Public Summary

The Sea-Air-Farm Project

Demonstrating the potential of far offshore floating airborne wind farms

Visualisation of offshore floating wind park with multiple Airborne Wind Energy systems

1. Executive Summary

Ampyx Power’s Airborne Wind Energy System (AWES) generates electricity from wind using an aircraft flying 500m high. Due to its small overturning moments, AWES could be deployed in deep water on small anchored floating platforms.

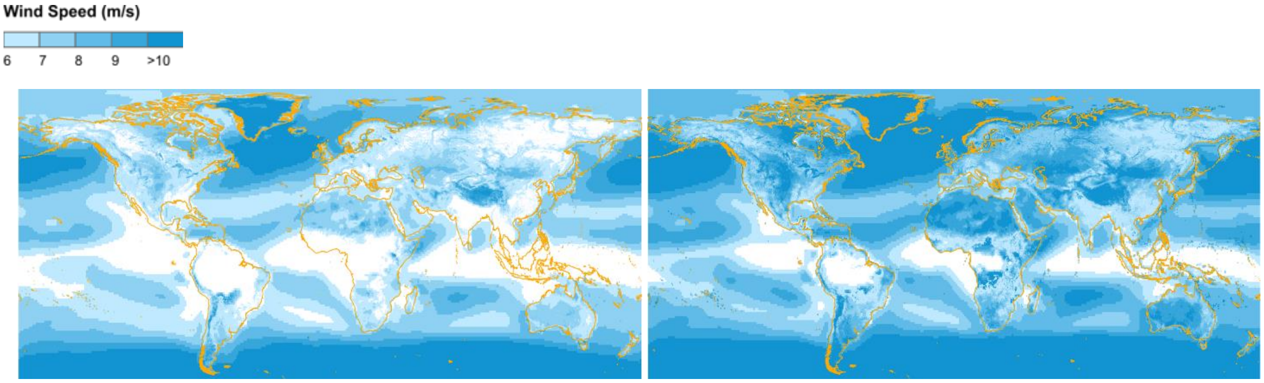
In the **Sea-Air-Farm project**, a consortium with Ampyx Power, ECN (Energy Research Centre Netherlands), Marin (Maritime Research Institute Netherlands) and Mocean Offshore researched the offshore application of one floating AWES and the possibilities and limitations of an entire airborne wind park with multiple systems, far-offshore and in deep waters.

The project research indicated that such a wind farm seems possible and competitive. In the following pages, the results are described in more detail.

Consortium partners and sponsors of the Sea-Air-Farm project.

2. What is Airborne Wind Energy?

Airborne Wind Energy (AWE) generates electricity from wind using airborne devices flying higher than the top of wind turbines in order to tap the stronger winds at these heights while avoiding the expense of tower construction. With AWE, wind deployment becomes economically feasible for more locations in the world.



Average wind speed at 100 m vs. 400 m

Ampyx Power is developing an ‘Airborne Wind Energy System’ (AWES) with an autonomous rigid wing aircraft that is tethered to a generator on the ground. It moves in a regular cross wind figure-8 pattern at an altitude from 200m up to 450m. When the aircraft moves, it pulls the tether which drives the generator. Once the tether is reeled out to a maximum length of ~750m, the aircraft automatically descends towards a lower altitude causing the tether to reel in. Then it ascends and repeats the process.

The aircraft performs fully automatically. The aircraft takes off, flies and lands from a platform. It generates power, lands when necessary, guides itself back to launch position and launches again when the wind picks up, all without the need for human interaction. All this is made possible by utilizing a vast array of sensors which provide the autopilot with critical information to perform the task safely.

3. Prototypes AP3, AP4

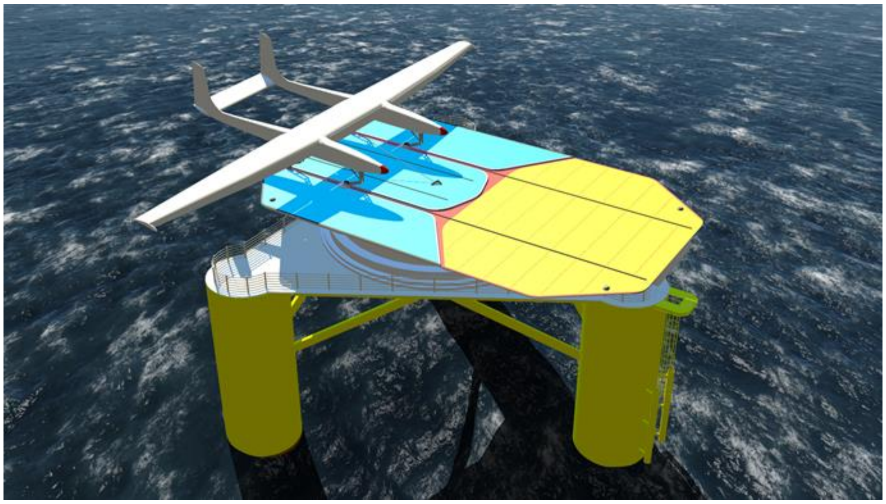
After 3 generations of prototypes (AP0-AP2) Ampyx Power has started the production of its 150kW prototype AP3 in 2017. This prototype is designed to demonstrate the safety and autonomous operation of the system. With AP4, the next upscaled prototype, the emphasis will shift to power generation, aiming at a capacity of 2 MW.

