loading on floating units in a park configuration, further development and optimisation of the floater motion control system, and optimisation of the mooring system.

Technology Development from Hywind Scotland Pilot Park to Large Scale Parks

In order to develop the Hywind technology into a commercial, large scale competitive offshore wind solution, further development is needed. The main focus is to reduce the cost of energy to a level which makes floating offshore wind the most attractive and preferred alternative for renewable power production. This can be achieved by improving the concept itself, industrialising and scaling the technological solution as well as reducing the risk. The Hywind concept is mainly based on existing technologies used either in the oil and gas industry or the wind industry, adapted to floating and marine application. Due to this fact Hywind will benefit from the general development in these related industries making the components more cost efficient, safer and suitable for the marine environment. Examples of this development are larger wind turbines, improved reliability, more advanced and efficient marine vessels as well as more cost efficient electrical infrastructure.

However, in some areas the Hywind technology has more specific needs and potential for cost improvements. These areas are installation methods for shallow water areas, repair of major components at site, mass production of substructures as well as alternative anchoring solutions.

Improved installation methods for shallow water sites are a technology needed for areas where deep water is not available close to shore. Several alternative solutions are identified, however more work is needed to validate, qualify and commercialise these technologies without increasing the cost of installation. The solutions considered require investments in new type of vessels and will therefore not be realised before a commercial scale project is under development. It will therefore be of vital importance to time this development and investments in order to meet the project needs. In June 2014, the Hywind Installation Challenge was launched as an open innovation challenge on Statoil's Innovate website. The campaign was open until 15 November 2014, and during this period a large number of proposals for new installation methods were received from the industry. Going forward, Statoil will work together with the companies with the most promising solutions to develop the ideas further.

Exchange of major components is a general issue for offshore wind as the expensive vessels with long mobilisation time are needed. There are also relatively strict weather limitations related to some of the lifting operations and as new sites tend to be more exposed to wind and waves, these operations are becoming increasingly expensive and unpredictable. Due to the fact that Hywind is a floating structure in deep waters, all lifting operations will be between two floating bodies, a more challenging task than between a bottom fixed turbine and a jack-up vessel. The limitations related to such operations are currently being studied and new solutions are looked into in order to improve the maintainability. Hywind also has the alternative to tow the whole unit to shore. This holds a potential reduction in both downtime and cost as the operations can be done in sheltered waters, but is currently considered to be a more expensive operation than the standard procedure for bottom fixed turbines, especially where deep water quays are not available. The tow-to-shore procedure is currently being studied in order to increase the understanding of the related costs and downtime.

A mass production supply chain of the spar substructure is not established in the industry today. Huge improvements are foreseen as more efficient production techniques, simpler design and logistical solutions are implemented. Efforts are being made to develop such solutions, however this has to be done together with local industry as well as be timed correctly with market development of floating offshore wind, as this might require investments from the supplier industry.

New anchoring solutions for alternative sites are under development in order to have a fit-for-purpose and cost efficient solution for installation of Hywind anchors. Several alternatives are developed or under development, however these need to be qualified and adapted to Hywind application. A wider selection of anchors and anchor line solutions will make the Hywind technology even better suited for different seabed solutions as well as reduce the seabed footprint of the anchor solution.

All these areas are worked with through internal improvement programs in Statoil, as well as in cooperation with the supplier industry. This will be a continuous effort going forwards balancing time to market, cost improvement potential and use of resources.

3 Goto Island Project

Tomoaki Utsunomiya

3.1 Device Description

In the Goto Island Project, funded by the Ministry of the Environment, Japan, a pre-stressed concrete (PC)-steel hybrid spar has been developed. The hybrid spar consists of PC rings at the bottom part and steel cylindrical shells at the upper part. Figure 28 shows the general view of the prototype model and Fig. 29 shows the dimensions of the same model. There is an expectation that using concrete for the bottom part will be beneficial for reducing the CAPEX.

Fig. 28 General view of the prototype model

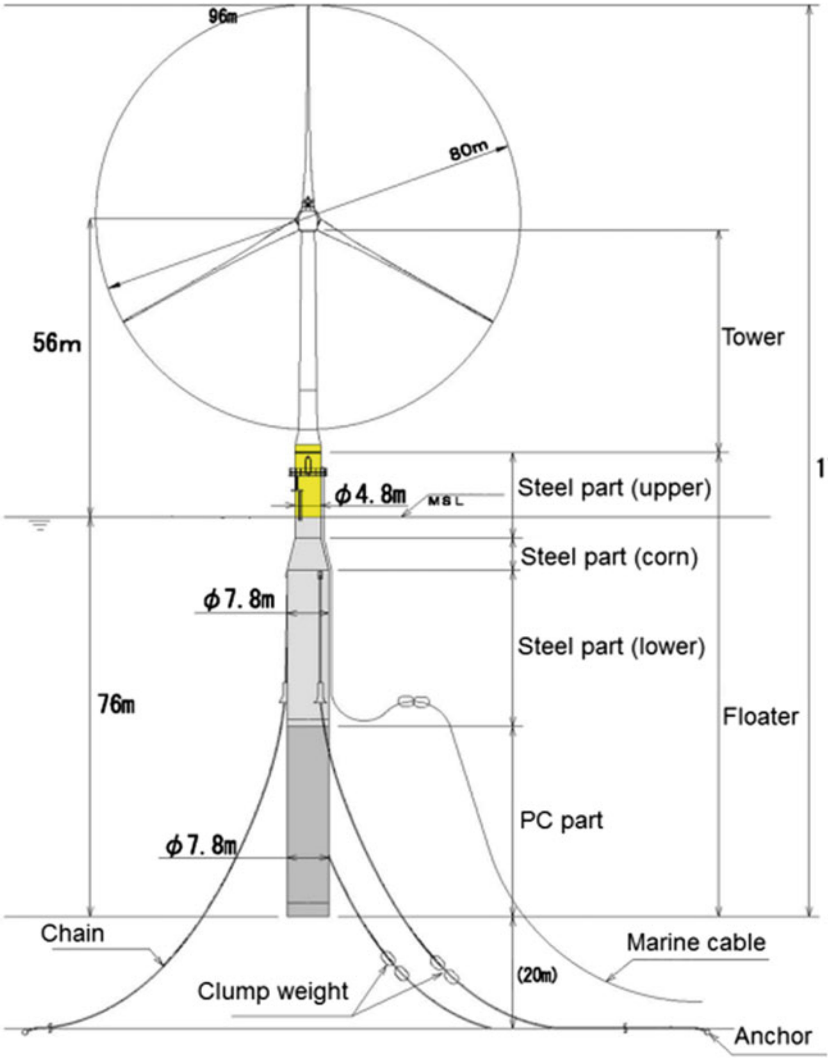


Fig. 29 Dimensions of the prototype model

The prototype model supports a downwind turbine, HTW 2.0-80 (Hitachi Ltd.), the rated output of which is 2 MW and the rotor diameter 80 m. The tower is made of steel, similar to a tower for a land-based wind turbine.

