The extensive R&D behind the Weptos WEC

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ABSTRACT: The Weptos wave energy converter (WEC) has been through rigorous research and development (R&D), which has brought it to the forefront of the wave energy sector. This paper presents an overview of the technological advances that have been made in the development of the Weptos WEC technology together with its current specifications. This includes details about how these specifications have been obtained, illustrating the substantial R&D efforts that lies behind, and power and levelized cost-of-energy (LCoE) estimations for various locations.

1 INTRODUCTION

1.1 *General*

In the past years, extensive research and development (R&D) have been done on the Weptos wave energy converter (WEC). All the different parts of the device has been carefully analyzed and improved, bringing the technology to the forefront of the wave energy sector. The Weptos technology brings high power performance, based on proven Salter's ducks design, with high power to weight ratio, high load factor and effective 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.

The paper intends to illustrate the R&D that has been done, mainly through experimental model testing, which has led to the various remarkable characteristics that this wave energy converter has.

1.2 *The Weptos WEC*

The Weptos WEC is an A-shaped floating structure that absorbs wave energy through multiple wave absorbing bodies, the rotors. These rotors have their shaped inspired by the Salter duck, of which their high efficiency has been proven already in the 70's (Salter, 1974).

Figure 1. Artist impression of a full-scale Weptos WEC.

The A-shaped structure has the particularity that it can adjust the angle between the two legs, from 13° up to 120°. This has several important advantages that improve the device on several fronts:

- The amount of incoming wave power can be adjusted, meaning that the structure can be widen in small wave conditions and completely closed in storm conditions. This enables smoothening of the energy production across the various occurring wave conditions.
- Extreme loads on the structure during storm conditions are being significantly limited in size, to such an extent that these are in the same range as those occurring during average wave conditions. This means that the structure does not need to be further strengthened beyond the needs corresponding to power production wave conditions, in order to handle the loads of extreme wave conditions.
- The A-shaped structure provides a natural power smoothening effect, as the rotors on a leg interfere with a wave successively, avoiding peak loads on the power take off and thereby resulting in a very high load factor.

The wave power absorbed by the rotors is mechanically transferred through a common axle that turns in one direction. Due to the relatively constant rotation of this axle and the smooth power transmission from the rotors, a standard synchronous generator solution can be used. The power take off is thereby very simple, direct and fully mechanical, which results as well in very high power train efficiencies.

The structure is moored through a single anchor leg mooring (SALM) system. The system is very compact, has a minimal footprint on the seabed and allows 360° weather-vanning.

2 TEST MODELS

2.1 *Overview*

The advances of the different parts of the technology have all been verified through model tests. Therefore, up to now 7 different physical models have been used, which were directly related to the technology, in even more test campaigns.

Besides the physical test campaigns, additional R&D has been done to prepare, support and compare the model tests, and to investigate further developments of the technology. These have been done by numerical models to represent the motions of the rotors, of the structure and the mooring, in order to model the power production and loads on the system.

2.2 *The first idea being model tested*

As from the first test model, which was at the beginning of what has led to the current design of Weptos WEC design, some strong basic principles were already present. The most visible is the adaptable opening angle of the A-shaped design of the technology, but as well a common uni-directional rotating axle for all wave-activated bodies was already present. The physical test model, which was based on wave overtopping and wave mill principle (Kofoed, 2001), gave unsatisfactory power performance results. This was thereby the first part that needed to be addressed and significantly improved.

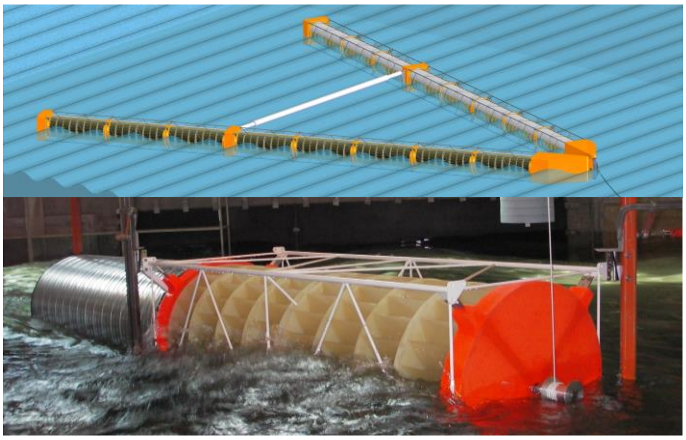

Figure 1: Illustration of the full scale design (top figure) in 2007 and the test model (bottom figure), which represented a scaled section of one of the legs.

