Wave Dragon 1.5 MW

North Sea Demonstrator Phase 1

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EUDP J.nr. 64010-0405
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FINAL REPORT

PROJECT DETAILS

Project title	Wave Dragon 1.5 MW North Sea Demonstrator Phase 1
Project identification (program abbrev. and file)	EUDP 2010-II 64010-0405
Name of the programme which has funded the project	EUDP 2010–II Bølge
Project managing company/institution (name and address)	WAVE DRAGON FREDERIKSBORGGADE 1 DK-1360 COPENHAGEN
Project partners	Aalborg University Sterndorf Engineering ApS
CVR (central business register)	DK 2621 9841
Date for submission	September 2015

1. CONTENT

2. SUMMARY

Wave Dragon is a well-proved overtopping type wave energy converter. The next step in the development of the Wave Dragon technology is the deployment of a full-scale device in open sea. The development of a 1.5 MW Wave Dragon demonstrator will be based on experiences from 20.000 test hours with a smaller prototype.

This project is the phase 1 of a full-scale 1.5 MW demonstrator project at the test centre DanWEC, Hanstholm. The main objectives of this phase are:

i) delivering a certified design of the device and
ii) delivering a detailed feasibility study of the total project.

Initially WD designed a 1:50 scale model of the 1.5 MW device and Aalborg University was then responsible for basin tests of the model. The primary result of the basin tests was the establishment of the max forces in the mooring cables in survival floating positions of the platform in the environmental conditions at DanWEC with a 100 year return period.

Based on the results from the laboratory test Dr. Techn. Olav Olsen has as external consultant to WD been responsible for the detailed design of the construction.

GVA Consultants AB and Lars Bergdahl, Chalmers have as external consultants to WD been responsible for the mooring analysis.

Joe MacEnri (previously ESB International), MT Højgaard, Per AARSLEFF, Sterndorf Engineering, have all delivered important input to the feasibility study.

Based on the final reports from Olav Olsen and GVA, STATEMENT OF FEASIBILITY has been issued by DNV - GL


No. 2014-0645

DNV·GL

STATEMENT OF FEASIBILITY

This is to state that

WAVE DRAGON – Wave Energy Converter Structure

has been evaluated in accordance with DNV-RP-A203 Technology Qualification /1/ for its intended use as reported in DNV Technical Report 2014-0645, /3/. DNV GL considers the technology feasible as defined in /2/ and thereby suited for further development and qualification according to DNV-RP-A203.

Technology owner:	**Wave Dragon ApS, Blegdamsvej 4, 2200 Copenhagen, Denmark**
Name of technology:	Wave Dragon 1.5 MW Demonstrator
Description:	Floating wave energy converter structure made of concrete
Intended use:	Offshore energy production
Main uncertainties:	Subsequent qualification activities should address the aspects as detailed in /3/, section 4.
Involvement:	DNV GL has been involved in the qualification process as required according to /1/ and has identified the main challenges as reported in /3/.
Reference documents:	/1/ DNV-RP-A203, Qualification of New Technology, July 2013
	/2/ DNV-DSS-401, Technology Qualification Management, Dec. 2012
	/3/ DNV Technical Report No. 2014-0645 Rev 02 "Concept evaluation of Wave Dragon - Wave Energy Converter structure at DanWEC in Hanstholm, Denmark", 6 February, 2015.

The qualification process is in progress and new sources of uncertainty may be discovered as qualification progresses. Attention is drawn to the iterative nature of the TQ process /1/.

Høvik, 2015-02-09
for DNV GL AS

Hege Berg Thuesen · Head of Section

Philipp Rohrer-Baumgartner · Project Manager

3. DANISH SUMMARY

Wave Dragon er et velgennemprøvet bølgekraftanlæg af opskylstype. Det næste trin i udviklingen af Wave Dragon teknologien er udlægning af et fuldskala anlæg på åbent hav. Udviklingen af et 1,5 MW Wave Dragon demonstrationsanlæg er baseret på erfaringerne fra 20.000 timers test af en mindre prototype.

Dette projekt er 1. fase af et 1,5 MW fuldskala demonstrationsprojekt ved testcentret DanWEC i Hanstholm. Hovedmålene i 1. fase af 1,5 MW projektet er:

i) levering af et certificeret design af anlægget og
ii) levering af et detaljeret feasibility studie for det fulde projekt.

Indledningvis designede WD en 1:50 skalamodel af 1.5 MW anlægget og Aalborg University var derefter ansvarlig for gennemførelse af bassin tests med modellen. Det primære resultat af bassinforsøgene var fastlæggelsen af de maksimale kræfter i forankringskablerne i overlevelsespositioner for den flydende platform i de forventede maksimale vind-, strøm- og bølgeforhold indenfor en 100 års periode ved DanWEC.

Baseret på resultaterne af bassinforsøgene på AAU har Dr. Techn. Olav Olsen som eksterne konsulenter for WD været ansvarlig for den detaljerede projektering af anlægget.

GVA Consultants AB and Lars Bergdahl, Chalmers har som eksterne konsulenter for WD været ansvarlig for forankringsanalyserne.

Joe MacEnri (tidligere ESB International), MT Højgaard, Per AARSLEFF, Sterndorf Engineering, har alle leveret vigtige input til feasibility studiet.

På grundlag af de færdige rapporter fra Olav Olsen og GVA har DNV –GL udstedt STATEMENT OF FEASIBILITY.


No. 2014-0645

DNV·GL

STATEMENT OF FEASIBILITY

This is to state that

WAVE DRAGON – Wave Energy Converter Structure

4. BACKGROUND

4.1. INTRODUCTION

The Wave Dragon wave energy converter has followed a TRL-based development: from laboratory-based R&D, to the real sea testing of a prototype at 1:4.5 the scale of a North Sea unit, rated at 20 kW. It was the World's first floating device delivering wave-generated electricity to the grid in 2003.

Wave Dragon is now ready to undertake a full-scale demonstration of a pre-commercial unit. The steel-built prototype will be up-scaled to a 1.5 MW demonstrator unit for the North Sea, built in reinforced concrete. The demonstrator will be deployed at the DanWEC test centre in Hanstholm (DK) and will undergo a test program lasting 1½ years, aimed at refining the present knowledge on device performance and sub-systems behavior, as well as at gaining further offshore operational experience.

After the completion of this phase, the demonstrator will become the first pre-commercial unit of Wave Dragon, producing up to 1,500 MWh/year of wave-generated electricity in the North Sea. This will enable the final stage of commercial exploitation of this technology in countries like Denmark, the UK, Ireland and Portugal.

4.2. THE DEVELOPMENT OF WAVE DRAGON

Wave Dragon is a wave energy converter of the over-topping type; a floating hydro-electric dam and represents a unique, innovative development of a state of the art technology within the field of Wave Energy converters.

Wave Dragon achieves exceptional wave energy conversion efficiencies with very few moving parts. The heart of the Wave Dragon unit is a large floating reservoir. Two reflector wings concentrate the power of oncoming waves which pass up a curved ramp and into the reservoir. The water returns back to sea through a battery of low-head turbines connected directly to permanent magnet generators.

