Index - Final Report

1. Final report

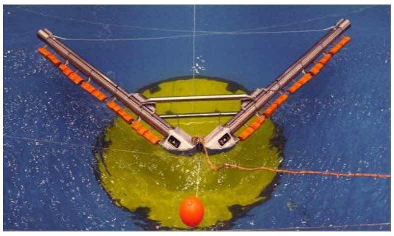
1.1 Project details

Project title	Weptos WEC Hanstholm
Project identification	Energinet.dk project no. 2013-1-12039
Name of the programme which has funded the project (ForskVE, ForskNG or ForskEL)	ForskEL
Name and address of the enterprises/institution responsible for the project	Weptos A/S, Prins Georgs Kvarter 11, 7000 Fredericia
CVR (central business register)	15649089
Date for submission	09.06.2015

1.2 Executive summary

The Weptos project was prospectively divided into 3 phases, and project plans and budget have been made until the ending of phase 3, where a decision on further commercial development can be made.

Phase 1: Construction and testing of WEPTOS Lab. model
Phase 2: Engineering and construction of large-scale test model (Kattegat)
Phase 3: Putting at sea and test of large-scale test model (Kattegat)



Phase 1: Model tests providing detailed power performance data

Phase 2: Detailed engineering providing reliable cost data

Phase 3: Construction and full scale testing and demonstration

To describe and communicate the new design, we have published an animation with relatively detailed documenting of the design and function of the Weptos WEC. Please visit www.weptos.com for further information.

Funding for phase 2 was applied for in September 2012 (ForskEL) and was prioritised for and approved in December 2012.

In August/September 2014 an additional funding was applied for and granted for the project.

The added value achieved by this was a significantly better knowledge and data for the determination and calculation of the structure and anchoring, greater risk-hedging of critical components (PTO and anchoring), ability of international marketing of the project. Hereto also knowledge sharing with international university as the project has been given the opportunity to test the model at FloWave TT Ocean Energy Research Facility - Edinburgh University, using 3D waves and with ocean currents - the results from this is of significant importance.

The WEPTOS wave energy converter, of which the shape of the rotors have been inspired from the Salter's duck WEC (invented in 1974), is currently being developed by Tommy Larsen of WEPTOS, Denmark. The WEPTOS WEC is a rotating structure, composed of two symmetrical frames that support a multitude of identical rotors. All the rotors that are connected to the same frame are co-axial and induce torque to a common axle. Another particularity of this concept is that the angle between the two main frames is adjustable. This allows the device to adapt its configuration relative to the wave conditions, improving its stability and survivability, and reducing its required installed power while inducing a high capacity factor.

Phase 2 (which is the objective of the current project 2013-1-12039) has the objective to design, optimize, test and engineer the rotors and power take-off, as well as the main structure, of the device. This will provide a detailed description of the costs and provide a full-scale Weptos design ready for construction phase (Phase 3) at project completion. This phase has been composed out of several different R&D projects, which are:

- The first part of the present project has been to identify the wave loads on the rotor and the loads that the rotors would transfer to the structure.
- Then the outline for testing a new PTO (power take off) combined with possible findings about the geometry of the rotor was established. For proof of concept for the new configuration, experiments have been initiated building a smaller scale model to test at Aalborg University, Department of Civil Engineering and subsequent analyses and evaluation have been done and compared with previous results. Both the PTO and geometry of the rotor fulfilled the expectations we had for the improvements that we had developed.
- At this point, we then had found more detailed solutions to the main elements and were optimistic about the possibilities of obtaining a high level of detail of the design in the technology, as next step was – Design, model testing and engineering of the main structure. A miniature lab model was produced, designed to meet the exact weight ratio in all details, and was a reliable and comparable way to test towards a full scale WEC. The tests of this in the "Deep Basin" at AAU are considered to be validating for the full scale WEC regarding the new design and the implementation of the new developments. Especially more detailed information of the loads in the lightweight structure and mooring was investigated. The structural loads have significantly been reduced in the latest miniature model. This mainly results from the new design of the structure, which has been changed in to a relatively small, lightweight and shorter structure from a relatively heavy structure that was much more imposing than the rotors themselves and twice longer.
- Experimental tests have also been performed – with positive outcomes and overalls success - at the advanced FloWave TT facilities at the Edinburgh University. The test campaign at FloWave TT was analysing the influence of currents, the misalignment of the scaled model with the wave direction, 3D waves, bi-modal seas and extreme wave conditions. In general, it can be concluded that the Weptos WEC can handle all different conditions without any particular risk, due to its weather vaning system, its mooring design and its efficient safety mechanism (corresponding to closing the opening angle of the scaled model in larger wave conditions). It will be directed into