2.3 *Proof of concept*

The “proof of concept” tests were the result of the many early stage improvements of the general concept. This model consisted of 4 rotors (Salter duck’s inspired shape) that were positioned inclined to the wave propagation direction and they delivering there absorbed power to a common axle. At the end of this common axle, the PTO and measuring equipment situated. These basic elements are still present today and are part of the strong advantages of this system.

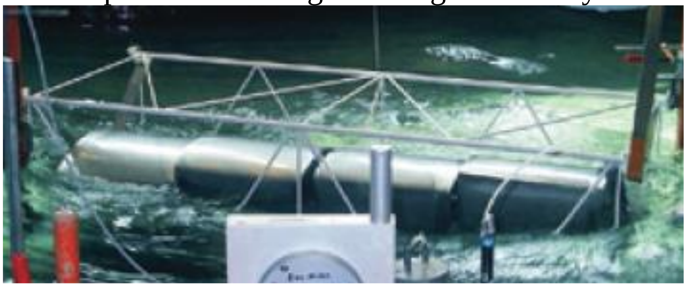

Figure 2: The first model containing Salter’s duck inspired rotors and a very simple Coulomb type PTO system based on a ratchet mechanism between the rotors and the common axle.

2.4 *One rotor setup*

The “single rotor model” aimed at identifying the general performance of the wave absorbing mechanism, the rotor, and to optimise the weight distribution in it. The shape of the rotor is based on the design of the Salter’s duck, which was invented in the 70’s, and has always presented remarkably high efficiencies. These efficiencies have been reproduced and a lot of knowledge and experienced have been gained relative to the design and PTO control (Pecher, Kofoed, & Marchalot, 2011).

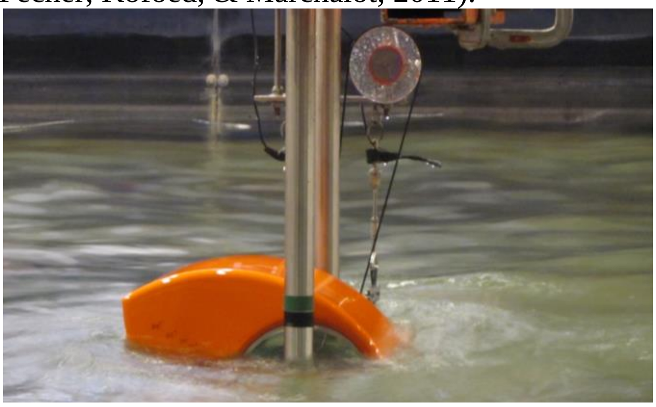

Figure 3: Picture of the model with one rotor, which was mainly used to benchmark its power production capabilities, and to optimize its weight distribution and PTO control.

2.5 *Large scale model testing*

The “Large scale model testing” at CCOB (University of Santander, Spain) aimed at demonstrating and assessing the Weptos WEC system as a whole. It validated the stipulated power performance and its high capacity factor, the effectiveness of the A-structure to naturally smoothen the absorbed power and to reduce loads on the structure in extreme waves to the same order of magnitude as in average wave conditions. The power production of the Weptos WEC, based on the results of these tests, can be estimated for many different sizes of the device and locations with a very high accuracy. This model was already equipped with electrical generators, providing realistic and fully controllable PTO loads, just like real offshore wave energy plants will do (Pecher, Kofoed, Larsen, & Marchalot, 2012; Pecher, Kofoed, & Larsen, 2011).

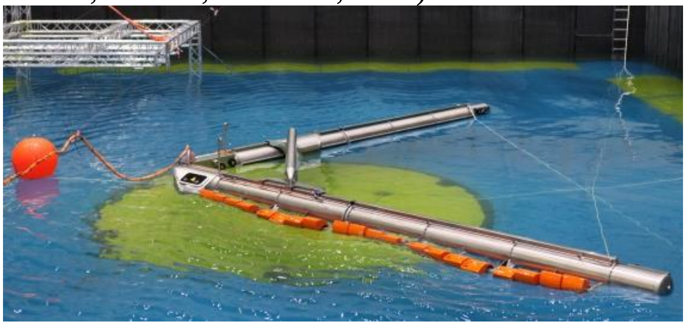

Figure 4: The first complete model that was tested in the CCOB test facilities in Santander (Spain).