The spar floater is a simple cylindrical structure with varying diameters. The outer diameter of the upper part is 4.8 m, whereas the outer diameter of the lower part is 7.8 m. The main reason for the variable diameter is to control the natural heave period. The natural heave period should be long enough, that is, well apart from the wave energy dominant range (typically 4–14 s). The bottom of the spar floater is filled with ballasting solids and sea water, as the center of gravity is designed to be lower than the center of buoyancy.

The spar floater is moored by three catenary mooring chains (R3S studless chains). The nominal diameter of the chains is 132 mm. Among the three mooring lines, two of them are equipped with clump weights in order to increase the weight of the lines. Only the weather-side mooring lines are equipped with the clump weights.

The mooring lines are anchored to the sea-bed by drag-type anchors. The pre-installed mooring lines were test-tensioned with the maximum design loads. The design and installation of the prototype model are presented in more detail in Utsunomiya et al. (2015a, b).

3.2 Concept Development

The spar concept presented herein was first examined experimentally by using 1:100 scale models of the 2 MW prototype model as shown in Fig. 30 and in Table 6. In the experiment, a simple cylindrical shaped floater with constant diameter (Fig. 30a) and a stepped cylindrical shaped floater with variable diameter (Fig. 30b) were used. The experimental results for wave responses were compared with numerical simulations using Morison's equation as the wave force formula. The results showed that the stepped cylindrical shaped floater may be applicable as

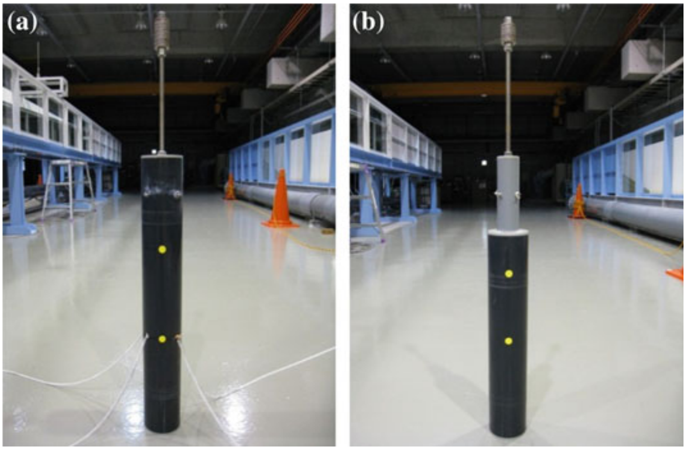


Fig. 30 1:100 scale models of the 2 MW prototype model **a** simple cylindrical shaped floater (*left*), **b** stepped cylindrical shaped floater (*right*)

Table 6 Dimensions of the 1:100 scale models (in prototype model scale) and the significant values of the responses in irregular waves at $\boldsymbol{H}_{1/3}$ = 12 m, $\boldsymbol{T}_{1/3}$ = 13.4 s

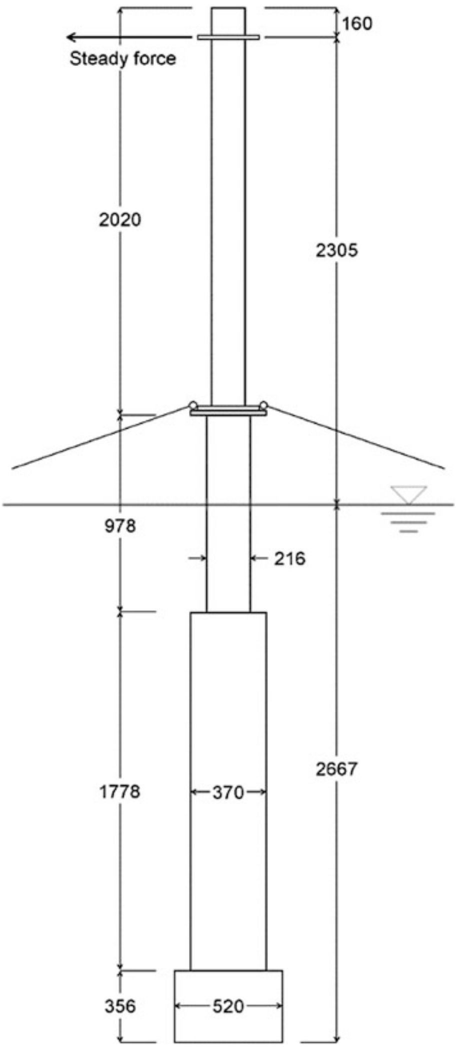
Description	Simple cylindrical shaped floater	Stepped cylindrical shaped floater
Draft	60 m	60 m
Outer diameter	8.9 m	8.9 m (lower part), 4.8 m (upper part)
Center of gravity	KG = 24.8 m	KG = 24.8 m
Fairlead location	4 m below water line	4 m below water line
Natural period in surge	174 s	168 s
Natural period in heave	16 s	27 s
Natural period in pitch	28 s	54 s
Surge response	5.68 m	6.62 m
Heave response	6.14 m	1.50 m
Pitch response	11.76°	4.22°

Fig. 31 1:22.5 scale model of the 2 MW prototype model in the deep sea wave basin at National Maritime Research Institute (Japan)

a floating foundation of a wind turbine, although the simple cylindrical shaped floater would be pessimistic. More details can be seen in Utsunomiya et al. (2009a).

In the next development stage, a stepped spar with 1:22.5 scale of the 2 MW prototype model was examined in the deep-sea wave basin at National Maritime Research Institute in Japan, as shown in Fig. 31 (Utsunomiya et al. 2009b). The dimensions of the 1:22.5 scale model are shown in Fig. 32. Here, the wind loadings at the hub height were simulated by a steady horizontal force using a constant weight. Both regular and irregular waves with/without the steady horizontal force were examined in the wave tank experiment. The experimental results were then compared with the simulations using Morison’s equation. Table 7 summarises the

Fig. 32 Dimensions of the 1:22.5 scale model of the 2 MW prototype model (in mm)



experimental results and the comparisons with the simulations. Good agreement was observed between the experiment and the numerical simulations. More importantly, no surprising phenomenon was observed in the wave tank experiment. From this experiment, confidence was gained that the spar concept for floating wind turbine would be feasible.

Subsequently, at-sea experiment of a hybrid spar using 1:10 scale model was made in Sasebo port, Nagasaki prefecture (Utsunomiya et al. 2013a). The purpose of this experiment was to demonstrate the feasibility of the hybrid-spar concept. The demonstrative experiment included:

Table 7 Summary of the 1:22.5 scale model experiments and simulations (in prototype model scale). The responses are the significant values for the irregular waves at $\boldsymbol{H}_{1/3} = 2.25$ m, $\boldsymbol{T}_{1/3} = 11.86$ s

Description	Experiment	Simulation	Exp./Sim.
Natural period in surge	111.5 s	113.5 s	0.98
Natural period in heave	27.5 s	27.5 s	1.00
Natural period in pitch	25.0 s	25.6 s	0.98
Natural period in yaw	23.3 s	24.3 s	0.96
Surge response	1.117 m	1.190 m	0.94
Heave response	0.571 m	0.573 m	1.00
Pitch response	1.590°	1.554°	1.02

1. construction of the hybrid-spar foundation using PC and steel, the same as the prototype;
2. dry-towing and installation to the at-sea site at 30 m distance from the quay of the Sasebo shipbuilding yard;
3. generating electric power using a 1 kW horizontal axis wind turbine; and
4. removal from the site.