the waves or the currents, depending on which induces the largest forces, while it can handle the waves and currents from any direction (whenever the other one is larger), in the range of the tested parameters (100 years wave and 1.5 m/s currents).

- A report has been made regarding the benchmark of WECs, which we consider a milestone showing the Weptos technology as convincing. The goal of this study is to provide a technological and economic comparative analysis of different Wave Energy Converters (WECs) at various development stages.
- A study has been performed on the Levelized Cost of Energy of a 90 MW Weptos WEC project. This work has been done in analogy with the Cost of Energy calculations made in the wind energy sector, which makes the outcomes very comparable. Conclusions are that the Weptos WEC appears to have a levelized cost of energy (LCoE) in the same range as offshore wind turbines (0.128 k€/kWh against 0.129 k€/kWh).

1.3 Project results

The Weptos wave energy converter (WEC) has been through a rigorous research and development (R&D), which has brought it to the forefront of the wave energy sector.

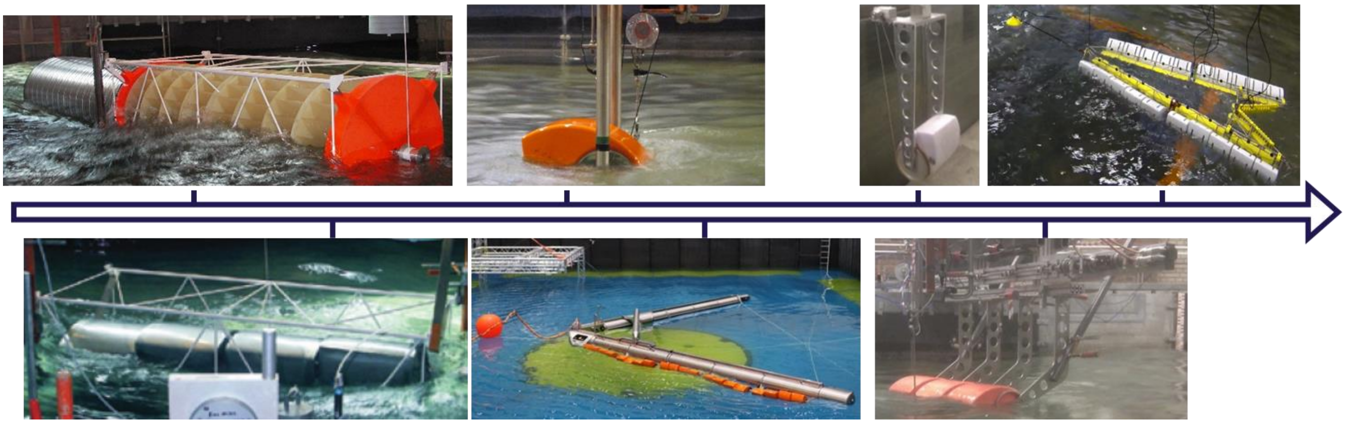


Figure 1: Overview of the test models.

The Weptos technology brings high power performance, based on proven Salter's ducks design, with high power to weight ratio, high load factor and efficient storm survival mechanism (resulting in low extreme-to-average structural and mooring load ratios) all together. This leads to a multi megawatt device that, with a light support structure, can handle storm conditions, resulting in rigorously estimated Cost-of-Energy figures that in the long term (commercial deployment) are more than competitive with offshore wind turbines.

1.3.1 The main design updates

The main changes to the design of the Weptos WEC, which have been made during this project, are given in the following list. These following details of the machine have been designed and engineered in details, including specifications, shop drawings and manufacturing process.