2.6 *Wave loads on rotor model*

The “Wave loads on rotor model” 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 5: The “wave load on rotor model”.

2.7 *3-rotor PTO test model*

The “3-rotor PTO test model” 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 up and downward motions.

Figure 6: The PTO test model, where the new design of the PTO was tested and optimized.

2.8 *Structure and mooring test model*

This “structure and mooring test model” was a very accurate reproduction of what is intended to be the full scale model, in design as well as in weight, and thereby incorporated as well 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, 2014). The second test campaign was performed in deeper water conditions at FlowaveTT (UK), where wave current interactions, 3D waves and bi-modal seas were the main focus (Pecher, Kofoed, & Larsen, 2014).

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

3 MAIN OUTCOMES FROM R&D

3.1 *General*

Throughout the development of the Weptos WEC, the design of the full scale device has been significantly optimized, which has significantly increased its power production, while reducing its weight and cost. This resulted in a tremendous improvement of its cost-of-energy. In the next figure, two artist impressions are given of the design of a full Weptos WEC, spaced by approximately two years. An overview of the earlier design is given in (Pecher, Kofoed, & Larsen, 2012).

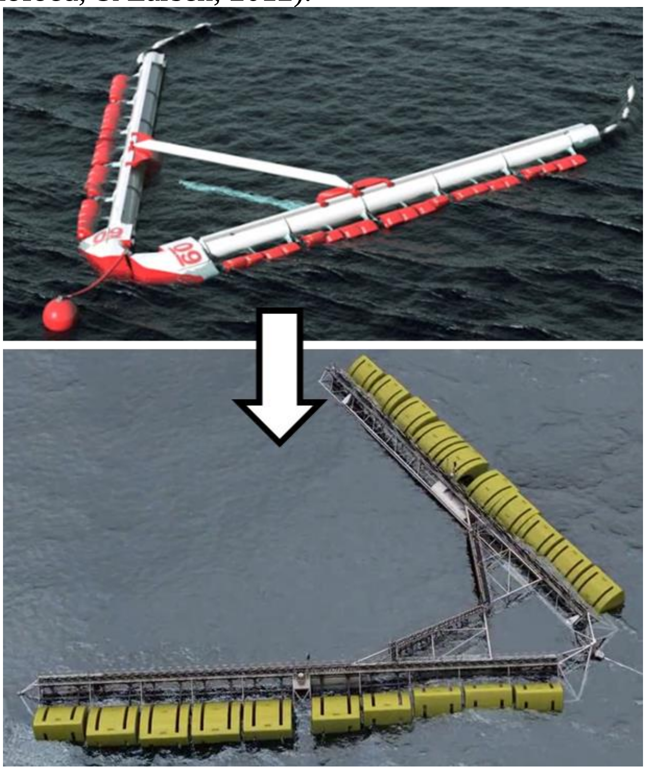

Figure 8: Artist impression of a full scale Weptos WEC in 2012 and in 2014, indicating the tremendous advancements in its design. (Pecher, Kofoed, & Larsen, 2012; Weptos A/S, 2011, 2014)

Visually, the main differences that can be observed are:

- The reduction of 20 to 10 rotors per leg.
- The significant increase in size of the rotors compared to the structure.
- The significant reduction in size of the bearing structure.
- The positioning of the generator system in the middle, compared to in the front.

Other main difference, which are more difficult to spot with the eye are:

- The rotors are engaged with the power transmission axle during up and down strokes, priory this was only during upstroke motions of the rotor.
- The mooring system has been significantly upgraded in terms of materials and design while it still remains a single anchor leg mooring (SALM) system.

3.2 *Main outcomes from test models*

Some of the most obvious outcomes of each of the models are given in the next table.

Table 1: Summary of some of the main obvious outcomes of the different lab models.