During the at-sea experiment, wind speed, wind direction, tidal height, wave height, motion of the spar, tension in mooring chains, and strains in the tower and

Fig. 33 General view of the at-sea experiment

the spar foundation have been measured. Figure 33 shows the general view of the at-sea experiment, and Fig. 34 shows the schematic representation of the 1:10 scale model of the 2 MW prototype model. In Fig. 35, the power spectrums of the roll

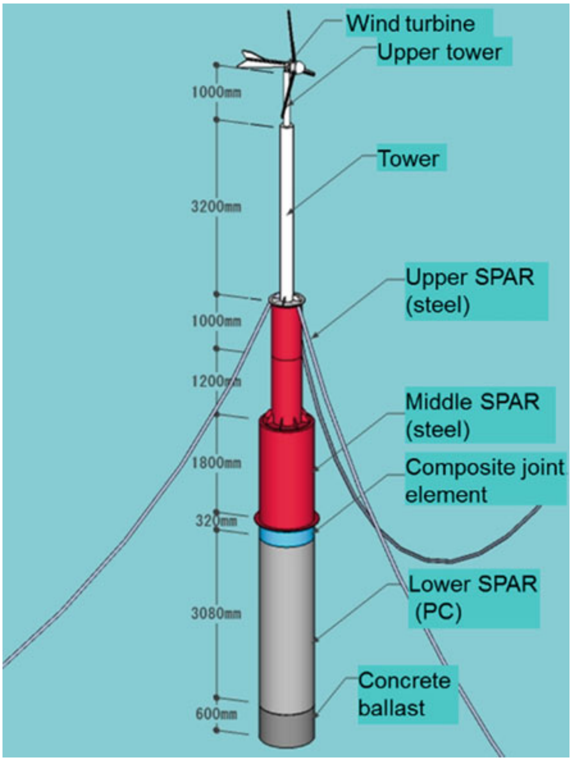


Fig. 34 Schematic representation of the 1:10 scale model of the 2 MW prototype model

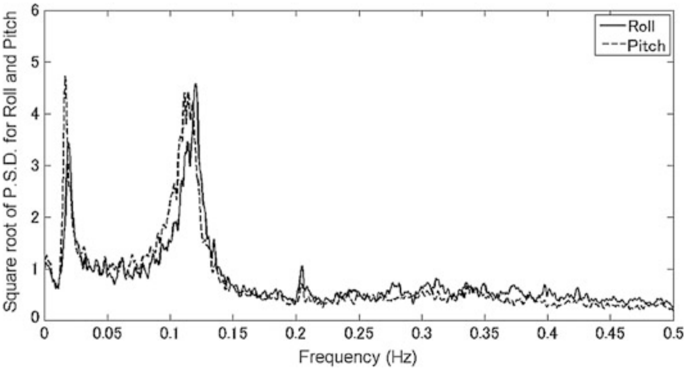


Fig. 35 Power spectrum of roll and pitch responses of the 1:10 scale model

and pitch responses are shown. Each spectrum has two clear peaks, corresponding to surge and roll natural frequencies for roll motion, and sway and pitch natural frequencies for pitch motion, respectively. Through this at-sea experiment, the feasibility of the hybrid-spar concept has been confirmed.

3.3 Prototype Testing

Demonstration Project Outline

From the fiscal year of 2010, the demonstration project on floating offshore wind turbine was kicked-off by the Ministry of the Environment, Japan (Utsunomiya et al. 2015a). The ultimate objective of the demonstration project is to reduce the greenhouse gas emission through commercialisation of FOWTs in the Japanese exclusive economic zone (EEZ). Towards the commercialisation of FOWTs, the demonstration of the technical feasibility in a real sea environment is critical, as well as gaining social acceptance. Thus, the demonstration project was initiated as a national project in Japan.

Figure 36 shows the master schedule of the demonstration project. The project will spread over 6 years. In the project, two demonstration models have been installed. The first one is called the *half-scale model*, since the model is almost half in the length dimensions of the 2 MW *full-scale model*. The second one is called the *full-scale model*. The reason why two models have been installed is because a

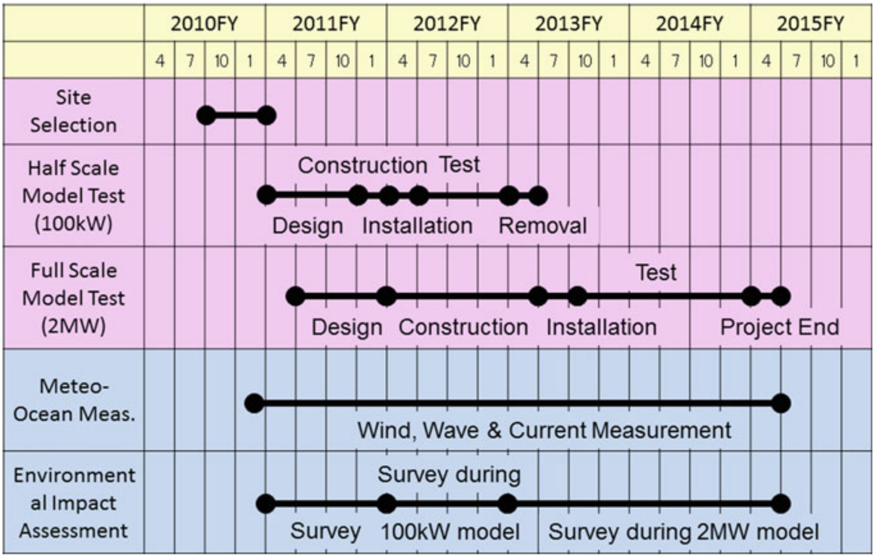


Fig. 36 Master schedule of the demonstration project on FOWT

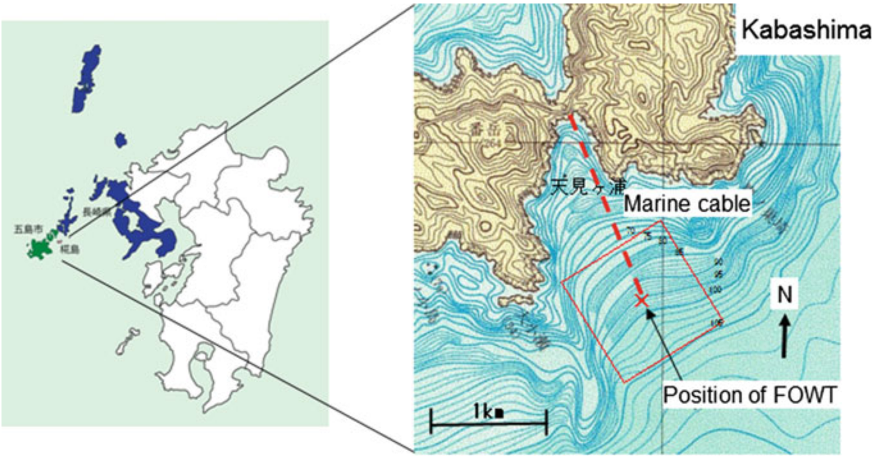


Fig. 37 Demonstration site of the project, Kabashima, Goto city, Nagasaki prefecture

step-by-step approach is preferred in order to reduce possible technical risks. Another reason is because the social acceptance would be gained by such a step-by-step approach.