Review on the Rotor, including:

- The rotor design
- Materials
- The rotor structure incl. bearings, PTO connection to the rotor and safety mode function for the rotor
- Manufacturing process for the rotor

Review on the PTO, including:

- Detailed design and engineering of the PTO system
- Rotor to axle power transfer system
- Design and engineering of power transmission axle with shaft, bearings and couplings
- Generator system including gearbox and power electronics

Review on the structure, including:

- Updated design and engineering of the bearing structure
- New principle of structure to control angle
- New design of the bridge and boat landing

Review on the mooring, including:

- Review on the mooring concept
- Detailed design and engineering of the whole mooring and electrical cable system

Review on the safety mechanism, including:

- Review on the angle adjustment system

1.3.2 The test campaigns

These changes have resulted from extensive R&D, including various experimental test campaigns. These test campaigns with their main specifications and outcomes are:

The "Wave loads on rotor model" experimental test campaign aimed at measuring the wave loads on the rotors and the loads that the rotor would transfer to the structure of the Weptos WEC (Pecher & Kofoed, 2013b).

Figure 2: The "wave load on rotor model".

The main outcomes were the wave impact forces on rotors coming from different directions and loads from rotor transferred to WEC structure.

The "3-rotor PTO test model" experimental test campaign was constituted of an advanced power take off (PTO) and modular generator system. This lead to many significant changes and improvements in the PTO design and control. This model will often be used again in the future to test modifications to the PTO design and control (Pecher & Kofoed, 2013a). One of the main outcomes of this test model was the implementation of a 2-way PTO system, meaning that the rotors transfer power to the common axle during both up- and downward motions.

Figure 3: The PTO test model, where the new design of the PTO was tested and optimized.

The main outcomes were the validation of the new PTO system with 2 way acting PTO (up and down stroke of rotors), improved design of the rotors (width, inertia, design , …), improved configuration of the rotors (space between them vs power absorption and smoothening), optimized PTO control.

The "structure and mooring test model" experimental test campaign was using a very accurate model reproduction of what is intended to be the full scale device, in design as well as in weight, and thereby incorporated also the updated structure.

This test model has been used during two tests campaigns. The first one investigated and optimised the new mooring design and provided measurements of the structural and mooring loads, up to 100 year wave conditions in shallow water conditions (Pecher & Kofoed, 2014a). The second test campaign was performed in deeper water conditions at FloWave TT (UK), where wave current interactions, 3D waves and bi-modal seas were the main focus (Pecher & Kofoed, 2014b), and was made possible by the additional funding from ForskEL, autumn 2014, as well as MARINET (EU FP7) providing the access to FloWave TT.

These two test campaigns have provided a wide range of reliable data relative to the mooring, structure and the motion of the WEC under many different wave conditions. Herewith, reliable estimations of maximum forces to dimension the main structure can be made and also more accurate performance estimations, due to insight in wave current estimations.

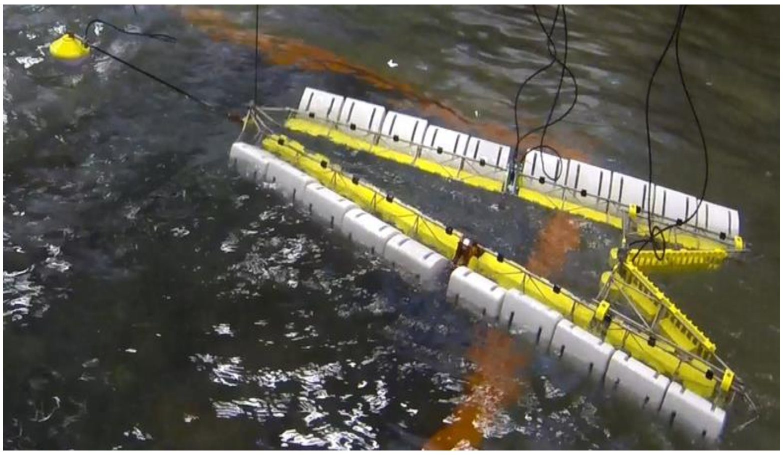


Figure 4: The second full model, representing the new structural design and resulting in a reliable mooring design.