4. Why floating Airborne Wind Energy?

The availability of sites for conventional off-shore wind parks will become increasingly scarce in the future. This calls for expansion of the operating envelope of wind power technologies. The availability of sites is currently very much restricted to shallow waters. The cost of offshore wind power increases significantly with water depth, due to the increased costs of foundation works either bottom-fixed or floating. Due to its much smaller overturning moments, Ampyx Power AWES could be deployed on relatively small anchored floating platforms, allowing economical deployment of AWES in places where deployment of conventional offshore wind turbines is economically or technically impossible.

5. Sea-Air-Farm project

In August 2016 the Dutch ministry of Economic Affairs (RVO) granted subsidy to research the floating application of the Ampyx Power AWES under the TKI-WOZ R&D program. A project consortium with ECN (Energy Research Centre Netherlands), Marin (Maritime Research Institute Netherlands) and Mocean Offshore was formed to contribute to the technology development of floating AWES based on Ampyx Power's prototype AP4, and to explore the possibilities and limitations of an entire airborne windfarm with multiple systems, far-offshore and in deep waters. ECN validated the aerodynamic tools, modelled installation and O&M scenarios, and calculated the yield and costs. Mocean Offshore designed the floating platform, which was tested in Marin's test basin. Ampyx Power conceptually designed the AP4 aircraft and the entire offshore windfarm, studied the certification framework and managed the project.

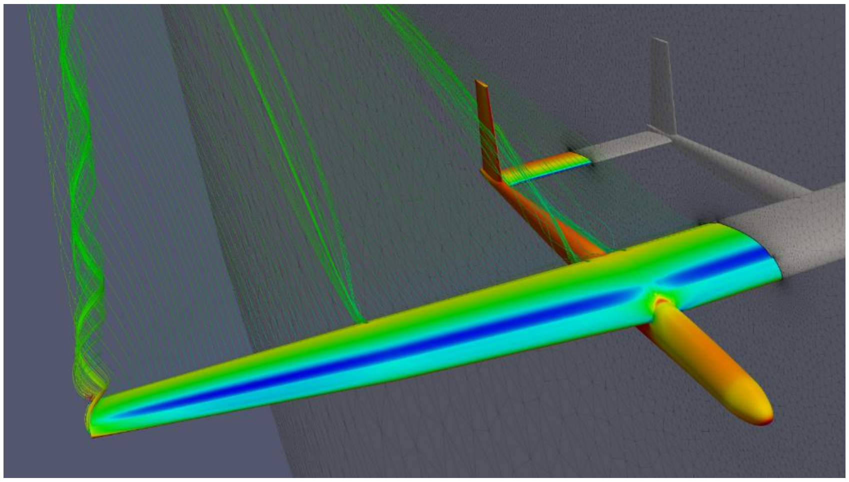


Floating Airborne Wind Energy System Ampyx Power

6. Third party aerodynamic model validation and integration

ECN validated Ampyx Power's aerodynamic models. First, they compared the results from two open-source 'Computational Fluid Dynamics' (CFD) solvers with different modeling approaches.

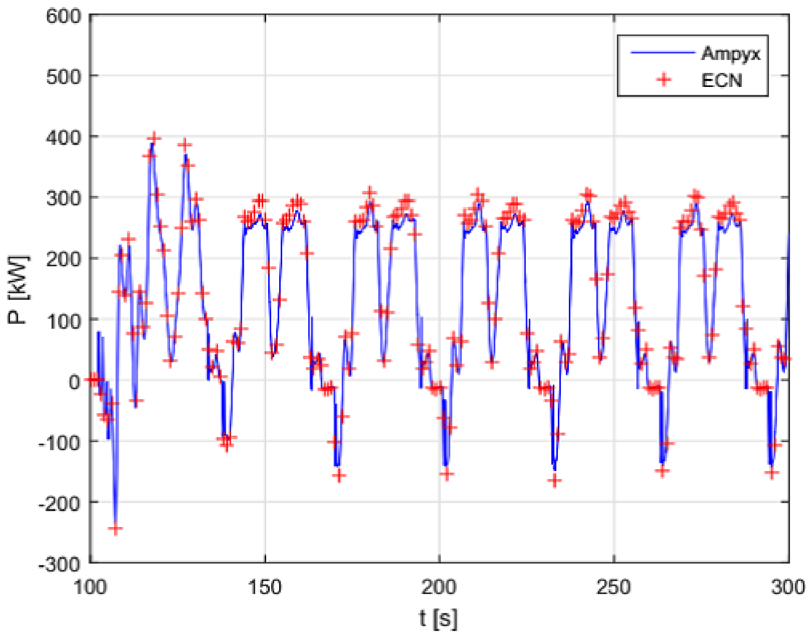
Ampyx Power uses a pressure-based solver 'OpenFOAM' to calculate the 2D and 3D aerodynamic performance of their aircrafts, while ECN compares these results with the CFD solution from a density-based solver 'SU2', developed for wind turbine technology. The comparison indicates extremely good agreements between the two codes in 2D. This sets a high level of confidence on the generated results. The 3D results from both codes show a good agreement on the force distribution along the aircraft, while achieving <20% difference in the total aerodynamic forces. Further investigation is required to identify the cause of this discrepancy. Overall, this verification study clearly shows the advancement in CFD to achieve an independent solution despite the different methods, and provides an in-depth understanding of the complex flow field around the aircraft and tether.