Figure 37 shows the site of the demonstration project. The site is about 1 km offshore of Kabashima Island, Goto city, Nagasaki prefecture. The mean water depth is 97.2 m at mean sea level (MSL). A marine cable has been installed for the grid-connection. The distance to the shore from the FOWT along the marine cable is about 1.8 km.

Half-Scale Model

Figure 38 shows the outline of the half-scale model, and Fig. 39 shows the dimensions. The lower part of the spar is made of pre-stressed concrete (PC) whereas the upper part is made of steel. The spar was moored by three catenary anchor chains whose nominal diameter was 56 mm (G3 stud chains). The mooring chains were anchored to seabed by concrete sinkers (200 ton-force(tf) in air) at two ends and by a Danforth-type anchor (10 tf in air) at one end.

The wind turbine for the half-scale model is SUBARU 22/100, the rated output is 100 kW and the diameter is 22 m. The original wind turbine of SUBARU 22/100 was an upwind-type, but for this particular project, the wind turbine was modified to a down-wind type. Also, the maximum power was limited to 40 kW in order to increase the possibility of occurrence of wind speed above rated wind speed, where pitch control of the blades is made.

The structural design of the floating wind turbine was made by relying on the time-domain numerical simulations. Some details of the numerical simulations and the experiments used for validation are presented in Utsunomiya et al. (2014a) and in Kokubun et al. (2012). The half-scale model was installed offshore in June 2012 as the first grid-connected floating wind turbine in Japan. Figure 40 shows the general view of the half-scale model with an access ship.

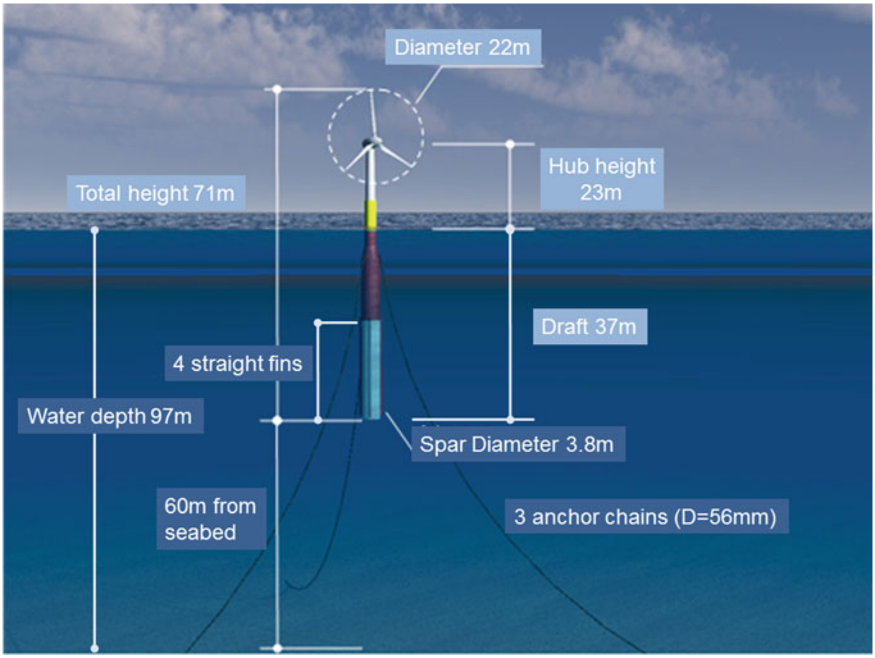


Fig. 38 Outline of the half-scale model

Fig. 39 Dimensions of the half-scale model (in m)

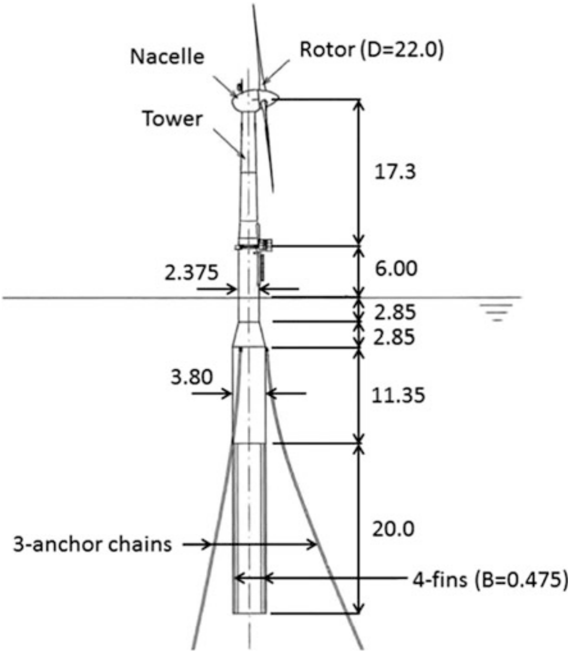


Fig. 40 General view of the half-scale model

During the demonstrative experiment of the half-scale model, the FOWT was attacked by two separate sever typhoons. Among them, Sanba (international designation: 1216) was a record-breaking typhoon event, with a maximum wind speed of 36.8 m/s, as the 10-min average wind speed, measured at the top of the nacelle by the cup-type anemometer. At the same time, the maximum wave height of $H_{1/3} = 9.5$ m and the wave period of $T_{1/3} = 13$ s was recorded by a wave buoy close to the site (for 1-h reference period). The maximum wave height of 9.5 m exceeded the design wave height of 8.4 m corresponding to a 50-year return period event. However, the half-scale model survived for the severe typhoon with no

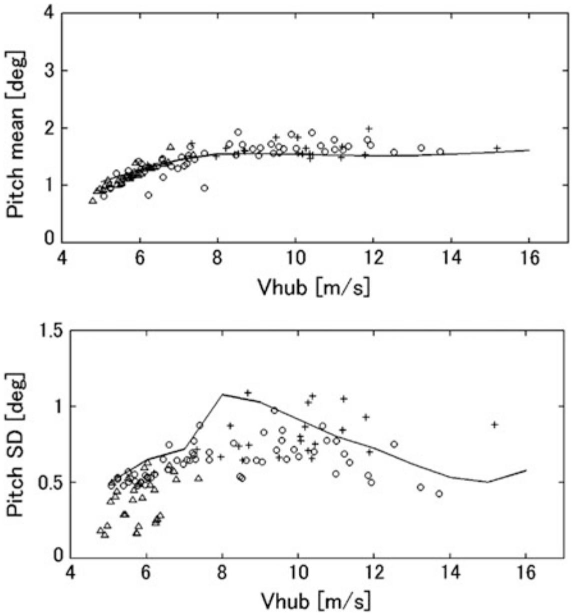


Fig. 41 Pitch responses for the half-scale model. *Solid line* simulation for turbulence intensities (T.I.) at IEC category A; + T.I. above IEC category A; *circle* T.I. between IEC category A and C; *triangle* T.I. below IEC category C. *Top* mean values. *Bottom* standard deviations

damage. The behavior during the typhoon event is reported in more detail in Utsunomiya et al. (2013b) and in Ishida et al. (2013).