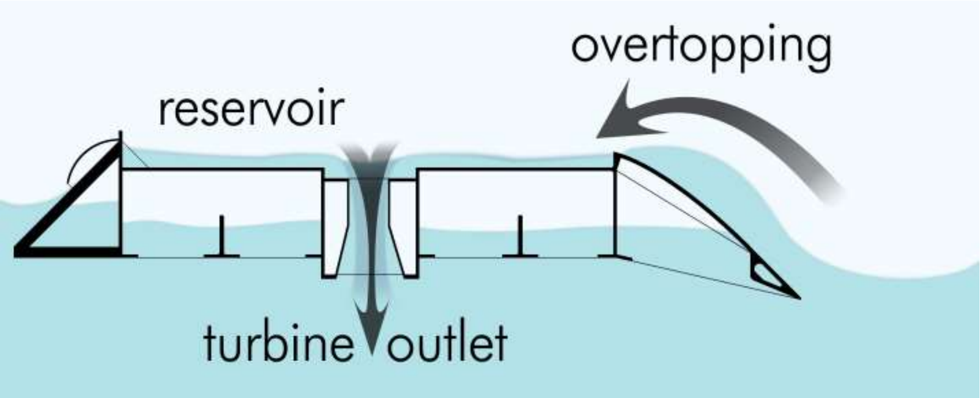


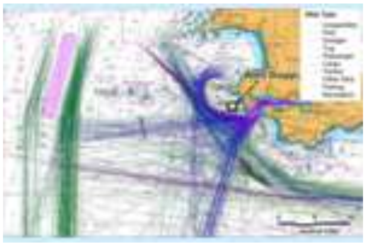
*Figure 4.1: Wave Dragon working principle:
1) Overtopping, 2) reservoir storage and 3) turbine power-take-off.*

Figure 4.2: The 58 m wide prototype scale 1:4.5 of a 4 MW device in Nissum Bredning 2003 - 2010 showing the two reflectors that focus waves towards the ramp and the reservoir that stores overtopping water [2]

The reservoir and wings are connected to a forward mooring buoy by hawsers. The whole structure weather-vanes to face oncoming waves naturally. The forward buoy is moored to anchors on the sea floor. Multiple redundancies ensure structural integrity. Each element of the unit is based on existing proven technology, adapted for use in this particular case. Care has been taken to avoid the technical risk of novel elements or materials.

The key to Wave Dragon's success is its wave energy conversion efficiency combined with a long lifetime of low operation and maintenance costs. Developed over 20 years with 12 years of tank and scale testing; Wave Dragon's proprietary design and control methodology gives exceptional performance in a wide range of sea states.

Table 4.1 The development stages of Wave Dragon

#	Phases	To be obtained	
1	Scale 1:50 Test in Wave tanks 1998 – 2002 1m€	Hydraulic behaviour Survivability Response different wave climates ENS & EU: 50%	
2	Scale 1:1 in a real sea modelling the North Sea in 1:4.5 20kW 2002 – 2010 5m€	Power production, grid connection Operational management Model laws valid Survivability ENS, PSO, EU: 50%	
3	Scale 1:1 in the Celtic Sea 7MW In planning 25m€	Scaling feasibility Demonstration O&M CT, WAG, EU	

A Wave Dragon prototype was deployed in Nissum Bredning in 2003 and has been operating for more than 20,000 hours connected to the grid. This was the world's first grid-connected floating wave power device, and the extensive testing of the prototype has proved the concept. The tests have verified that an average annual wave-to-wire efficiency of 18% for a full scale device in a North Sea wave climate can be expected. This corresponds to 2 percentage points more than predicted at this stage of development and it is only 3 percentage points below the long term target for the device.

Wave Dragon is expected to be built in four sizes, optimized for 1.5 to 12 MW of capacity, depending on the wave climate at a given site as illustrated in Table 3. A full-scale Wave Dragon power station will be an array of individual units connected to shore by undersea transmission cables, similar to those deployed in offshore wind farms. There is no theoretical limit to the number of units in an array; a typical power station may be 15-1,200 MW capacity (10-100 units).

Expected deployment sites will typically be 5-25 km offshore to exploit high power wave resources. Typically, water depths in excess of 30 m are preferred. Wave Dragon has very little environmental impact and its visibility from shore will be low.

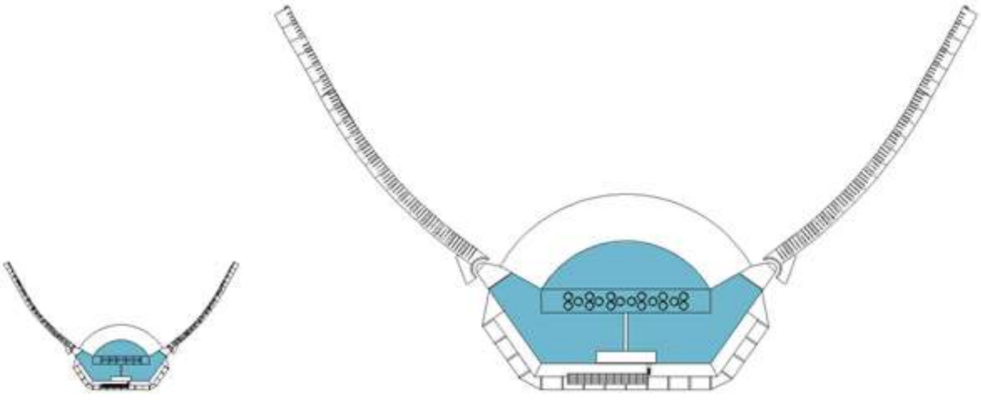


Figure 4.3: The Nissum Bredning prototype 1:4.5 scale deployed 2003 and the 1.5 MW device to be deployed DanWEC.

Table 4.2 The Wave Dragon layout for different sea condition

Wave climate:	**0.04 kW/m**	**12 kW/m**	**24 kW/m**	**36 kW/m**	**48 kW/m**
Weight	237 tons	6,500 tons	22,000 tons	33,000 tons	54,000 tons
Width	58 m	152 m	230 m	270 m	320 m
Length	33 m	96 m	150 m	170 m	220 m
Wave reflector length	28 m	84 m	126 m	145 m	190 m
Height	3.6 m	12 m	16 m	16.8 m	18.1 m
Number of turbines	7	8	16	16-20	16-24
Generator type	Permanent magnet synchronous generators				
Generator rating	7 x 3 kW	8 x 185 kW	16 x 250 kW	16-20x350kW	16-24x500kW
Device rated power	0.02 MW	1.5 MW	4 MW	7 MW	12 MW
Water depth	6 m	>15 m	>20 m	>25 m	>30 m
Annual output	0.06 GWh	4 GWh	12 GWh	20 GWh	35 GWh
Mooring type	Single point	Single Point Mooring with 5 - 8 legs			

The actual report deals with the phase between phase 2 and phase 3 as shown in Table 4.1 and with a layout as shown for a 12kW/m wave climate as illustrated in Table 4.2.

Information related to the Phase 1-3 projects in Table 4.1 can be found in [1], [2] and [3].