CFD model

Second step was for ECN to evaluate the power generated using a free vortex wake model coupled to the lifting line model, named Aerodynamic Windturbine Simulation Module (AWSM), one of ECN's software packages containing state-of-the-art aerodynamic models originally developed for horizontal axis wind turbines. In this framework, AWSM is used to calculate the aerodynamic forces generated by the aircraft and from there, deduce the power production at different wind speeds. The results provided by AWSM are verified against the simulations of a higher fidelity, but more computationally expensive computational fluid dynamics (CFD) code. The comparison shows a good agreement between the two approaches, confirming that relatively simple and efficient free vortex wake codes, like AWSM, can be used to obtain an accurate estimation of power generated by AWES.

The research showed a good agreement between the power prediction obtained by ECN and by Ampyx Power. ECN's power predictions are 5% higher than those of Ampyx Power for a wind speed of 15 m/s. A larger difference of 14% higher is seen at the cut-out wind speed of 25 m/s. These differences can be explained by the fact that Ampyx Power's CFD simulations include the full fuselage, whereas ECN's AWSM models only the wings of the aircraft.



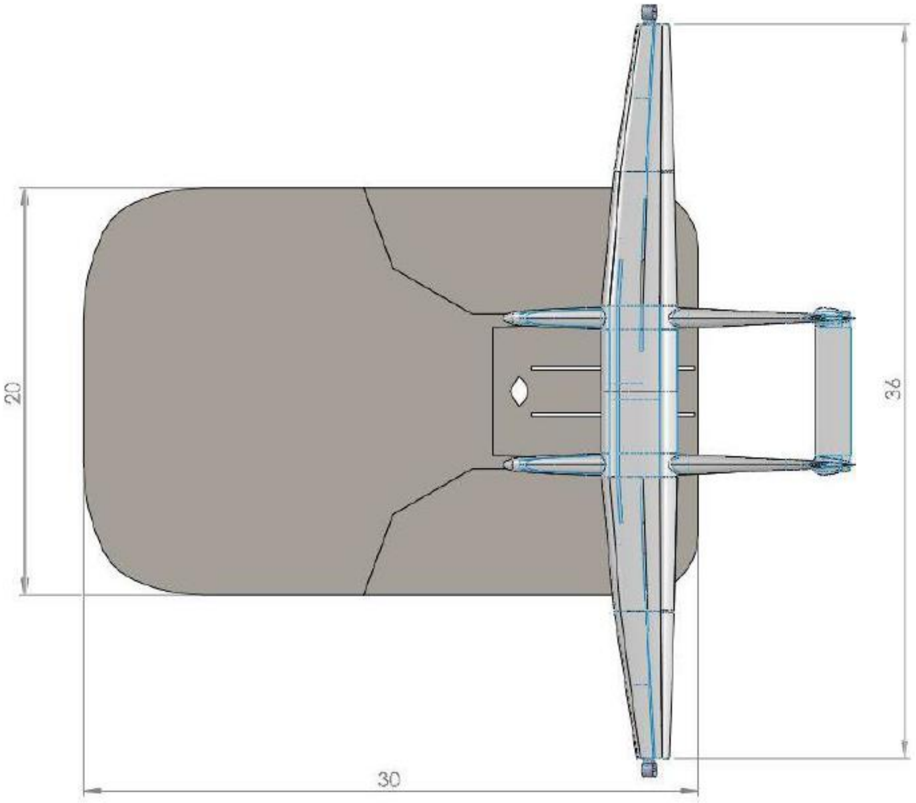
Power produced over time as modelled by Ampyx Power's CFD 6-DOF model and by ECN's AWSM model, for an AP3 at 15m/s wind speed at pattern height

Both AWSM and CFD models demonstrated that the wake effects of the AP4 aircraft were minimal: wake losses of 1% in a windfarm with a spacing of 600m, this is an order of magnitude smaller than for WTG's.

ECN validated the aerodynamic modelling tools used by Ampyx Power to define aerodynamic behaviour, power curve and wake losses, and found good agreements.

7. Conceptual Design AP-4

The project is based on the performance of Ampyx Power's AP3 design scaled-up to 2 MW cycle power size. Such an aircraft would have a span width of 36m and a weight of 3.5 Metric Tonnes, while the launch and land platform would measure around 20 x 30m.



Indicative dimensions of AP4's 2 MW aircraft on the launch and land platform.

However, a mere scaling of AP3 would not per se result in optimal performance, and hence Ampyx Power explored a range of design optimizations for the various sub-systems. They assessed the ability to follow optimal power production trajectories for different patterns, the pattern size and heights and tether lengths. This resulted in the identification of a number of considerations, which will be discussed below.