The main outcomes were the validation and improved mooring design, validation of new structural design and measurement of structural and mooring loads in power production and extreme wave conditions, motions of the WEC, and in shallow and deep water conditions. Wave-current interaction on the WEC in power production and extreme wave conditions, with different opening angles. Structural and mooring loads under different directional spreading of 3D waves and bi-modal seas.

Figure 5: The small-scale model in the FloWave test facilities

1.3.3 The main technical project results

The structural designs has gained great improvement, its characteristics are:

- Very light-weight structure, where a large part (over 50 % depending on the scale) of the total weight corresponds to ballast in the rotors.
- The adaptable opening angle of the structure enables to regulate the incoming wave power, and thereby to maximize the use of the generator system, and to control the structural and mooring loads.
- The loads in extreme wave conditions are kept in the same range as the once in power production sea states, as by closing the opening angle down to 13°. At the same time, this changes the structure from a cantilever to a simple supported beam and thereby a strong triangular structure is being made with minimal projected wave front.

Figure 6 presents the resulting bending moment in the middle of a leg of the Weptos WEC for different opening angles and sea states (from mild power production sea states up to a 100 year storm). This was obtained with the structure and mooring full test model and for the environmental conditions at DanWEC Point 1 (DanWEC, 2010).

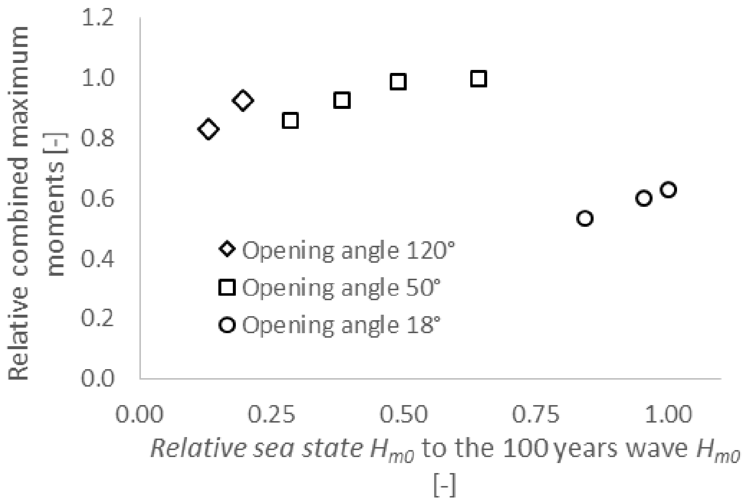


Figure 6: The relative maximum combined bending moments in the middle of a leg of the structure against the relative significant wave height (Pecher & Kofoed, 2014a).

The basics of the PTO design were present from the beginning, but still has been significantly upgraded.

Its characteristics are:

- Fully mechanical transmission, resulting in very high efficiency.
- Power transmission from the rotors to the axle at both up and down strokes of the rotors. Enables to maintain approximately the same rotational speed and smoothening factor as with twice the amount of rotors (with a one way PTO system).
- The transmission between rotor and power transmission axle gears up the rotational speed and simultaneously torque down at a very early stage of the PTO system.
- Generator house is integrated in structure and located in the middle of the leg, in order to half the torque at the end of the axle (compared to having the generator house at an end of the legs).

The power production benefits from the efficient rotors and the A-shaped design of the WEC. The main characteristics of the power production are:

- Low average to peak ratio during power production. This results from the A-shape of the structure, which naturally smoothens out the power production by de-phasing the absorbed power by the different rotors, and the two way PTO system, which transfers power from the rotors at any up or downward movement.
- High load factor, which is the ratio between yearly average power production and installed generator capacity, is due to the low peak-to-average ratio of power production and the adaptable opening angle of the WEC, which enables to regulate the amount of incoming wave power. A larger opening angle (up to 120°) will be used in small wave conditions, which maximizes the exposed width , while this gets gradually reduced with increasing wave conditions, when the installed capacity of the generator system is reached (and thereby wave power).
- Scale of the WEC can be adapted in order to optimize the power production and LCoE to a specific location. This mainly corresponds to having the right rotor size for the corresponding wave conditions. In general it can be assumed that the larger the rotor is, the larger its wave absorbing capability is.