4.3. WHY A CERTIFIED DESIGN?

During negations with potential finance investors in the period 2008-2010 it has been noted, that almost all contacts from countries like UK, Portugal, Spain, France and southern Germany has expressed uncertainty in scaling up from the tested all-steel built Wave Dragon in scale 1:4.5 of a 4 MW unit to a full scale unit constructed in reinforced concrete.

The use of reinforced concrete for offshore constructions is not a well-established construction method in these countries – whereas this is common in Denmark and Norway in connection with offshore wind foundations and large offshore oil and gas platforms.

Ships and barges have been produced in quite high numbers but primarily in USA during war times where steel prices were quite high. Several 80 year old concrete ships are still floating even if no or very little maintenance work has been carried out. Concrete is the preferred material for Wave Dragon due to a very long lifetime without maintenance, a much more constant - and in many parts of the world also much lower price - than steel built offshore constructions.

As a consequence of this barrier for getting finance Wave Dragon decided to take a major step forward by developing a design certified by DNV-GL for a Wave Dragon suitable for the DANWEC test site of the coast of Hanstholm – this site is described in chapter 5.1

5. DESIGN BASIS

This chapter describes the background information used in the design and certification process.

The development of the design basis was performed under the supervision of Sterndorff Engineering. The work included determination of joint probability metocean parameters for the design of the structure and moorings.

The geometry of Wave Dragon is very complex in comparison with a ship hull, and this makes it very difficult, if not impossible to determine the hydrodynamic loads on the construction by means of numerical analyses with present state-of-the art hydrodynamic programmes. Therefore, the most reliable estimations of the hydrodynamic loads are those obtained by model testing.

Aalborg University has been the responsible partner for basin tests of a 1:50 model of the new 1.5 MW device type designed by WD. They built and tested the model in order to establish the forces in the mooring lines for varying floating positions of the platform. Several survival floating positions of the platform were tested in environmental conditions with a 100 year return period as at the DanWEC test site.

5.1. THE DANWEC SITE

The dominant load on a wave power plant as Wave Dragon is the wave load. To determine this load, it is necessary to define the design wave height and the relation between the significant design wave height and average period. Design contour design significant wave height versus wave period for the waters off Hanstholm is established based on wave measurements from the period 1998-2007 supplied by Hanstholm Harbour. The existing measurement data have unfortunately proved inadequate, yet a design contour of wave height/period, in which we dare trust, has been established - see figure 5.5

In the period from 20 January to 11 May 2011 DHI conducted a site survey of currents and wave conditions at a position about 500 m NW of Hanstholm Harbour [4]

The Figures 5.1. and 5.2 show some of the important results from the survey.

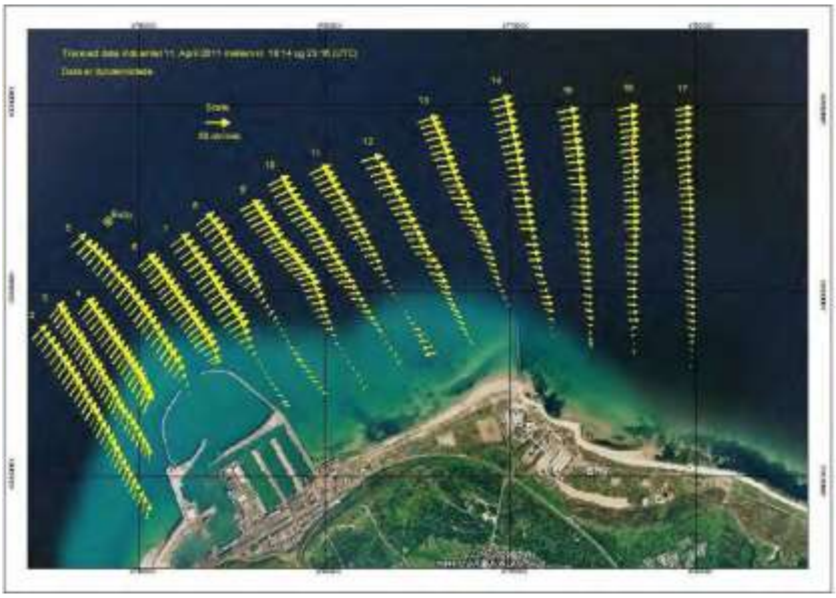


Figure 5.1 Measurements of currents at Hanstholm taken from [4]

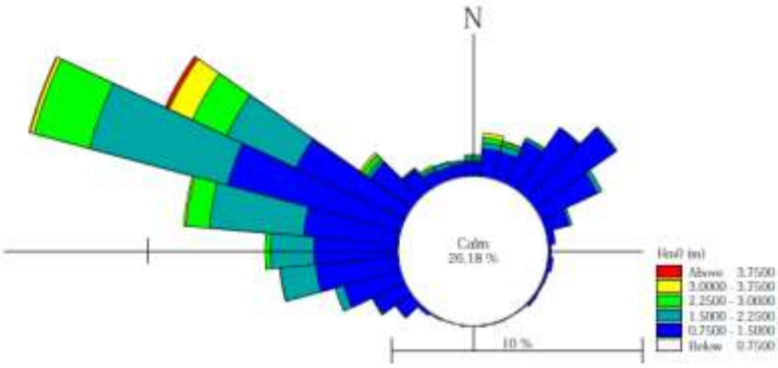


Figure 5.2 Measurements of wave heights at Hanstholm taken from [4]

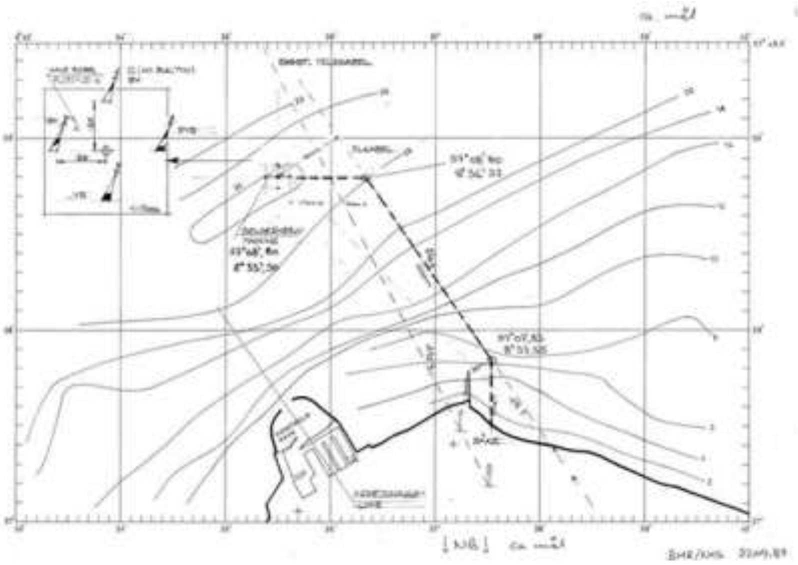


Figure 5.3 Location of the test site used by Danish Wave Power Aps 1989 - 1996 [6]