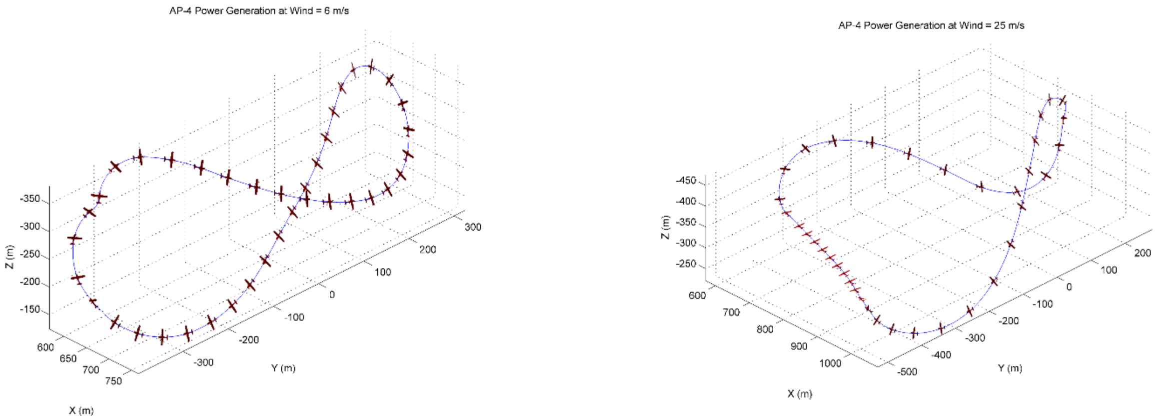
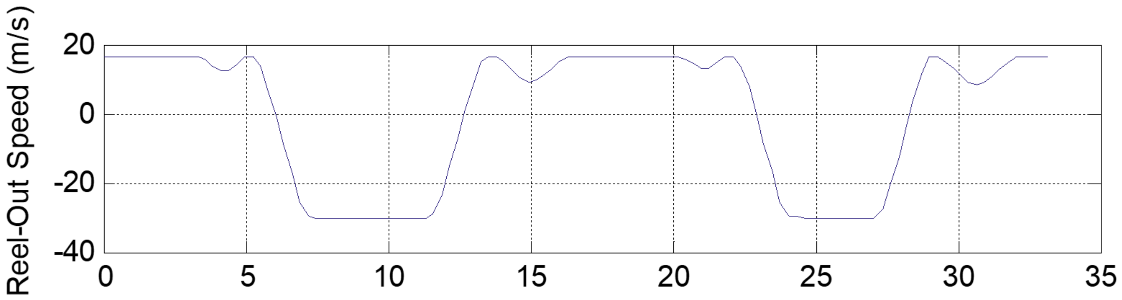


Illustration of the lemniscate trajectory at wind speeds of 6m/s (left) and 25m/s (right) at pattern height.

A combination of high-lift and high controllability is not obvious and becomes more critical as the aircraft size increases. While the size of the plane substantially triples from 12m wing span for AP3 to around 36m for AP4, the vertical space in which the aircraft flies its power production patterns does not increase. It becomes more and more important to fully optimize its configuration, roll behavior, and control effectiveness, all in relation to an optimal flight pattern for power production. The existing suite of aerodynamic tools does not provide the answers, and Ampyx Power has come to the conclusion that the best way to make progress in this complex field is through testing small scale models from various aircraft lay-outs at high velocities and under a wide operational envelope. Testing in water basins is an interesting option to explore, as it would allow to test small models at high relative velocities, while maintaining the correct Reynold figures.

The impact of the flying speed of the aircraft, in combination with the reel-in and reel-out speed of the tether was also assessed. The challenge will be for the integrated systems of generator, drive train, winch and tether to meet the speed requirements.

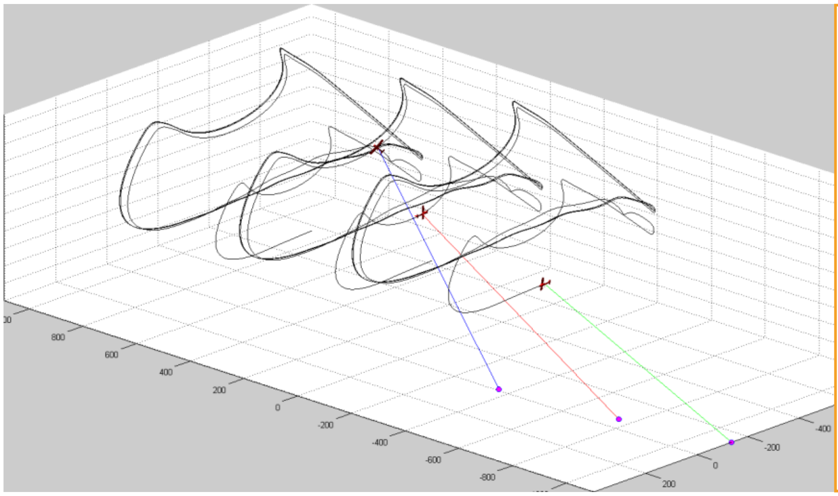


Optimal tether Reel-in and Reel-Out Speed over time (seconds) for lemniscate trajectory at 12 m/s wind speed at pattern height.

Main issues in the scaling are: the increased inertia of the drum, the heat production within the tether during repetitive bending over sheaves, slippage of the tether over the sheaves and drum, and the efficiency of the drive train/generator over the entire range of the cycle. Innovative solutions that can overcome these challenges have been identified; however, they should be further worked out and de-risked by building and testing partial prototypes (breadboards).

The modelling of 2MW system, including aircraft, tether and winch hinted to a number of scaling challenges with respect to the controllability of the aircraft and efficient mechanical power transfer. Solutions exist, but need to be worked out and validated.

Within an AWES windfarm, multiple aircrafts will fly simultaneously within each other's zone of operation. Model testing demonstrated that Ampyx Power's control strategies have the potential to enable synchronous flights from a spacing of around 350m. Such flying requires a window of only a few seconds to correct any deviation from the prescribed pattern and to avoid contact with the neighbor's plane or tether. The control system is accurate enough to match this requirement. However, remaining issues still to be investigated are: how to deal with wind shifts over the windfarm, how to deal with emergencies (such as tether release), and how to smoothen the park power output.