- The power production can also be increased by having more rotors on a single Weptos WEC. This increases its power production approx. linearly.
- Broad bandwidth of the wave-to-wire efficiency due to the high efficiency of the whole power transmission chain and the adaptable opening angle between the legs.

A new mooring design has been developed, which is very simple and efficient. It has shown to be usable and reliable even in shallow water conditions with the Weptos WEC. Its main characteristics are:

- Safe and reliable mooring design due to its simplicity and high safety factor (which is easy to incorporate).
- Allows 360° weather-vaning of the system
- Very low footprint on seabed
- Maximum WEC excursion due to wave loading is approximately equal to the water depth.
- Easy (dis-)connection system of the WEC.

The following figure presents the resulting forces in the hawser of the mooring system under calibration and a 100 year storm for the environmental conditions at DanWEC Point 1. The calibration was obtained by manually pulling the WEC backwards (in surge) up to stretching the two main mooring members.

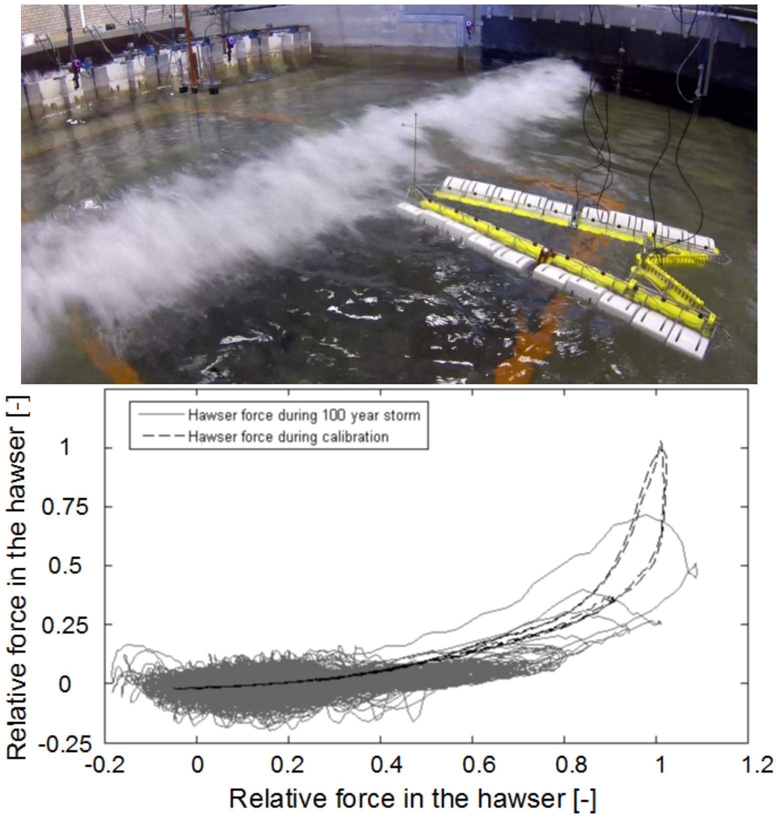


Figure 7: The top picture shows a breaking wave during a 100 years storm test. The bottom graph illustrates the relative force in the hawser against the relative significant wave height, obtained with the structure and mooring model. The manual mooring calibration curve and the resulting hawser force during a 100 year storm in shallow waters are given (Pecher & Kofoed, 2014a).

1.3.4 Benchmark Study (Techno-economic assessment)

Throughout the research & development of the Weptos technology, its LCoE has been estimated. This is perceived to be very important as it shows if any further research & development efforts are still required and if that effort is worth of it at all. As, if a technology in development does not have a TPL between 7 and 9, it is not commercially-viable (Weber, 2012).

This benchmark study has carried out a comparative analysis of the development stage of eight different wave energy converters, both in technical and in economic terms. The outcome of the analysis are presented in the related report, a short summary will be given here.