Figure 41 shows an example of the platform responses during power production. The dynamic behavior during the power production can be predicted well by the numerical simulations. It is noted that the standard deviations of the pitch response are affected by the turbulence intensities of the wind, although the mean values of the pitch response are insensitive to the turbulence intensities (Utsunomiya et al. 2014b).

Full-Scale Model

After removal of the half-scale model from the site, the full-scale model was installed at the same site. Figure 28 shows the general view of the full-scale model in completion and Fig. 29 shows the main dimensions.

The structural design was made by following the ClassNK guideline (ClassNK 2012). The design load cases were set-up as given by the ClassNK guideline, and then, the time-domain simulations were made for all design load cases. The sectional design loads were then determined as the maximum value at the corresponding section among all design load cases. The load calculations were made by the validated program for the half-scale model test. More detailed design procedures are presented in Utsunomiya et al. (2015b).

Figure 42 shows the photographs of the different construction phases and procedures. The precast pre-stressed concrete (PC) segments were fabricated in a factory of Hume pipe at Kitakyushu city, Fukuoka prefecture. The precast segments were fabricated as a 1/4 part of the circular section (outer diameter: 7.8 m) with the

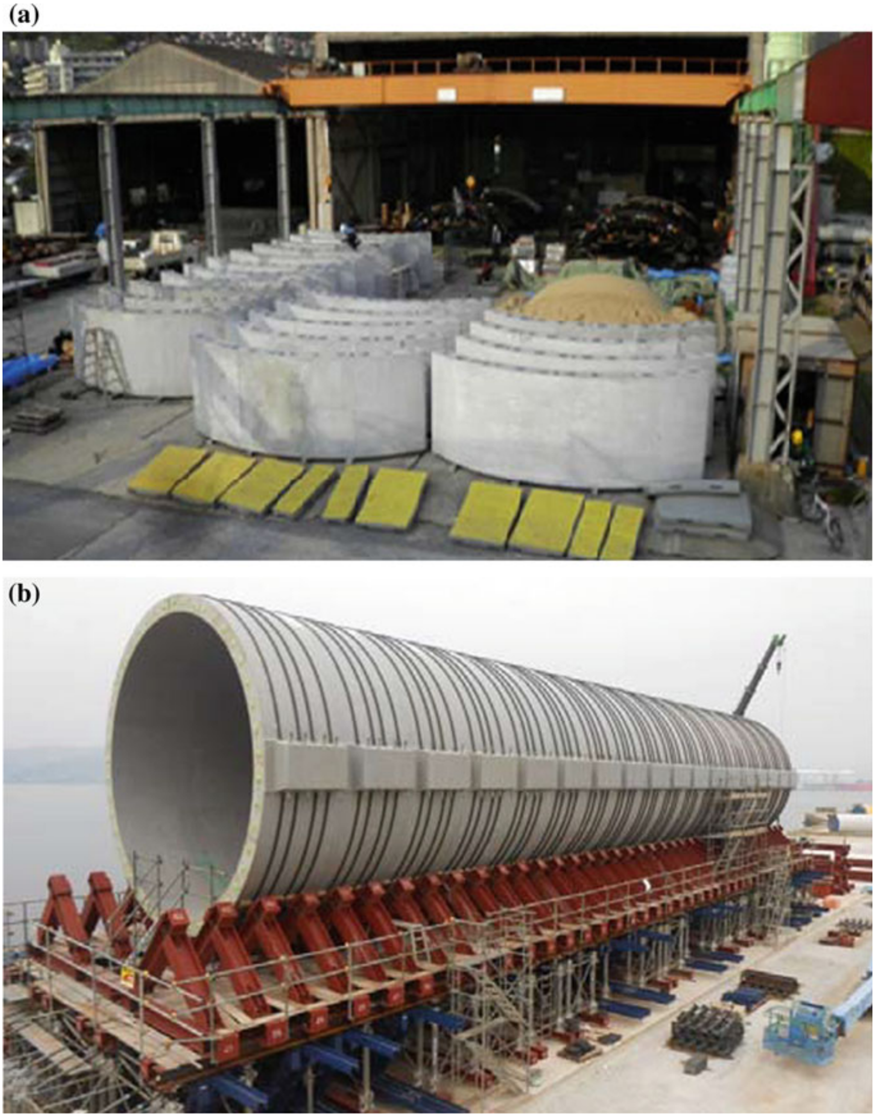


Fig. 42 Construction and installation procedures. **a** Fabrication of the concrete segments. **b** Construction of the PC part of the spar structure. **c** Joining the PC part and the steel part, and completion of the hybrid spar. **d** Dry-towing of the hybrid spar. **e** Upending of the hybrid spar. **f** Assembly of the rotor. **g** Towing to the demonstration site

height of 2 m because of the restrictions for land transportation (a). After the accelerated curing with vapor, the demolding and the air curing, the completed PC segments were transported to the construction quay at Matsuura city, Nagasaki prefecture by using conventional truck transportation. At the same time, the steel

Fig. 42 (continued)

part of the spar structure was fabricated at a shipyard in Sakai city, Osaka prefecture. The completed steel part was then transported to the same construction quay at Matsuura city by using a conventional barge.

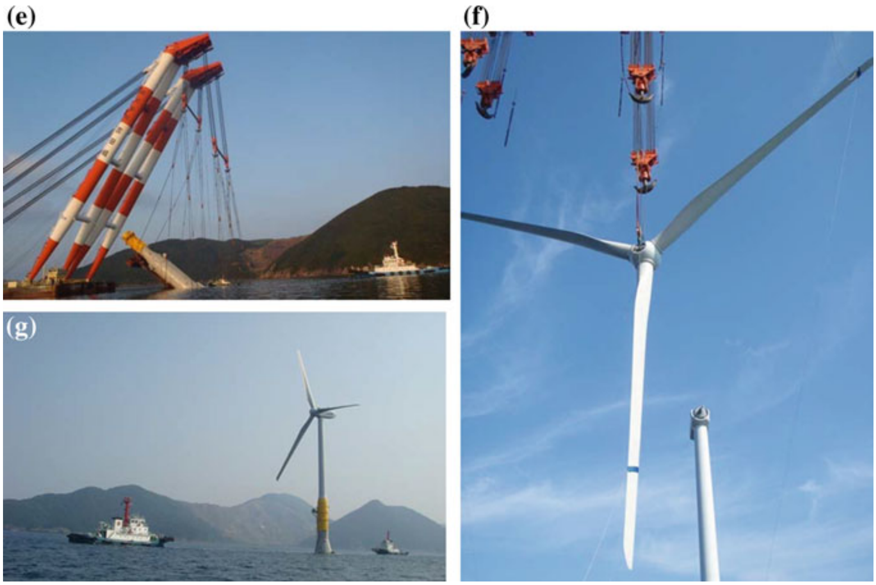


Fig. 42 (continued)