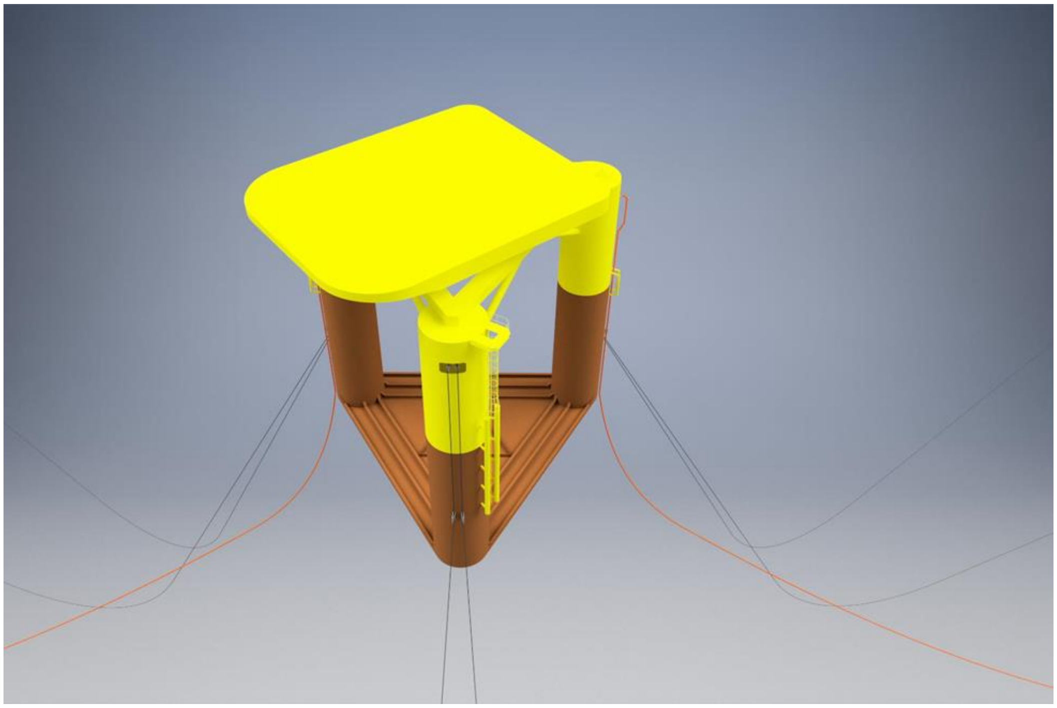
Model testing demonstrated that Ampyx Power's control strategies have the potential to enable synchronous flights from a spacing of around 350m, with a tether length of up to 750m.

3D visualization of the interference with platforms of approximately 350m apart.

8. Floating Platform design

Visual comparison between three, 2MW AP-4 systems on floating platforms, next to a 6MW WTG on a spar (Hywind design). Important to note is the difference in draught, which enables the Sea-Air-Farm solution to be towed to most ports, contrary to the spar design.

Mocean designed the floating platform following a methodical design procedure with parametric optimization using numerical simulations based on a 9-year metocean datafile.



The selected floater concept consists of a three-column semisubmersible floating structure, with a free-floating water displacement of 1259 mt, and a structural mass of 491 mt. The draught is 11m without any ballast, and 16m under full load. The catenary mooring system uses drag embedded anchors and results in a footprint radius of 500m. For the inter array cables, a 'Lazy S' overlength solution has been chosen, using subsea buoyancy.

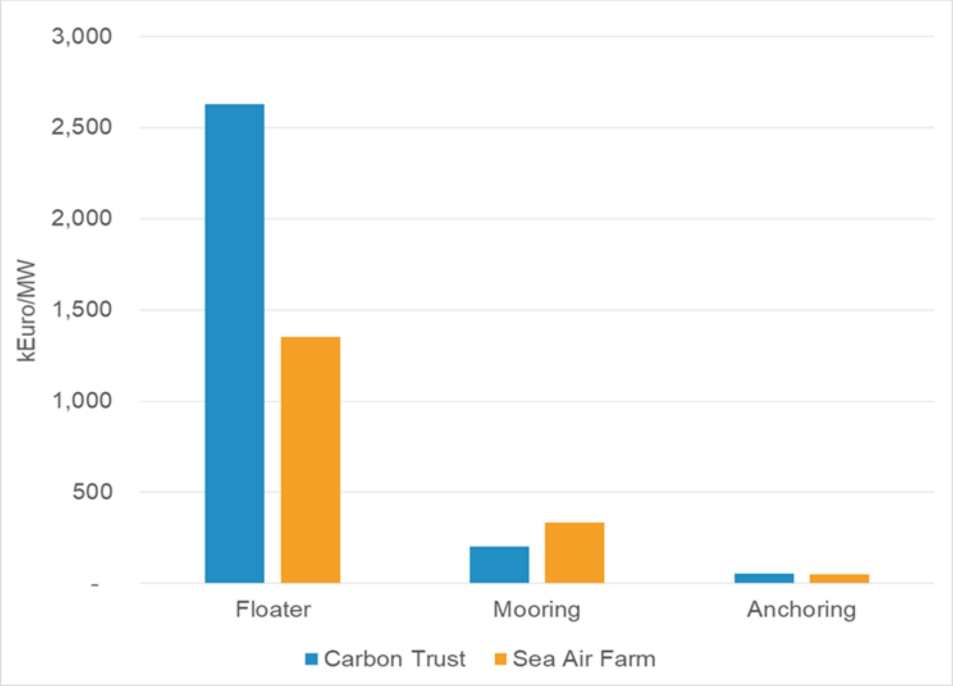
The dynamic response of the unit is assessed using numerical time domain simulations. For the Ultimate Limit State, 50-years storm conditions were applied (Hs = 9.9 m, Tp = 12.4 s, wind speed 27 m/s, current 1.8 m/s). During these conditions, a maximum roll angle of 23° was found, while the main deck area is kept free of wave impacts.