Hs\Tmo1	3	3,5	4	4,5	5	5,5	6	6,5	7	sum
0,125	0%	1%	1%	0%	0%	0%	0%	0%		4%
0,5	2%	6%	7%	5%	3%	2%	1%	0%	0%	27%
1	0%	2%	7%	8%	6%	4%	2%	1%	0%	30%
1,5	0%	0%	1%	5%	6%	4%	2%	0%	0%	18%
2		0%	0%	0%	4%	4%	2%	0%	0%	11%
2,5				0%	0%	2%	2%	1%	0%	5%
3				0%	0%	0%	1%	1%	0%	3%
3,5					0%	0%	0%	0%	0%	1%
4						0%	0%	0%	0%	0%
sum	3%	9%	16%	19%	19%	16%	9%	4%	2%	98%

Figure 5.4 Scatter diagram from Hanstholm based on measurements in front of the Harbor at about 15 meter water depth In summery the data at DanWEC in Hanstholm, [6]

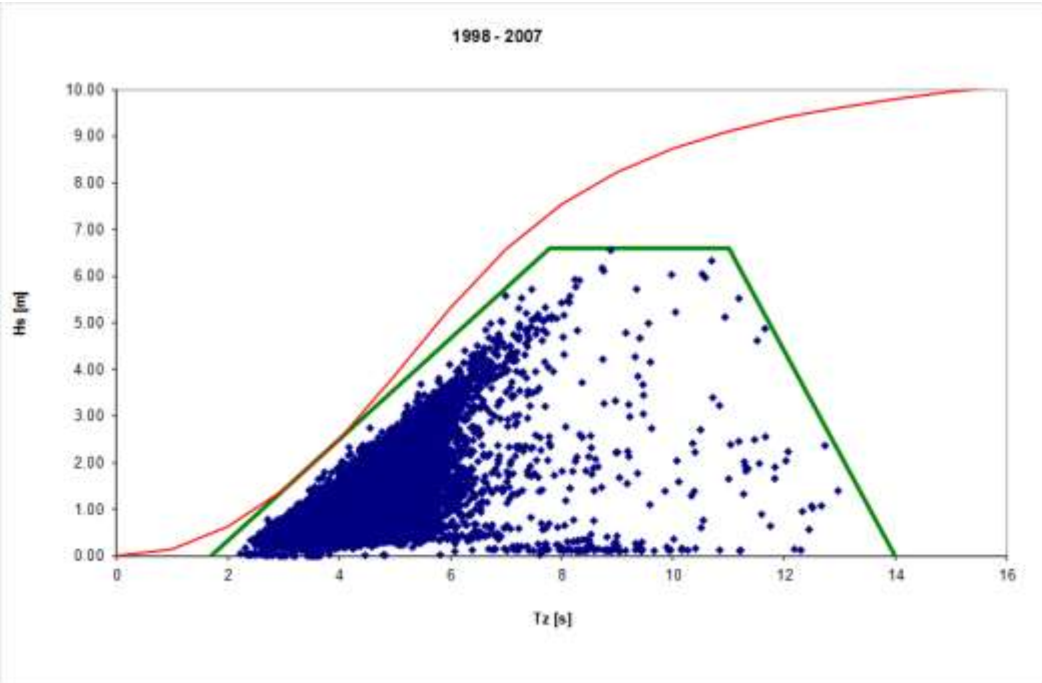


Figure 5.5 Design 3-hour wave height/wave period contour[5]

5.2. NEW REVISED DESIGN OF THE 1.5 MW DEVICE

Figure 5.6 Comparison of CFD simulations with Nissum Bredning web-cam pictures. The overtopping patterns are quite alike and the numerical results are also in line with model tests in scale 1:50 [66]

The results of the test with the scale 1:3 pilot (compared to the 1.5 MW device) in Nissum Bredning were very satisfying. The measured performance was in line with results from laboratory test, and CFD simulations have shown that the visual observed run-up patterns of waves on the double curved ramp are not an occasional event. The changing of overtopping from the center section to the side sections during a wave period is a very desirable result of the overall design of the ramp in combination with the geometry of the wave reflector wings.

The new revised design of the 1.5 MW device is therefore not much changed with regard to the overall geometry. The major difference is that the load bearing structural parts of platform are now to a high degree modular and thus faster and cheaper to construct. The new design of the structures under the reservoir ensures at the same time more stability and a higher number of separated buoyancy chambers. The stability and thereby the efficiency of power conversion plus the survivability is much improved with the revised design.

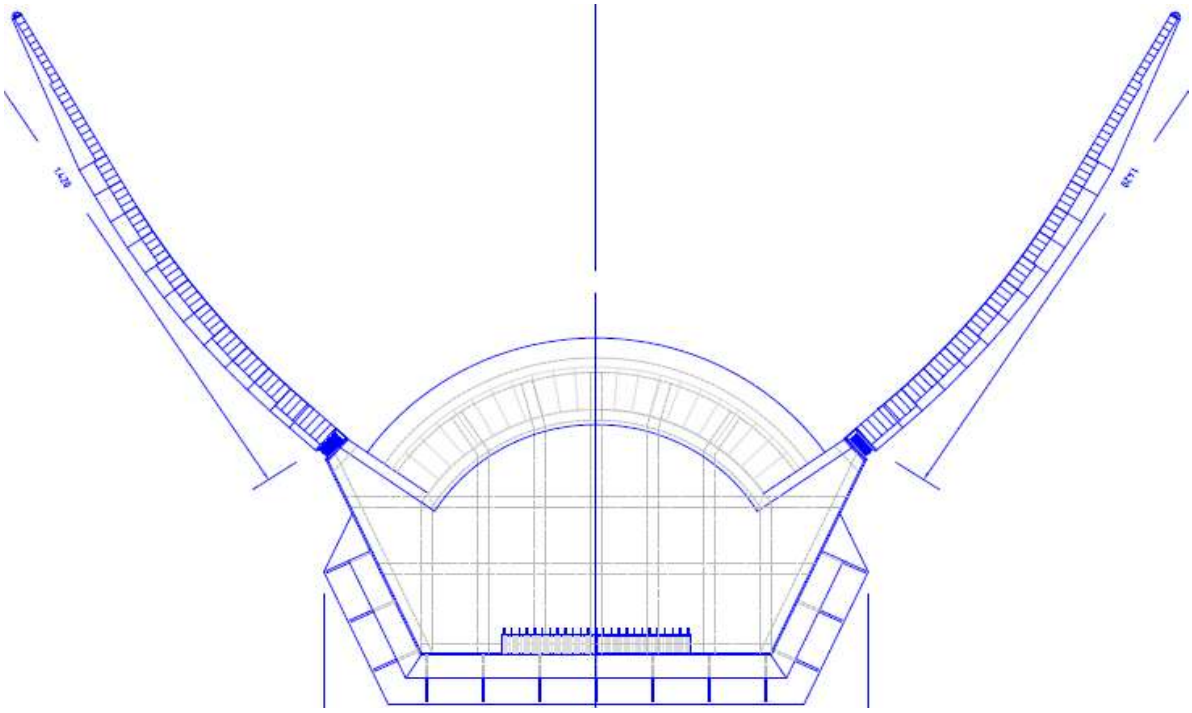


Figure 5.7 Plane drawing of the new model.