Test model	Main outcome
First idea	Decent general idea, but power performance design is not at a satisfactory level.
Proof of concept	The new wave absorbing principle “the rotors” absorb a lot of wave power, even in oblique waves.
One rotor model	High efficiency can be obtained from the rotor under different wave conditions and optimized balancing of the rotor.
Large scale model	Same efficiency as single rotor, efficient smoothening of the power, structural loads in extreme in same order of magnitude as in power production sea states, all sub-systems work.
Wave loads on rotor model	Wave impact forces on rotors coming from different directions and loads from rotor transferred to WEC structure.
3-rotor PTO test model	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.
Structure and mooring test model	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.

3.3 *Structural design & loads*

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 pow-

er, 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 9 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).

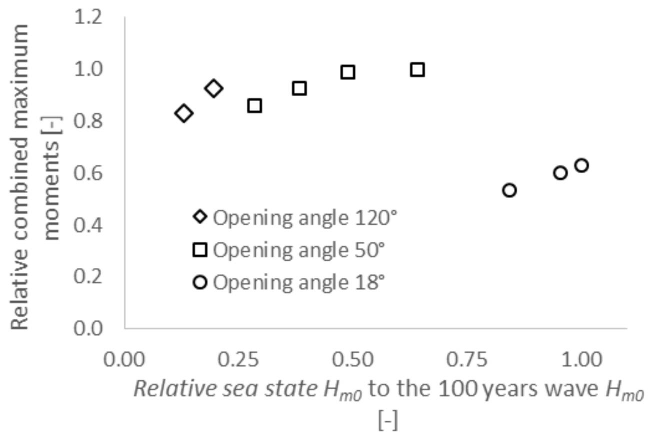

Figure 9: The relative maximum combined bending moments in the middle of a leg of the structure against the relative significant wave height (Pecher & Kofoed, 2014).

3.4 *PTO design*

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 up or 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 the rotational speed up and torque down simultaneously at a very early stage of the PTO system.
- Generator house is built in 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).

3.5 *Power production*

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.

3.6 *Mooring design & loads*

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-vanning 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.

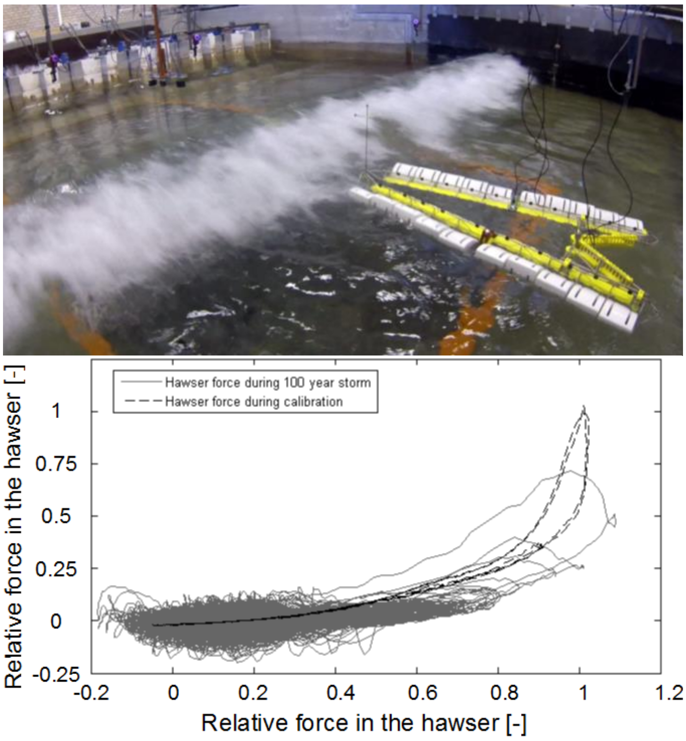

Figure 10: The top picture shows a breaking wave during a 100 years storm test. The bottom graph illustrates the relative force in the hawser against the relative significant wave height, obtained with the structure and mooring model. The manual mooring calibration curve and the resulting hawser force during a 100 year storm in shallow waters are given (Pecher & Kofoed, 2014).