During Service Limit State, the following conditions were applied: Hs up to 3.5m with 4 different Tps, wind speed up to 15 m/s, current speed up to 0.8 m. A maximum roll angle of 12° and a maximum lateral offset of 7 m were found. These motions were substantially determined by the overturning moment caused by the tether forces.

Array cable loads have been derived from the simulations and pass the acceptance criteria (100kN compression and .48rad/m bending).

During the project, Marin performed scale model tests, which provide an accurate indication of the damping coefficients of the platform. A calibration study of Mocean's numerical models showed that the damping of the model tests is higher than used in the numerical simulations, the results can therefore be interpreted as conservative.

A section of 10 units was modelled in a 3D environment to ensure that no contact occurs between the unsupported part of the array cable and the mooring lines under various extreme conditions.



Comparison of the costs/MW of Mocean's AP4-floater to the costs for a comparable WTG-floater. As it is the survival conditions of the platform that are driving the design, and not the weight or forces from the AWES. So, future scaling up will hardly affect the weight or cost of the floater.

Mocean analysed both the production costs and the installation costs for various scenarios for the load out, ballasting, transport and installation of the units. The results form the basis of ECN's installation modelling. Key in the logistics analysis is the limited draught of only 11m in unballasted conditions; however, (partial) ballasting is required to increase stability before going offshore. Ampyx Power explored the landing of its aircraft on Mocean's platform design. The landing modelling integrated Ampyx Power's landing algorithms, platform movements due to waves, and plane movements due to gusts, all modelled in Monte-Carlo simulations from the 9-years

Buchan Deep metocean wind and wave dataset. The results showed that the limiting factor in safe landing are the wind gusts rather than the platform movements. While the platform dampens out the relatively small high-frequency movements, the larger platform movements are at such a low frequencies that the aircraft's landing algorithms can correct for it.

> Mocean's design of the floater resulted in a semi-submersible platform that fulfills all the requirements for a safe operation in offshore conditions. The movements of the platform have considerably less impact on landing than initially expected. Future design iterations will lead to further optimization and considerable cost reductions. It is the survival conditions of the platform that are driving the design, and not the weight or forces from the AWES. So, future scaling up will hardly affect the weight or cost of the floater.

The low initial draught of around 11m is a unique selling point for this floater, as it allows most ports to serve as marshalling harbor - contrary to most of the floating competition. The main aim for another future design iteration should be to further reduce the draught / increase the stability before ballasting. (Also the limited height of the system consist of a competitive advantage, as it allows production behind bridges)

Based on the initial assumptions, it was concluded that a soft mooring would be the best option. Considering the considerable horizontal movement during power generation, the environmental impact of the mooring chains, and having reduced the assumption of the distance between facilities (from around 700m to around 350m), it would be useful to re-assess the optimal mooring. It may turn out that semi-taught foundations or even a Tension Leg Platform (TLP) is a competitive alternative.

9. Marine modelling of the floating platform

The scale testing in the basin of Marin proved to add significant value to the existing design tools, mainly because of the different scaling of the AP4 floater compared to other marine structures that are much larger. Scaling and modelling the wave loading and mooring forces on floating structures is common practice at Marin; however, for the simulation of the tether forces on the platform, a novel system of 4 winches was designed, which jointly simulated the direction and tension from the forces during power production.

The testing was successful and provided important feed-back on the validity and sensitivity of several design parameters.

Floater in Marin's water basin

10. Deepwater wind farm design

In order to develop insights in the operations and costs of an entire AWES windfarm, a virtual wind farm was designed. We selected the Buchan Deep site in the East of Scotland. An important consideration was the fact that Statoil has built its Hywind offshore demonstrator on this location, and hence a lot of environmental and soil data are available in the public domain. In addition, 9 years of wind and wave data have been purchased for the design, modelling and testing work of all project partners.