Figure 5.8 Old and new model seen from the underside

5.3. MODEL TEST AT AALBORG UNIVERSITY

The new model in scale 1:50 was tested in the offshore basin at AAU in several configure-tions of floating levels and stiffness in the mooring system. A comprehensive description of the performed test can be found in [14] [15] and [67]

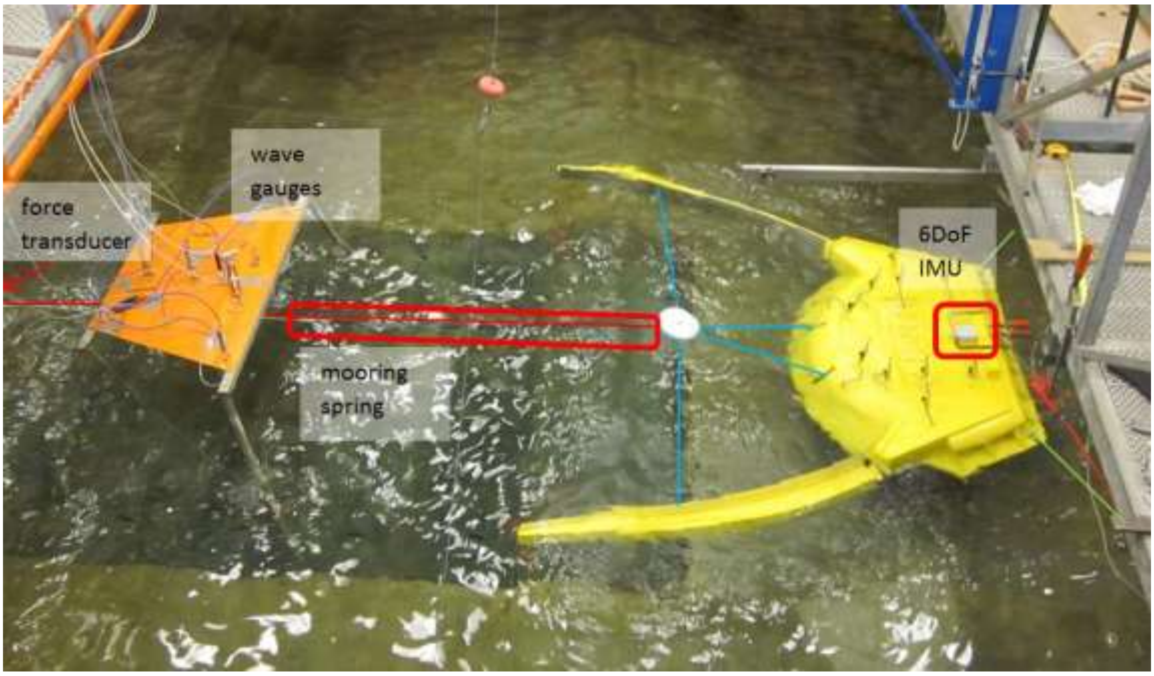


Figure 5.9 Experimental setup of the 1:50 scale model tests

5.4. SUMMARY

Based on the test with the scale 1:3 pilot (compared to the 1.5 MW device) in Nissum Bredning a new 1:50 scale model of the 1.5 MW device was designed by WD. The scale model was tested in the offshore basin at AAU and the expected design wave loads in the main mooring line corresponding to a return period of 100 years at DanWEC has been found. The design loads are described in: "WD-DanWEC Design wave loads in the main mooring line, February 26th 2013 [68]. The developed new full-scale design: "WD 1.5 fuldskala prototype-a.dwg" [20] was the primary deliverance to Dr. Techn. Olav Olsen. OO has based on ACAD drawing developed a 3D model in Microstation. GVA Consultants AB and Lars Bergdahl, Chalmers have been responsible for the mooring analysis based on the data delivered by WD and OO.

References in this chapter [4], [5], [6], [66], [67] and [68]

The reports and articles developed during this phase of the project are: [5], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [28], [30], [66], [67] and [68]

6. DESIGN

This chapter describes the detailed design work.

Dr. Techn. Olav Olsen is considered the world's most experienced designer of offshore concrete structures. OO was the responsible partner for the detailed design of the Wave Dragon structure. The design work had to take into account loads enforced by:

- The large volume of water in the reservoir on the deck of the platform
- The open bottom compartments with variable air pressure for adjustment of the ramp crest level

6.1. OVERALL DESIGN

The overall design drawing by WD/EFM is: "WD 1.5 fuldskala prototype" [20].

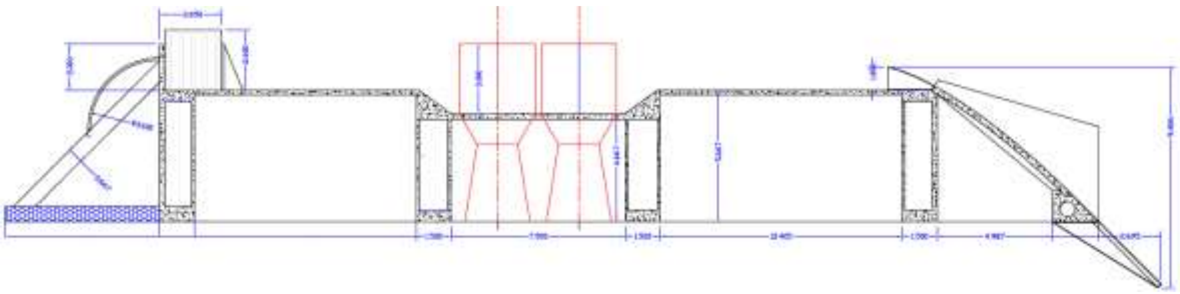


Figure 6.1 Vertical section in the WD platform

The overall design is more easily understandable through the plots from the 3D model below.