At the construction quay in Matsuura city, four segments were firstly joined together to form a ring-shaped part with the outer diameter of 7.8 m and the height of 2 m in the horizontal position. The completed ring-shaped parts were then assembled together to form a circular cylinder by using post-tensioning steel bars for the bottom half of the spar structure (b). After the completion of the PC part of the spar structure, the upper steel part was joined to the lower PC part by using a floating crane (c). The completed hybrid structure was dry-towed to the north area of the Kabashima Island, where the wave conditions are gentler than those at the demonstration site (d). Then, the hybrid-spar structure was upended with the help of a floating crane (e). After completion of the upending, the sea water was filled to stabilise the spar at the design draft. Then, the solid ballasting material was filled, where part of the sea water was replaced by the solid ballast. The tower sections (divided in two pieces), the nacelle, and the rotor were then assembled by using a floating crane (f). Having a weather window of more than three days, the temporary moorings at the north construction area were unhooked. Then, the floating wind turbine structure was towed to the demonstration site by using two tug-boats (g). As soon as it arrived at the demonstration site, the pre-laid anchor chains were hooked-up to the spar structure.

Final hook-up of the mooring chains was completed on October 18, 2013. After connection of the marine cable for the grid-connection, it began to operate from October 28, 2013 as the first multi-megawatt floating wind turbine in Japan (Fig. 28).

As of April 2015, the prototype model has been operating with no major accidental matters. During the operation, the prototype model was also attacked by several typhoons of moderated strength, but it behaved as it was so designed. This prototype testing has proven the feasibility of the hybrid-spar as a cost-effective solution for a floating wind turbine.

3.4 Commercialisation Pathway

With the success of the prototype testing mentioned above, the next step will be to form a moderate level wind farm using the same proven technology. Also, it is desirable to increase the rating of the turbine. Very recently, Hitachi Ltd. has completed the development of 5 MW downwind turbine (HTW 5.0-126; see Saeki et al. 2014). This turbine could be used for next-generation floating wind turbine using the hybrid-spar technology.

4 Sway

Jørgen Jorde and Eystein Borgen

4.1 Device Description

The Sway concept was originally developed for the electrification of offshore oil and gas platforms in the North Sea for depths of 100–400 m. From 2001, Sway AS has developed the SWAY® floating Wind power system. The Sway system can enable large scale power production for export to the onshore grids around the world in countries where water depths of greater than 50–60 m are available offshore. Outside the southern part of the North Sea (which is very shallow) most coastal waters world-wide have suitable water depths. This also allows floating wind parks to be placed outside a visible distance from shore, thus reducing potential visual impacts. The general configuration of the Sway system is shown in Fig. 43.

The Sway system consists of a horizontal axis wind turbine mounted in a downwind (or upwind) configuration on a floating tower, anchored directly or via a tension/torsion leg to the seabed. The floating tower gains its stability from ballasting the slender tower in addition to fixing it to the seabed through a tension leg (long or short). The concept is based on the entire floating tower turning (yawing) with the wind, enabling the use of tension cables (wire stays) for structural re-enforcement. The yaw mechanism is placed at the bottom of the tower, which

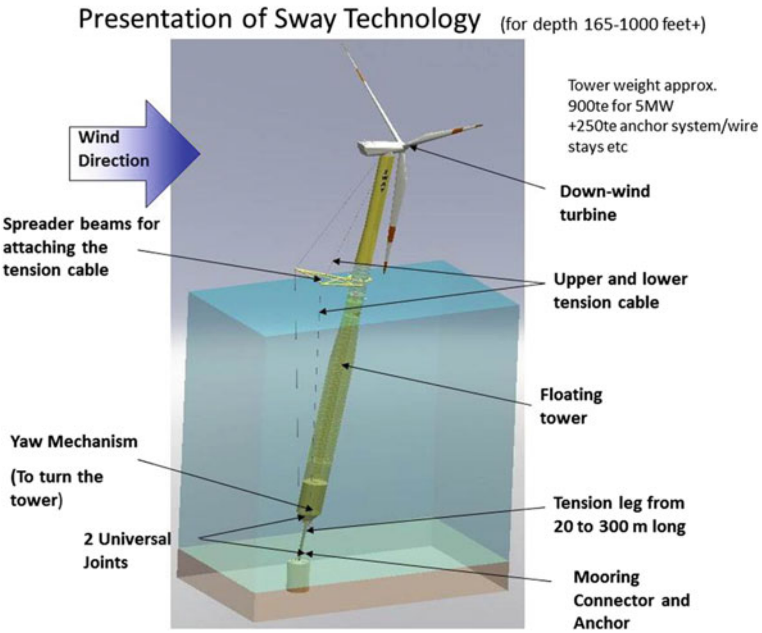


Fig. 43 Sway technology

allows the nacelle with the generator to be fixed to the top of the tower, leaving the entire tower to weather vane. This feature also allows for an aerodynamic shape of the tower in front of the downwind rotor, minimising rotor turbulence. Another benefit of the yaw mechanism is that the wire stays remain in the direction always facing the wind, significantly reducing the bending moments and fatigue damage of the tower structure. This patented feature is important for the deployment of turbines larger than 5 MW on the floating mono tower and allows turbines up to 10 MW to be installed on the floating tower. The power cable will be pulled in through a service pipe in the centre of the tower ensuring the cable is well protected inside the tower and kept away from the splash zone. An electrical swivel is placed in air at the cable hang-off point at the top of the service pipe inside the tower.

The turbine hub height above sea level, for a 5–7 MW WTG, will be approximately 80–100 m, while the remaining 60–80 m of the tower will be below sea level. The total weight of the steel in the tower and anchor system is approximately 1000–1500 tonnes. The system can be optimised depending on the water depth and environmental conditions at each installation site and size of wind turbine.

The original Sway system for 100 m+ water depth has been designed to resist the fatigue load for 20 years' service life and the 100-year storm condition in the North Sea and the Norwegian Sea, having one of the roughest environmental climates in the world. Dynamic analyses have verified an acceptable level of motion at the rotor under its working conditions in the downwind configuration on the Sway tower. The maximum pitch for normal operation will be about 8° and for extreme conditions (100-year storm) it will pitch a maximum of 15°.

A preliminary concept design was carried out for the Energy Technologies Institute (ETI) using 60 m water depth as a *worst case* minimum water level. The system was also tested for extreme tide differences of ±5 m (10 m range). The extreme loads and fatigue loads were only slightly larger than the original design for 100 m+ depth which indicate that it is fully possible to make the Sway tower work in as little as 60 m water depth. The fatigue loads without the wire stays were checked but found unacceptable (up to 4 times higher stresses in the tower) and therefore a mono tower connected directly to the seabed without the wire stays would not be economically feasible.