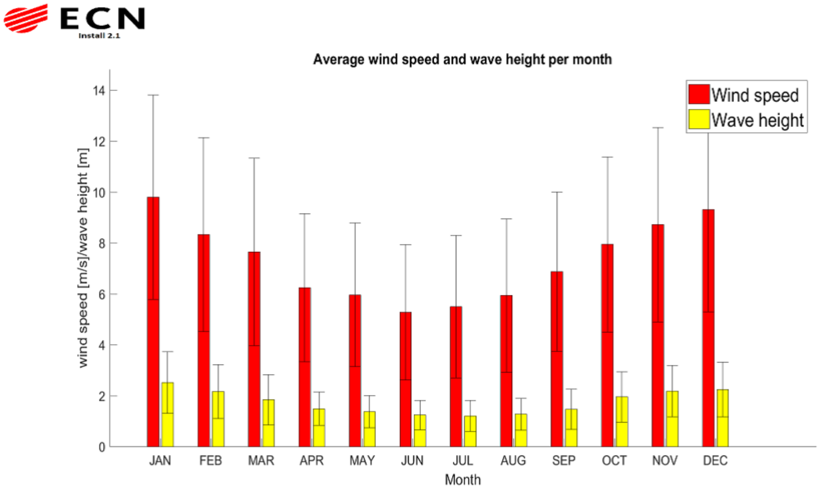
Annual average wind speed of 9.7 m/s at 400m altitude

Annual average significant wave height of 1.75m

10 year maximum significant wave height 9.5 m

Water depth around 100m

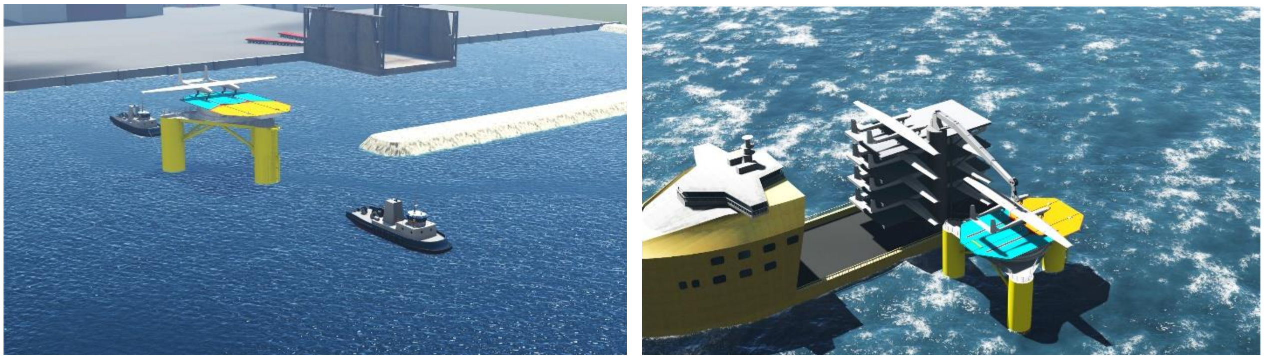
25km from Peterhead, taken as marshalling harbour



Metocean conditions at the Buchan Deep site, as derived from the 9 years dataset

11. Installation and O&M strategy

ECN modelled a range of installation and O&M strategies in close consultation with Ampyx Power and Mocean. The winning strategies make best use of the main advantage of the floater: its limited draught of around 11m in unballasted conditions. This enables easy and cheap submersing and towing, and eliminates the need for expensive cranes, while a vast majority of ports can be used as marshalling harbour. The large amount of 175 facilities justifies a dedicated Platform Service Vessel (PSV), which can be tailored to this application. While all the inspections and small repairs will be done on the floating platforms, for larger repairs the planes can easily be lifted on board of the PSV with a heave compensated crane. If major refits of the equipment inside the floater are required, the entire facility can be disconnected and towed to port.



The entire floating platforms can be easily towed offshore, while the lightweight aircrafts can be easily lifted onboard a dedicated Platform Service Vessel.

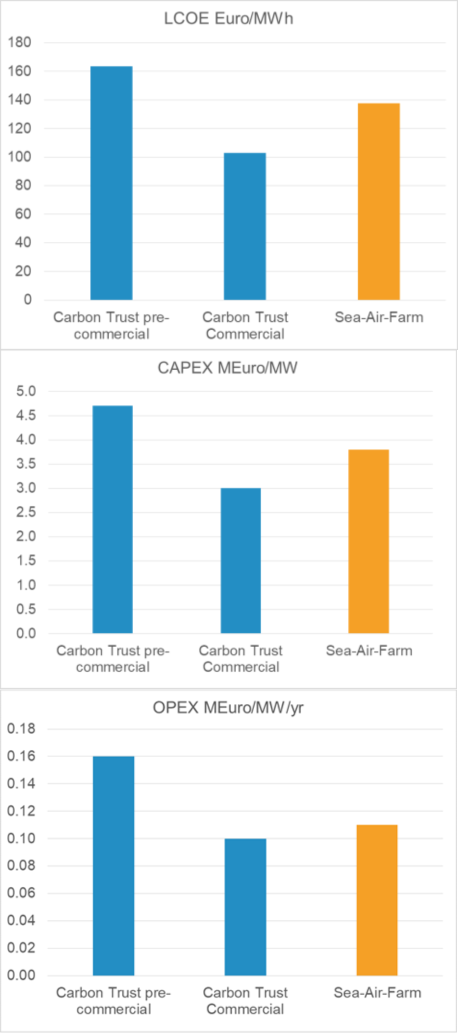
The O&M modelling demonstrated that the AP4 concept can be maintained, provided a specialized organization is set-up and dedicated tools are developed.

The O&M model and strategies have been built on important assumptions regarding inspection intervals and Mean Time Between Failure. The most important next step in this process is to align these assumptions with the component suppliers and with the certifying authorities. The first can only be done when the design of the AP4 is further progressed, the latter should start immediately.