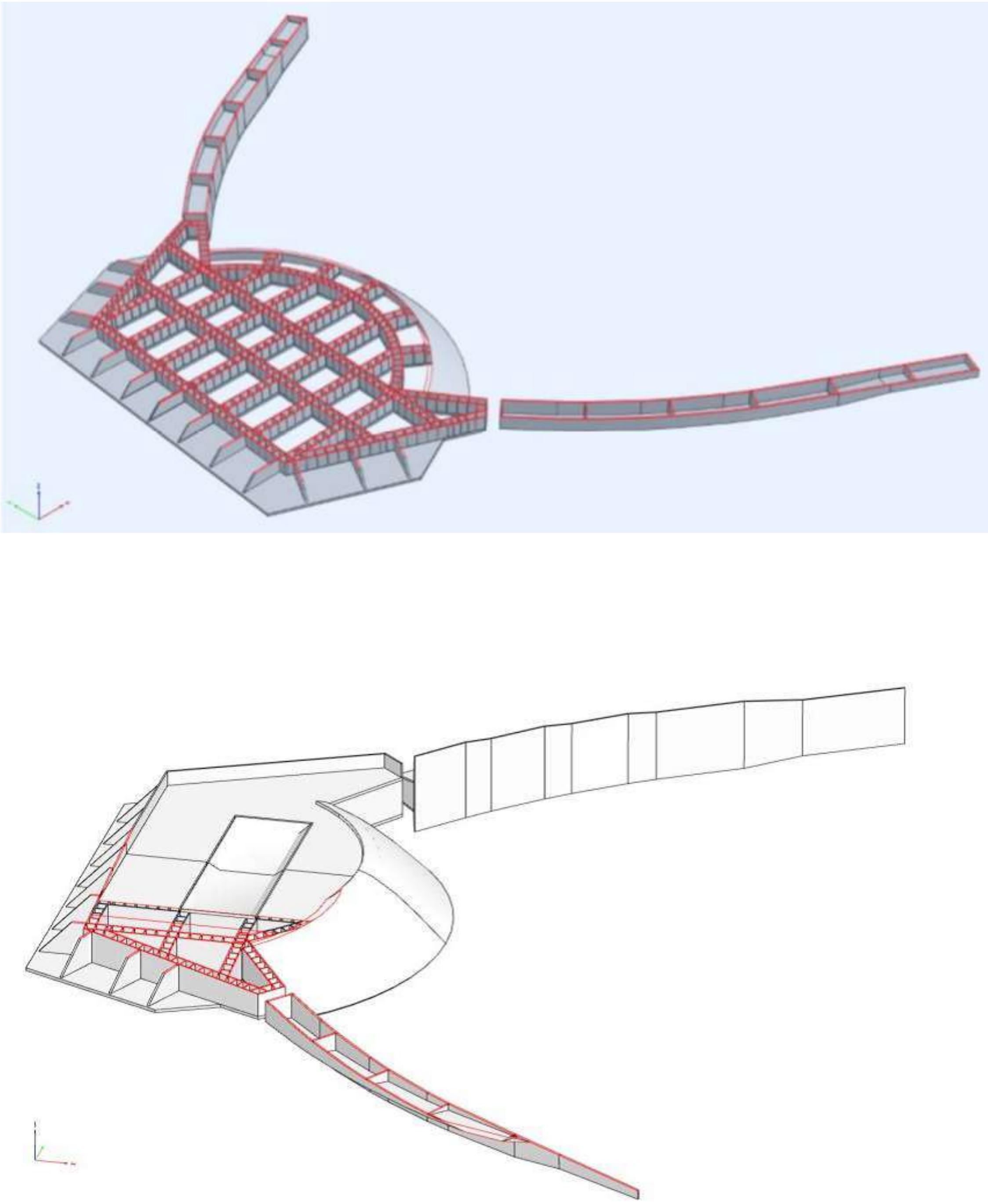


Figure 6.2 Overview of geometry - plots from OO's 3D model

6.2. OLAV OLSEN STRUCTURAL DESIGN

The structural design is described in [21] Dr. techn. Olav Olsen: "Wave Dragon 1.5 MW Structural Design Brief" and "…Report", Documents no.: 11816-OO-R-001 and 11816-OO-R-002, 2013, 18pp and 82pp.

OO rapport summary:

The Wave Dragon wave energy converter has been analysed for structural response due to various combinations of static loads and 1st order wave loads. All analyses are based on survival draught of the unit with a freeboard of approximately 0.5m.

It is found that wave response is in general much higher than static responses and ULS-A load combinations have been disregarded.

The reinforcement densities are in general relatively high. As an example the walls are reinforced by ø25c100 both directions. In some structural parts it is likely that the reinforcement amounts can be reduced by introduction of more post-tensioned reinforcement.

The main conclusion is that for the current size of the wave energy converter concrete may be used as the material but light weight aggregate concrete must be used if only natural buoyancy is taken into account. In this study, it is assumed that top and bottom plates of the ramp, as well as canopy and backing plates are constructed with 300m concrete plate. However, for the latest concept, lighter composite material is suggested for these parts, enabling a higher concrete density. The air supply-vent system in the open bottomed chambers will be constructed to secure the minimum necessary entrapped air volumes to maintain the survival floating level. It may be an advantage to use a concrete density of 1.8 to 2.0 ton/m3 as this will facilitate a higher floating level during the construction phase – it would also be an advantage if the platform could be raised higher than the planned operational level for instance during maintenance of turbines and other installations.

Non-linearity in wave forces has not been considered in this study. Wave loads are based on the assumption of constant water plane area during the wave cycle. Before going further with design it's recommended that non-linear analyses are carried out for comparison with linear theory.

A 3D-model has been prepared in Microstation. This model may be a starting point for any re-modelling related to for instance non-linear analyses.

6.3. GVA MOORING DESIGN

The mooring design is described in [22] GVA: “Mooring feasibility study Wave energy converter at DanWEC, Hanstholm”, GVA document: M0520-HY-RP-053-0001, 2014, 19pp

SCOPE

• Develop numerical hydrodynamic

• Calculate basic hydrodynamic properties which are input to the mooring analysis

• Assess damping properties and recalculate basic properties

• Calculate wave loadings for different drafts

• Mooring design is performed for 1 draft

• Evaluate impact of sea-bead properties on mooring design

…….

Conditions and input data

Catenary mooring lines connected to central buoy is considered. Moreover, a rigid connection between central buoy and platform with a 120 m distance between the central buoy to and the platform centre is studied.

The vessel is oriented 30° clockwise from East to meet the most probable wave directions.

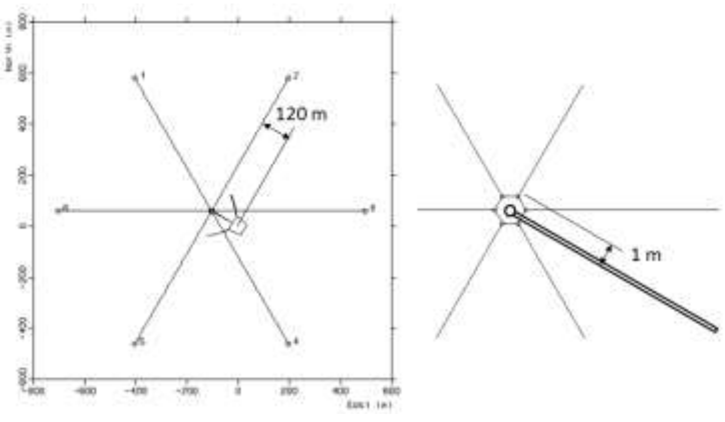


Figure 10-1 in GVA report. Overall system layout and close-up at central buoy

Requirements and safety factors according to DNV-OS-E301 Consequence class 1
Water depth 25 m
Draft 5.7 m
Damping (in MIMOSA/MOSSI file) is: 2.0·106 Ns/m in surge, 2.0·106 Ns/m in sway and 1.0·108
Nms/rad in yaw. This results in approximately 30 % of critical damping.
Headings as in Figure 6-1 calculated. For Headings W and NW the back mooring line is not in tension.
JONSWAP wave spectrum with parameters Hs = 8.28 m, Tp = 12.92 s, peakedness parameter γp=1.8 along with long-crested waves (cosine exponent n=0)
Wind and current are represented with a 900 kN static force that is acting collinear with the waves.
…..

The results of the calculations showed that a traditional catenary mooring system with chains is not feasible for the Wave Dragon DanWEC device since the inertia of the heavy chains makes the mooring very stiff. Replacing the chains with nylon (polyamide) ropes makes the mooring system much lighter and compliant.