The evolution of the Sway system started in 2001 and has resulted in an engineered verification of the original idea, and with several important improvements to optimise the system. Sway has developed a simulation tool, SwaySim, based on the non-linear code Usfos capable of dynamic simulation of the interaction of wind, waves, tide and currents with the entire wind turbine based on finite element time domain analysis. The software was validated to simulate the simultaneous co-functionality of rotor, tower, turbine, control system, waves and wind, which allows, for example pitch control together with varying wind to be simulated. This was used to identify critical design points and optimise the design for low weight and sufficient strength.

The Sway system uses a downwind rotor. The rotor tilt angle can therefore be tailored to an optimum tilt angle for maximum alignment with the wind, without the risk of the blades clashing with the tower. Meaning that the tower is tilting in “the right” direction when the rotor is placed downwind. Therefore, the fixed rotor tilt angle is reduced (instead of increased) when the wind pushes the tower back. As a result, the Sway tower can be designed with a smaller structure for a given wind turbine, due to the non-critical tower dynamic tilt angle for the Sway design, which results in considerably less tower costs per MW. Typical tower dynamic tilt angle for the Sway design are 5–8°. The rotor has a fixed tilt of 5°, hence typically only 0°–3° of an effective tilt angle between the rotor and the wind during operation is achieved, which is less than for an onshore turbine. For an upwind rotor, the resultant tilt would be 5 + 8 = 13° which is not favourable.

The Sway floating wind turbine system is designed for use with a standard offshore turbine in a downwind configuration, with a control system adapted for the floating support structure. A feasibility study was performed by Multibrid (Areva Wind) together with Aerodyn, Garrad Hassan and Sway. The study describes the modifications to be made on the Multibrid M5000 turbine and proves that the Multibrid M5000 turbine performs well in a downwind configuration, with a modified control system and a nacelle without yaw mechanism. The modifications to the turbine itself, except for the modification of the control system, are regarded as small.

Up to 2013, there have been few downwind WTG on the market, this is however changing now, and several large 2–3 bladed downwind WTGs are currently available.

A floating mono tower is exposed to extreme fatigue loading. Therefore, the Sway solution is to place the yaw bearing at the bottom of the tower, allowing the installation of a wire stay system from the bottom of the floating tower to the top on the up-wind side of the tower (no clashing with the rotor since the nacelle itself is fixed in one position on the tower). This system reduces the bending stresses in the tower by typically 30–50 %, which allows the installation of a double sized turbine on top of the same tower compared to an un-stayed tower. Hence the economy is considerably improved.

The subsea yaw system is a simple passive swivel without motoring (Fig. 44). The swivel bearing consist of maintenance free aluminium-bronze sliding pads against a high grade stainless steel, which have been qualified through more than 20-year service life on loading buoys in the offshore industry. The design wear life of the sliding pads in the Sway system is 60 years. However, this component is still designed to be changed out offshore to lower the O&M risk. The active yawing is done entirely by individual pitching of the turbine rotor. In no wind conditions, the turbine can be yawed by driving the rotor (using the generator in motor mode) and then use the individual blade pitch to create the necessary yaw moment. To eliminate the risk of not being able to unwind the cable in this manner the power cable is terminated at a slip ring arrangement at the hang-off inside the tower.

Finally, the Sway tower for 60–100 m water depth connects directly to a single anchor with a very moderate extreme anchor force (approx. 1000 t including load factors) compared to other tension platform systems with multiple anchor cables. Since the anchor system constitutes a considerable part of the total costs this system further reduces the total CAPEX per installed turbine.

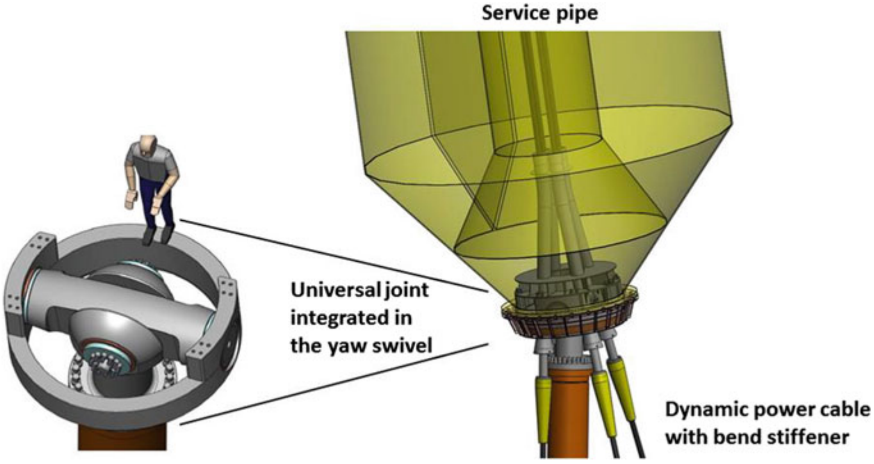


Fig. 44 Yaw system at the lower part of the tower

4.2 Concept Development

During the last years, Sway has successfully accomplished several technology milestones, which position the technology in one of the most developed stages compared to other existing designs. Figure 45 illustrates the technological evolution over last nine years, including a planned full-scale prototype.

In 2007, a 1:45 scale model tower was carefully tested by MARIN in their wave tank in the Netherlands. The results corresponded very closely to the simulations of the scaled down model. The tested and simulated static tilt of the tower varies from 2° at zero wind, up to 8° at rated wind speed. Above rated wind speed (12.5 m/s) the blade pitching to control the output power to 5 MW also reduces the rotor thrust forces. The wave-induced tower tilt variation is typically only ±0.5° at 8°.

In March 2011, Sway commissioned a 1:6.5 scale prototype off the coast of Norway near Kollsnes (northwest of Bergen) which was tested until the end of 2011. The objective of the model testing was to verify design assumptions and performance in a real environment, according to Technology Readiness Level 7. The testing was focused on the motions of the wind turbine/floating tower dynamics with the individual pitching control (IPC). The tower model had a total length of 29 m (16 m draught). It was installed at a water depth of 25 m. The initial testing was performed with an open loop control system demonstrating system stability, followed by a closed loop system, optimising control system variables for system motions versus power production maximisation. The testing was conducted in varying wind and sea conditions replicating appropriate full scale conditions. The