3.7 *Commissioning & Maintenance*

- Easy and safe access (boat landing) to the WEC through the calm area behind the WEC.
- Almost all PTO components (mechanical transmission from rotor to power transmission axle, the whole power transmission axle and all whole generator system) and a large part of the structure and its control system can be visually inspected and accessed when being on-board. So “light” maintenance can be done approx. 60 % of the time.
- All large components (metallic structure, and rotors, generator house, …) are neutrally-buoyant
- Mooring and electrical connection is “stress-free” (no permanent tension….)
- The WEC is accessible to mid-size wave conditions (approximately 60 % of the time), which is close to the wave conditions where the rated power is reached.

4 FULL SCALE ESTIMATIONS

4.1 *Introduction*

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.

4.2 *Power production and LCoE estimations*

For the four different location, for which power production and LCoE estimations are made, three different sizes of the Weptos WEC has been assumed. The size of a Weptos WEC and wave power level of the locations of implementation will get greater with time and experience, although that they are not necessarily correlated. Weptos WECs with more than 20 rotors have not been included. However, these will potentially also be part of its further development.

The size of a Weptos WEC is mainly characterized by the rotor diameter. A rotor diameter of 4.5 m was used for the demonstration model at DanWEC, for which most of the model tests have been targeted. A potential location for a commercial

Weptos WEC could be in the Danish North Sea (Point 3) with a rotor diameter of 6.8 m (increase of 50 %) or at EMEC (UK) or Yeu Island (France) with rotors diameter of 7.9 m (increase of 75 %). The generator capacity has been chosen taking the technical requirements of the WEC into account and in order to optimize the resulting LCoE value.

The wave conditions vary with the locations, but as most of the model tests and design studies were targeted at DanWEC Pt 1, which has very demanding extreme wave conditions, the scaling of the structure was assumed to be sufficient (and most probably excessive). Thereby, the structural design, which corresponds indirectly to the largest part of the CAPEX of the machine, is assumed to be conservative.

Table 2: The table presents specifications of the Weptos WEC at different locations and for different sizes of the system (Fernández-chozas, Kofoed, et al., 2014; Kofoed & Frigaard, 2009; Pecher & Kofoed, 2014).

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

+ 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).

Besides further improvements of the Weptos WEC and larger WECs possibly with more rotors, the installation of Weptos WECs at other locations and greater numbers will also contribute to further bring this LCoE estimations down. Other locations, possibly more energetic or with lower extreme to average wave conditions, will increase the power production and reduce relatively the structural requirements.

4.3 *TRL and TPL projections*

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).

In figure 11, a matrix is presented, which intends to show the technological performance and readiness level (TPL and TRL), which in others words illustrates how economic a technology can become and how far it is through its developments (Weber, 2012). In this TPL-TRL matrix, the TPL-TRL development trajectory of Weptos is given together with the estimated current TPL-TRL levels of some of the leading wave energy converters (Fernández-chozas, Pecher, & Kofoed, 2014).

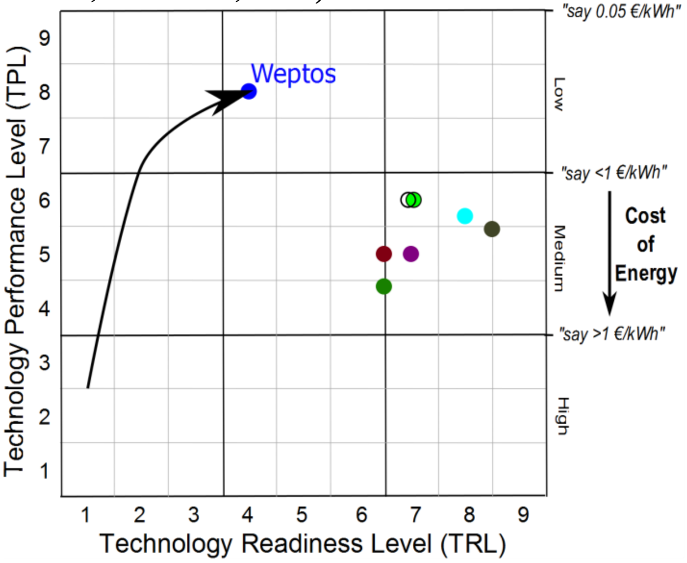

Figure 11: The development trajectory of the Weptos WEC, together with the current estimated TRL-TPL of some of the leading wave energy technologies.

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

5 CONCLUSIONS

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:

- 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.

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