GVA CONCLUSIONS

A large structure such as the WD-DanWEC, floating at or directly below the waterline, is subjected to very large wave forces whereby it is not feasible to moor with a catenary chainspread mooring system at 25 m water depth. It is however possible to design a highly compliant spread mooring system with nylon ropes, which reduces the dynamic forces in the lines. The vessel will though move far away from its equilibrium position when the environment forces are acting on it, thus the leeward lines will lie on the seabed.

REFERENCES IN THIS CHAPTER

The reports and article developed during this phase of the project are: [20], [21], [22] and [31].

7. CERTIFICATION

This chapter describes the certification process performed according to DNV-DS-401:

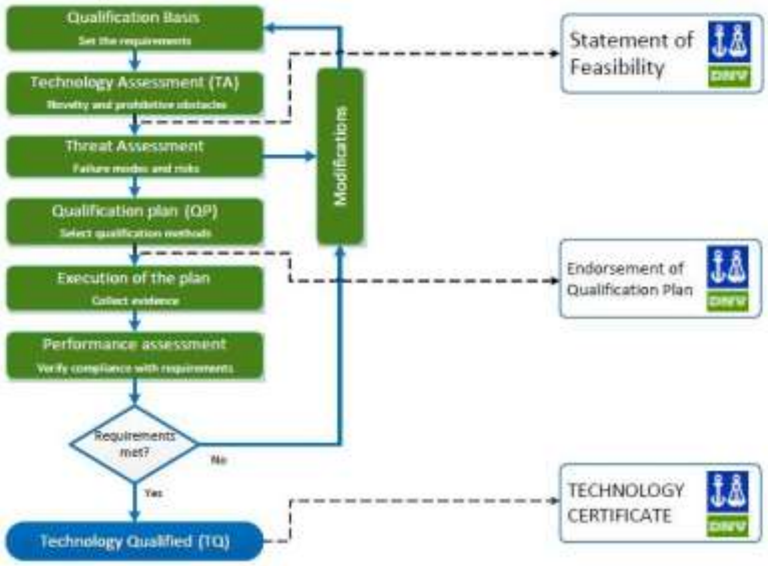


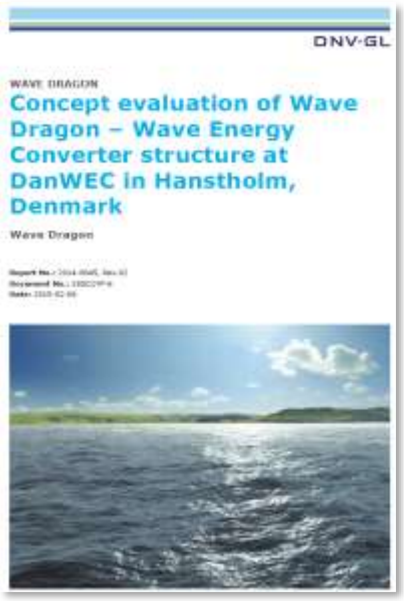
Figure 7.1 DNV GL Certification process overview

"Compared to the process described in DNV-DSS-401, this report can be seen as a Technology Assessment Report. Further steps in the process involve the establishment of a Technology Qualification Plan by Wave Dragon, which will be reviewed by DNV GL and upon finding it adequate will be followed by an Endorsement of Qualification Plan. After the execution of the Technology Qualification Plan by Wave Dragon, the results will be reviewed and in case of successful treatment of the identified challenges, a Technology Certificate by DNV GL will conclude the process."

7.1. DNV-GL REPORT

The certification process is described in the report:

[23] DNV-GL: "WAVE DRAGON Concept evaluation of Wave Dragon – Wave Energy Converter structure at DanWEC in Hanstholm, Denmark", Report No.: 2014-0645, Rev. 02, 2015, 18pp.



Excerpt from the report's EXCUTIVE SUMMARY:

"The purpose of the DNV GL involvement was to evaluate the feasibility of the concrete concept and to find any major structural deficiencies of the proposed design.
The available documentation has been reviewed and a set of comments and recommendations is given for the design brief as well as within the areas of hydrodynamics, structural design, stability and the mooring system.
DNV GL considers the presented concrete concept as feasible according to the definition in DNVDSS-401 Technology Qualification Management"

Excerpt from the report's CONCLUSION AND FURTHER WORK:

"The documentation available for the 1.5 MW Wave Dragon Demonstrator gives a good overview of the structural design of the Wave Dragon Unit and the mooring system even though the documentation is insufficient to document the structural strength of the Wave Dragon for the different design limit states. DNV GL distinguishes between the Wave Dragon concept per se and the Wave Dragon structure with the geometry as presented in the available documentation. DNV GL considers the concept of the Wave Dragon as feasible according to the definition in DNV-OSS-312 "Certification of Tidal and Wave Energy Converters", meaning that "the main challenges have been identified and judged to be reasonable by use of sound engineering practice"/8/.
However, the presented geometry needs to be revised for further development of the Wave Dragon Demonstrator structure. The two main issues as DNV GL sees it are the self-weight versus natural buoyancy and the design of the hinges between the main body and the wave reflectors. Based on the available documentation, further investigations have to be undertaken also in the areas as stated below:"

7.2. WHAT STILL HAVE TO BE DONE

DNV GL has in total listed 9 issues, which should be further investigated.

DNV GL list of issues (abbreviated)	**Wave Dragon comments**
Documentation of the environmental data to be used in the structural design. needs to be provided. These data need to include long term distribution of wave forces for fatigue design.	It is not yet decided if the Wave Dragon 1.5 MW demonstrator should be designed based on DanWEC environmental data only or generic data allowing deployment in more energetic sites
Before further hydrodynamic analyses are made, the final geometry of the Wave Dragon Unit has to be found considering the self-weight and reserve buoyancy.	The overall geometry of the platform is frozen and LWA concrete with a density of 1800 kg/m3 will be used for the bottom and the top slab. The air supply system is designed to hold residual air volumes in the chambers, adding to the natural buoyancy of the platform also when the system is not working.

When the final geometry is found, the stability of the Wave Dragon Unit has to be documented for operational and survival draft.	This is “standard” procedure and part of OO’s tasks for project phase 2.
Further investigations including non-linear wave theory for both operational and survival draft have to be undertaken. Calculations need to cover all limit states (ULS, ALS, SLS and FLS).	This is “standard” procedure and part of OO’s tasks for project phase 2.
Tightness and durability of the concrete structure have to be evaluated. Relevant criteria for water tightness need to be found and defined in the Structural Design Brief.	The criterias shall be defined by WD in close cooperation with OO.
The hinges between the wave reflectors and the main Wave Dragon Unit have to be designed. Since it is assumed that the loads to be transferred from the wave reflectors to the platform will be of considerable size, the surrounding regions will have to be designed as D-regions.	Standard range elastomer bearings as used in road bridges, are well documented and have a very long lifetime. The details of the joint have not been presented to DNV-GL at this design stage.
Special attention will also be given to the corrosion protection of the post tensioning tendons and the reinforcement in general. Crack width criteria will have to be found and defined in the Structural Design Brief.	This is standard procedure and part of OO’s tasks for project phase 2.
A feasible mooring design has to be documented, including geotechnical design.	A complete mooring study will be supplied when the final deployment site will be known.
Design of the structure for all limit states with final wave forces and applicable materials.	This is “standard” procedure and part of OO’s tasks for project phase 2.