In figure 8, a TPL-TRL matrix is presented that is used to illustrate how economic a technology can become and how far it is through its developments (Weber, 2012). This TPL-TRL matrix represents one of the main outcomes of the study as it presents the TPL-TRL of Weptos together with the estimated current TPL-TRL levels of some of the leading wave energy converters (Fernández-chozas, Pecher, & Kofoed, 2014).

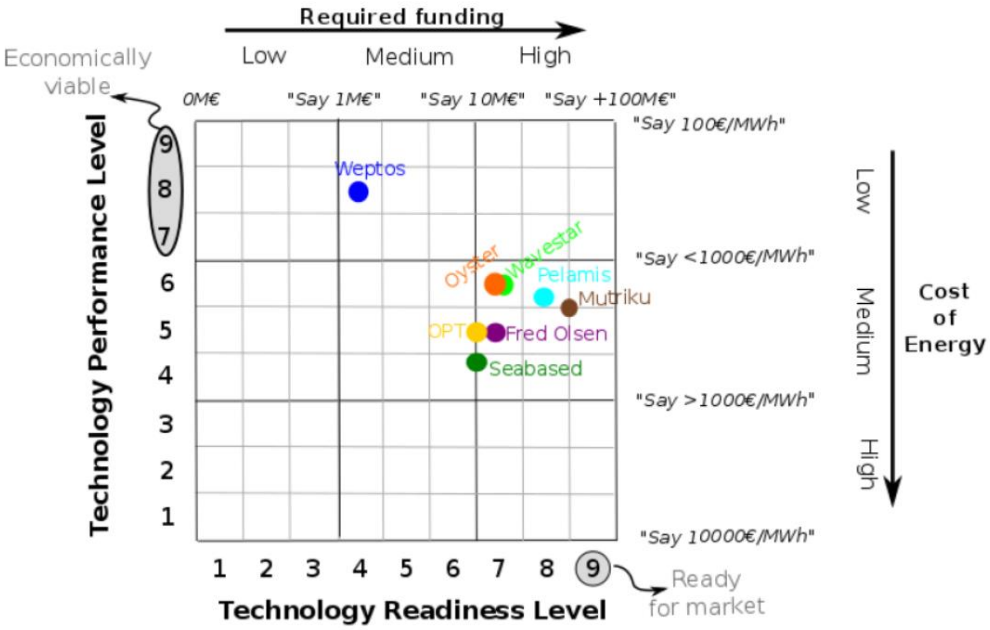


Figure 8: The development trajectory of the Weptos WEC, together with the current estimated TRL-TPL of some of the leading wave energy technologies.

Note that currently offshore wind turbines are at a TRL of 9 and a TPL of 8.

The matrix shows that all the WECs but Weptos, are at higher TRLs and lower TPLs. Conversely, Weptos is the technology with the lowest TRL and the highest TPL. This observation indicates that the development trajectory of all the WECs but Weptos seems to have been focused on increasing the TRL of the technology rather on increasing the TPL.

The result of that process is that most of these WECs have been tested in the real sea at various prototype and full-scales (high TRLs). Thus, these WECs have been advanced quite far in development while realizing all expected costs, and at present still have a relatively high COE (about 1000 EUR/MWh).

On the other hand, Weptos has not been tested yet in open-waters (lower TRL) and is focusing on increasing its TPL and afterwards advancing in the TRL range. This advancement aims to realize for the first time all project costs at high TPLs, i.e. at the point in development where the expected COE is lowest.

This indicates a more economical advancement of Weptos in the long-run.

Overall, Weptos is evaluated to have the best techno-economic rating of all WECs compared in this analysis. Although its direct competitors are much more advanced in their development (higher TRL), Weptos appears to have a far greater economic potential, which is actually at the same level that of offshore wind turbines.