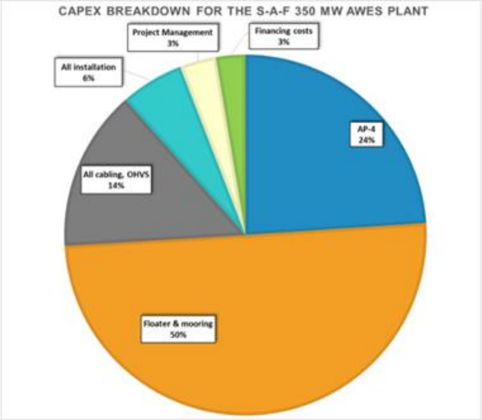
Furthermore, the O&M strategies have been optimized for a large-scale windfarm of 175 facilities. However, offshore implementation will start on a much smaller scale. It would be useful to review the O&M strategies and tools for such small windfarms. It is expected that an alternative to the dedicated PSV will have to be developed.

12. Levelized Cost of Energy (LCoE)

Based on all the project results as described above, ECN modelled the Annual Electricity Production at Buchan Deep to be 3,3MWh/MW/yr at an availability of slightly above 95%. This results in a LCoE of 137 Euro/MWh.



Charts comparing the LCoE results from ECN's S-A-F modelling with state-of-the art values as found in the Carbon trust [‘Floating offshore wind market and technology review, 2015’.](#)



A sensitivity study was conducted to illustrate the importance of the site-specific wind and wave conditions. An alternative location is chosen in a much calmer part of the North Sea: measurement platform K13. Although Buchan Deep has more severe waves compared to K13 (Hs, avg = 1.8m to 1.4m respectively), its wind regime is considerably lower. Therefore, the accessibility of installation and O&M vessels is much higher in K13, while higher yield in operations. The installation delay reduces by almost 30%, the installation cost is lowered by 4.5%. The annual energy production increases by 21.5% while the OPEX reduces by 21%. This results in the overall LCoE reduction of 19% to around 111€/MWh.

ECN's extensive cost modelling resulted in a LCoE of around 137 €/MWh for floating application on the Buchan Deep site, while a more favourable site (K13) would even result in 19% lower figures due to better wind resource while less waves. Such figures are quite promising, given the fact that MW-scale AWES are still at the very early stages of their technological and commercial development, and significant further cost reductions can be expected in the future.

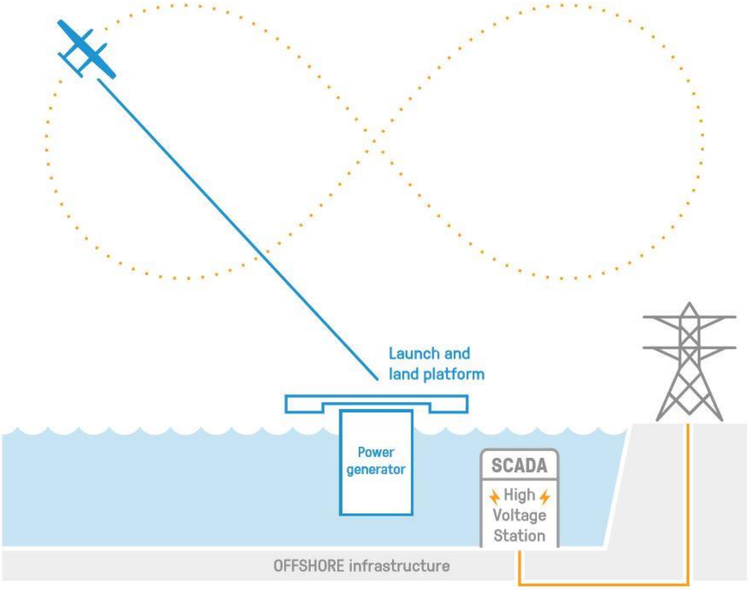
The main uncertainty in the current LCoE calculations were the costs, the lifetime and the performance of AP4 components. More detailed LCoE calculations can only be done when the design of the AP4 is further progressed.

13. Certification

The project made an extensive inventory of all certifying bodies and authorities involved in flying drones as well as floating devices, and their relevant guidelines and best practices. This review confirmed that only some scattered and loose requirements exist, and there is nowhere a start of any coherent framework.

In order to make a step forward in this, Ampyx Power has prepared a certification basis proposal for AWES based on tethered drones (CS-AP), to be submitted for acceptance to the European Aviation Safety Authority (EASA). Once accepted by EASA, we could make CS-AP available as a starting point certification basis for all tethered drone developments. Therefore, this specification can benefit the entire AWE community - and possibly beyond. Following expert consultation, EASA may eventually turn it into a Special Condition or Certification Specification for AWES.

This process has full support from Ampyx Power and EASA, however it is widely unknown amongst the remaining stakeholders (SODM, RWS, ILT, Grid owners, certifying bodies, utilities, insurers etc…). In order to gain broad acceptance of the CS-AP, an extensive consensus- and awareness-building campaign is required.



All blue sub-systems are to be certified in compliance with European Aviation Safety Authority (EASA) regulations. The grey/yellow sub-systems will have different certification authorities.

In addition to the certification aspects, also the consenting framework for AWE is virtually non-existing. Neither is the methodological framework to assess the environmental impact. As AWE develops beyond the prototyping stages, a tremendous amount of work will need to be done in this field.

14. External Communication

All project partners have presented project results at a wide range of national and international fora; copies of these presentations can be obtained from the respective partners. An animation that visualizes the installation and operation of the offshore windfarm, can be found on Youtube.

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