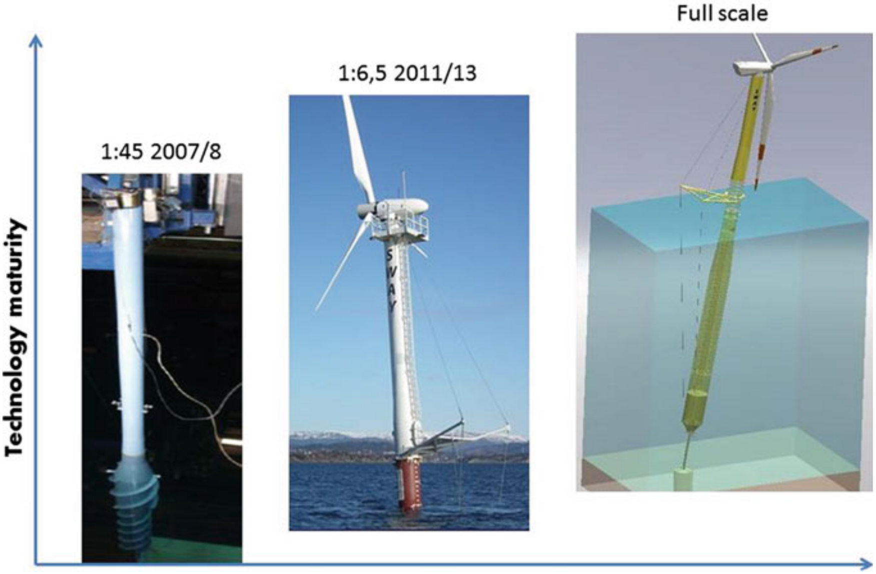


Fig. 45 Sway technology milestone

rotating tower was equipped with an aerodynamic fairing to reduce the turbulence level behind the tower for the down-wind rotor. The tests showed that this works well and no signature can be seen on the blade root bending moments when the blades passes the tower.

4.3 Prototype Testing

During the development of the Sway concept it was discovered that existing numerical design tools did not capture the design features of the Sway system, and a development program was initiated to develop a numerical tool, SwaySim based on the existing Usfos program suite (Fig. 46). Key features of the simulation program were validated through comparisons with available results, as well as through a small scale model test in moderate as well as extreme waves at MARIN in 2007 and 2008.

The validated SwaySim software was then used for further development and design of the Sway concept. In 2010, it was decided to validate the Sway concept through a large scale prototype, and funds were secured both from the owners as well as from public research funding. A scale of 1:6.5 of a 5 MW project would give a reasonably large tower, with a 7 kW turbine on top. The design of the scaled prototype was completed within a three-month period, with fabrication of the floating tower initiated immediately. The downwind configuration was the prime design focus at the time, and this concept required a downwind turbine with individual pitch control. Such a turbine was not commercially available, but a

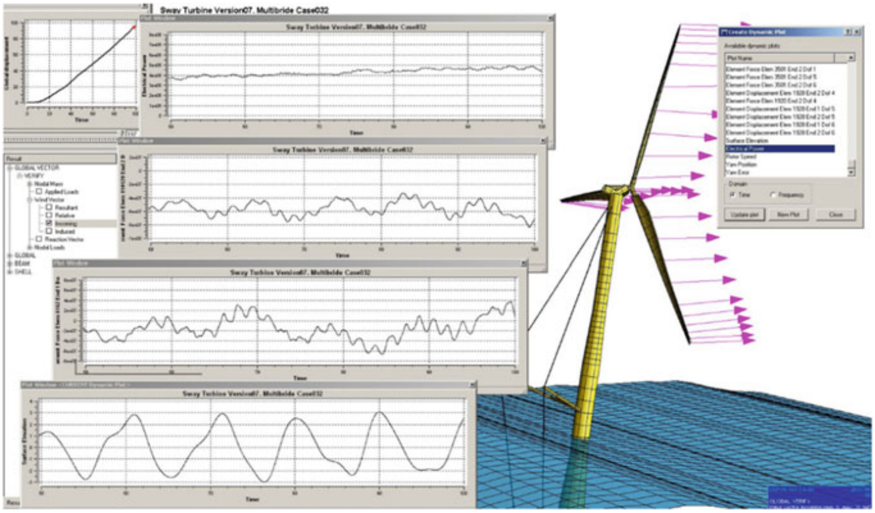


Fig. 46 SwaySim software

collaborative effort lead by Sway, with Step in Austria, Prototech in Norway, Garrad Hassan in UK and with blades from Denmark, resulted in a downwind scale turbine, with individual pitch control being designed and delivered within a four-month period.

The Sway scaled prototype was initially deployed in the spring of 2011, with testing in the fall. The installation was carried out outside Bergen, Norway, at Kollsnes, in protected waters which were intended to reflect scaled environmental conditions as shown in Figs. 47 and 48.

During a storm in December 2011, the wave heights exceeded 40 m in full scale, and were well outside the design conditions of the prototype. The water level in the J-tube inside the tower rose higher than the top of the J-tube for the scaled prototype. This flooded the tower and caused the device to sink. This incident was not linked to the concept as such and can easily be avoided in the full scale prototype (the root cause for this event is possible to avoid by having the J-tube termination at a higher level inside the tower, or alternatively have a water tight deck just below the top of the J-tube). The tower was recovered without any physical damage although the electronic equipment had to be replaced. The prototype was redeployed in the spring of 2012 with further testing carried out to the fall of 2013.

Fig. 47 Sway scaled prototype installed at Kollsnes, Norway

Fig. 48 Installed Sway scaled prototype

Through the prototype testing, the main concept features for the Sway device were demonstrated. These include the tower motions and stability with the producing downwind turbine on top, yaw bearing functionality and the yaw control through individual pitch control. The testing has also been used as a basis for several papers (Koh et al. 2013, 2015).

4.4 Commercialisation Pathway

Sway is a pioneer in the development of floating wind technologies, and is currently monitoring technology development projects and demonstrator projects that are carried out worldwide, in both benign and moderate sea conditions. These demonstrator projects will form a very good benchmarking basis for different concepts, and Sway welcomes results and commercial projects, which will open up the market for technically and economically advantageous concepts.

Further development and commercialising of the Sway concept will preferably involve industrial partners with key interests in the floating wind industry. On the other hand, this industry is only slowly evolving, with key projects mainly ongoing in Japan as well as UK and USA. Different stakeholders (government, academia, utility companies as well as industry) are currently spending significant time and resources in gaining knowledge and experience on design, installation and operation of floating wind.

Partnering for full scale projects in either stand-alone configuration (in conjunction with e.g. oil and gas applications or Baltic surface water circulation projects) will be likely routes for Sway in the future. Potential partners may either be industrial or financial, and will likely bring market presence to the table for initial projects.

Depending on market perception either an upwind/downwind catenary moored version of the Sway patents or a tension moored downwind version will be pursued. Further development will probably be focused on detail engineering and optimisation of the concept, as well as site specific engineering related to local conditions and regulations. Of particular interest for further investigations will be launching and tow-out methodologies from specific fabrication and assembly sites of interest. Sway has developed methodologies for different quayside water depths and for assembly both horizontally quayside and vertically at sea. The Sway tower can be towed both in a vertical position as well as in a slanted posture, depending on water depths available. More detailed studies of launching, tow-out and installations are likely to be requested for different demo sites, and may form part of the work ahead.

As a closing remark, Sway is looking forward to the upcoming commercialisation phase for floating wind power, which will have room for several design concepts, and where the Sway concept hopes to take a leading position.

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