1.3.5 Levelized Cost of Energy

Estimations of the power production and levelized cost-of-energy (LCoE) of the Weptos WEC at different location and for different sizes are presented in the following table. These estimations have been made based on the results from the extensive model tests and detailed designs of the full-scale Weptos WECs. The lab tests focusing on power production have been done in a generic way, so that they can be applied to a variety of locations and scaling ratios of the Weptos WEC. The lab tests on structural and mooring design were done especially for the wave conditions of DanWEC Pt1, as the extreme wave conditions there are very demanding relative to the average wave conditions, however they can be also be used for other locations. In general, shallow water conditions are much more demanding compared to deep waters, due to the increase in wave steepness and the occurrence of breaking waves.

Four different locations of interests have been chosen for analysis, namely DanWEC Point 1, Danish North Sea Point 3, Billia Croo at EMEC (UK) and Yeu Island in France. These locations were chosen as they are known places with available wave measurements and they are perceived to be realistic and representative for locations where the WECs could be installed. However, the applied methodology is generally applicable.

The presented values are representative for Weptos WECs if they had to be built “tomorrow” in small numbers. These numbers, do not include any assumptions regarding learning curves, large scale productions, potential benefits from further optimization of e.g. PTO control and others, nor other optimistic projections. They have been calculated using the calculation sheet made available by Energinet (Fernández-chozas, Kofoed, & Ejner Helstrup Jensen, 2014). Discount rates of 4 % were assumed together with project lifetimes of 20 years.

Table 1: The table presents specifications of the Weptos WEC at different locations and for different sizes of the system

<table>
<tr><th>WEC model</th><th></th><th><u>Demonstration</u></th><th colspan="3"><u>Commercial WEC</u></th></tr>
<tr><th>Location</th><th></th><th>DanWEC Pt 1</th><th>Danish North Sea Pt 3</th><th>EMEC</th><th>Yeu Island</th></tr>
<tr><td>Wave power level</td><td>[kW/m]</td><td>9</td><td>16</td><td>29</td><td>26</td></tr>
<tr><td>Water depth</td><td>[m]</td><td>29</td><td>39</td><td>~50</td><td></td></tr>
<tr><td>$H_{s,\ 100\ years}$</td><td>[m]</td><td>9.5</td><td>10.0</td><td>16.4</td><td></td></tr>
<tr><td>$T_{p,\ 100\ years}$</td><td>[s]</td><td>16.8</td><td>14.5</td><td></td><td></td></tr>
<tr><td>Rotors</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>amount</td><td>[#]</td><td></td><td>20</td><td></td><td></td></tr>
<tr><td>diameter</td><td>[m]</td><td>4.5</td><td>6.8</td><td colspan="2">7.9</td></tr>
<tr><td>width</td><td>[m]</td><td>5.4</td><td>8.3</td><td colspan="2">9.6</td></tr>
<tr><td>WEC</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Leg length</td><td>[m]</td><td>108</td><td>162</td><td colspan="2">189</td></tr>
<tr><td>Total weight</td><td>[ton]</td><td>1130</td><td>3532</td><td colspan="2">5480</td></tr>
<tr><td>Ballast weight</td><td>[ton]</td><td>490</td><td>2520</td><td colspan="2">4100</td></tr>
<tr><td>Generator capacity</td><td>[kW]</td><td>750</td><td>3200</td><td colspan="2">4000</td></tr>
<tr><td>Power production</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average $P_{electrical}$</td><td>[kW]</td><td>132</td><td>763</td><td>1087</td><td>1113</td></tr>
<tr><td>MAEP</td><td>[MWh/year]</td><td>1335</td><td>5329</td><td>9532</td><td>9758</td></tr>
<tr><td>Cost</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$LCOE^{+}$</td><td>[Euro/MWh]</td><td>376</td><td>137</td><td>97</td><td>95</td></tr>
<tr><td>Ratios</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Load factor</td><td>[%]</td><td>20</td><td>19</td><td>27</td><td>28</td></tr>
<tr><td>$Weight_{without\ ballast}$ / kW installed</td><td>[ton/kW]</td><td>1.51</td><td>0.32</td><td>0.34</td><td>0.34</td></tr>
<tr><td>CAPEX/kW installed</td><td>[kEuro/kW]</td><td>5.3</td><td>2.1</td><td>2.1</td><td>2.1</td></tr>
</table>

\+ at 4% discount rate and lifetime of 20 years

The LCoE of a demonstration project at DanWEC Pt 3 will be of 376 Euro/MWh. Note that the average wave energy content is relatively low at this location (6 kW/m), while the extreme wave conditions are high (100 years wave of 9.5m H_{m0}). This LCoE value will significantly decrease for larger sizes of the WEC being located in more wave energetic locations. For the few locations included in this study, conservative LCoE estimations below 100 Euro/MWh are obtained. The load factor for the greater WECs will be close to 30 % and they will result in very low weight per installed generator capacity, in the range of 0.34 ton/kW (Babarit et al., 2012).

1.4 Utilization of project results

The project results are being used in the design of the first offshore Weptos WEC. As all the finer details of the technology have been assessed and the design and engineering has been done carefully up to providing shop drawings, it is in fact ready to be built. The next step is to find the required financing to proceed with the development of the technology. This development means in practice that the first off-shore Weptos WEC will have to be built and tested. Advanced discussions, including pricing, have already been made with all required partners to build and operate the first offshore Weptos WEC, including generator manufacturer, offshore steel structure manufacturer, and other subcontractors. All (main) technical topics have thereby been addressed.

Figure 9: Overview of the main artist impressions over the several years of R&D.

The results have also made it possible to have much more precise estimations of the cost of the technology and how it will be used in practice. Due to the strong collaboration with DNV, detailed FMEA, classifications and general system review have been made, which resulted in clear safety level identification and requirements for offshore operations.

The Weptos technology is well protected by several patents, and hereto we expect the innovative technology still has the possibility of filing even further patents. Therefore, we keep most details regarding our technology as confidential as well as the many reports made by AAU within this project. We have referred to these reports in this final report.

1.5 Project conclusion and perspective

The Weptos WEC has gone through rigorous test campaigns and R&D in general. During this process, the focus has always been to improve the technology relative to the five essential features of wave energy converters (Pecher, A., Kofoed, J. P., & Larsen, T., 2014):

- Survivability
- Reliability & Maintainability
- Cost of energy
- Performance & Scalability
- Environmental benefit

This has led to a high Technological Performance Level (estimated average TPL of 8), and reduced unknowns and the overall technical and economic risk of the project, before moving on with its development. Furthermore, the resulting very promising Levelized Cost of Energy values (LCoE below 100 Euro/MWh) for full-scale Weptos WECs do not take learning curves or large production numbers or other potential further improvements into account and the structural requirements are set very high, making these values conservative. The Weptos technology is thereby considered ready for initial real sea prototype testing at a benign site.

The results, which are obtained and based on the studies from the testing both at AAU as well as at the FloWave TT facilities at the Edinburgh University, show a large perspective and prove that Weptos differs from other known projects in the industry, combining an very promising LCoE with high reliability. The result from the "WECs Benchmark Study – Final Report" also defines the Weptos technology differs significantly from other known projects.

From the LCoE study it is concluded that the Weptos WEC appears to have a levelized cost of energy (LCoE) in the same range as offshore wind turbines (0.128 k€/kWh against 0.129 k€/kWh). The obtained value is seen as a conservative average base case, which could be affected by various factors such as environmental resource and others (in both directions), just like it is the case for the offshore wind turbines.

A great advantage of Weptos, is that its cost will not (significantly) increase with additional water depth, it might even reduce it (and be favourable), while this is a significant additional cost parameter for off-shore wind turbines.

The presented values for Weptos are intended to be conservative and thereby do not include learning curves, which have shown to be significant in the development of wind energy. The unknown cost parameters have been taken over from the wind energy case and the same cost categories have been maintained.

It is expected to continue the development of Weptos technology to establish the basis for a new sustainable technology for the extraction of wave energy. A detailed design of a "small-scale real sea prototype" has been made to shop drawing level, and some funding is already secured. However, it is crucial for Weptos to find an external investor before further development of the Weptos technology will be continued, as this demands further liquidity to ensure the development towards commercialization.

1.6 Updating Financial Appendix and submitting the final report

The Financial Appendix has been updated and the final report submitted.

1.7 References

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