Concluding statements from CONCLUSION AND FURTHER WORK:

“DNV GL has received comments by Wave Dragon (WD-DanWEC, November 2014, Kommentarer til DNV GL-rapport) on most of the above mentioned aspects and considers these comments as a guideline for the next phase of the concept development.

…

DNV GL recommends as a first step to update the Design Basis to reflect the intensions and changed premises for the structural design of the platform.”

No. 2014-0645

DNV·GL

STATEMENT OF FEASIBILITY

This is to state that

WAVE DRAGON – Wave Energy Converter Structure

has been evaluated in accordance with DNV-RP-A203 Technology Qualification /1/ for its intended use as reported in DNV Technical Report 2014-0645, /3/. DNV GL considers the technology feasible as defined in /2/ and thereby suited for further development and qualification according to DNV-RP-A203.

Technology owner:	**Wave Dragon ApS, Blegdamsvej 4, 2200 Copenhagen, Denmark**
Name of technology:	Wave Dragon 1.5 MW Demonstrator
Description:	Floating wave energy converter structure made of concrete
Intended use:	Offshore energy production
Main uncertainties:	Subsequent qualification activities should address the aspects as detailed in /3/, section 4.
Involvement:	DNV GL has been involved in the qualification process as required according to /1/ and has identified the main challenges as reported in /3/.
Reference documents:	/1/ DNV-RP-A203, Qualification of New Technology, July 2013
	/2/ DNV-DSS-401, Technology Qualification Management, Dec. 2012.
	/3/ DNV Technical Report No. 2014-0645 Rev.02 "Concept evaluation of Wave Dragon – Wave Energy Converter structure at DanWEC in Hanstholm, Denmark", 6 February, 2015.

The qualification process is in progress and new sources of uncertainty may be discovered as qualification progresses. Attention is drawn to the iterative nature of the TQ process /1/.

Høvik, 2015-02-09
for DNV GL AS

Hege Berg Thurmann
Head of Section

Philipp Rohrer-Baumgartner
Project Manager

REFERENCES IN THIS CHAPTER

The DNV GL report: [23].

8. FEASIBILITY

The feasibility study is based on an update of several studies [50], [51], [52] from the last 12 years, hereby updated.

8.1. THE MARKET FOR OCEAN WAVE ENERGY

The market for ocean wave energy has been estimated by many authors during the last many years. Here we will quote several of these estimates to illustrate the size of the potential market.

The European Ocean Energy Association has in Oceans of Energy - Roadmap 2010-2050 [35] stated:

"The Roadmap for the development of the ocean energy industry in Europe provides a set of steps which, once implemented, would facilitate exploitation of the vast European ocean energy resources and enable the realisation of 3.6 GW of installed capacity by 2020, and close to 188 GW by 2050." In the www.waveplam.eu project report WAVE ENERGY: A GUIDE for INVESTORES and POLICY MAKERS it is stated "that a significant proportion of this to come from wave energy. It is projected that wave energy could have 529 MW installed by 2020 and nearly 100 GW by 2050. This represents 1.4 TWh/ year by 2020 and over 260 TWh/year by 2050, amounting to 0.05% and 6% of the projected EU-27 electricity demand by 2020 and 2050 respectively." [53]

The EC funded NEEDS project for the evaluation of energy policies and future energy systems, developed the following global scenario:

Table 8.1: Worldwide Ocean Energy projections: installed capacity

GW	2020	2025	2030	2040	2050
Very optimistic	20,4	40	61	149	309
Optimistic-Realistic	17	30	44	98	194
Pessimistic	4,8	7,4	10	20	40

Table 8.2: Worldwide Ocean Energy projections: generated electricity.

TWh	2020	2025	2030	2040	2050
Very optimistic	70	151	231	593	1281
Optimistic-Realistic	51	101	152	372	773
Pessimistic	14	22	30	69	152

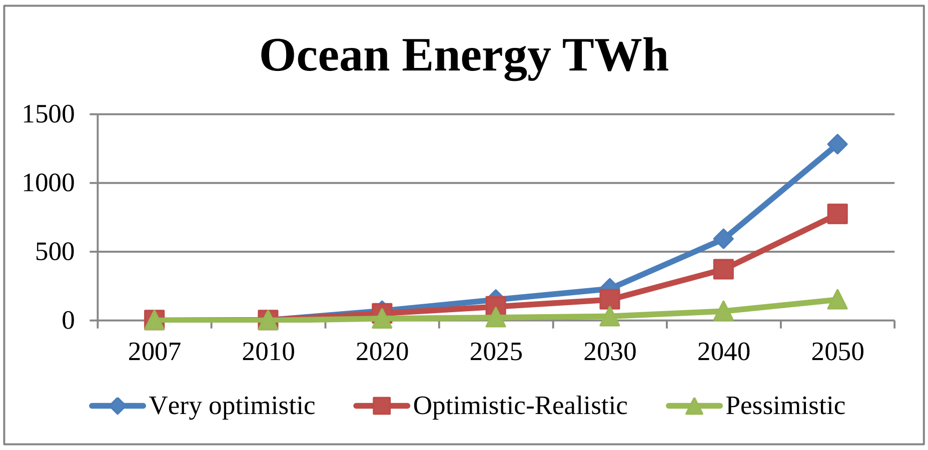


Figure 8.1: Worldwide Ocean Energy projections: power output.

The scene of Ocean Energy is changing very quickly. The market is growing fast, with more and more private and public companies investing in the sector, and with an increasing number of devices being deployed and grid connected. Thanks to this increased presence in the mix of the renewable energies, the public awareness is increasing. Ocean energy is emerging from the specialist domain were it has been relegated in the last decades, and is acquiring a very concrete and role both in the market, and in the public understanding of renewable energy sources.

The European industry is looking with growing expectation at ocean energy. However, in order to gain momentum, the ocean energy sector needs the same political and economic support that other renewables enjoyed in the past. This should be achieved with two main measures: dedicated financial incentives, and the removal of non-technological barriers such as the lack of coastal grid connection, or the administrative obstacles.

The International Panel of Climate Change (IPCC) has in the report [36] stated:

As most forms of renewables energy sources, wave energy is unevenly distributed over the globe. Increased wave activity is found between the latitudes of ~30^{o} and ~60^{o} on both hemispheres, induced by the prevailing western winds blowing in these regions. Particularly high resources are located along the Western European coast, off the coasts of Canada and the USA and the south-western coasts of Australia, New Zeeland, South America and South Africa.

Situated at the end of the long fetch of the Atlantic, the wave climate along the western coast of Europe is highly energetic. Higher wave power levels are found only in the southern parts of South America and in the Antipodes. Resource studies assign for the area of the north-eastern Atlantic (including the North Sea) available wave power re- source of about 290 GW and for the Mediterranean 30 GW. The similar figure for the west coast of United States is 150 GW.

The following map, statement and table is taken from the IPCC report [54]

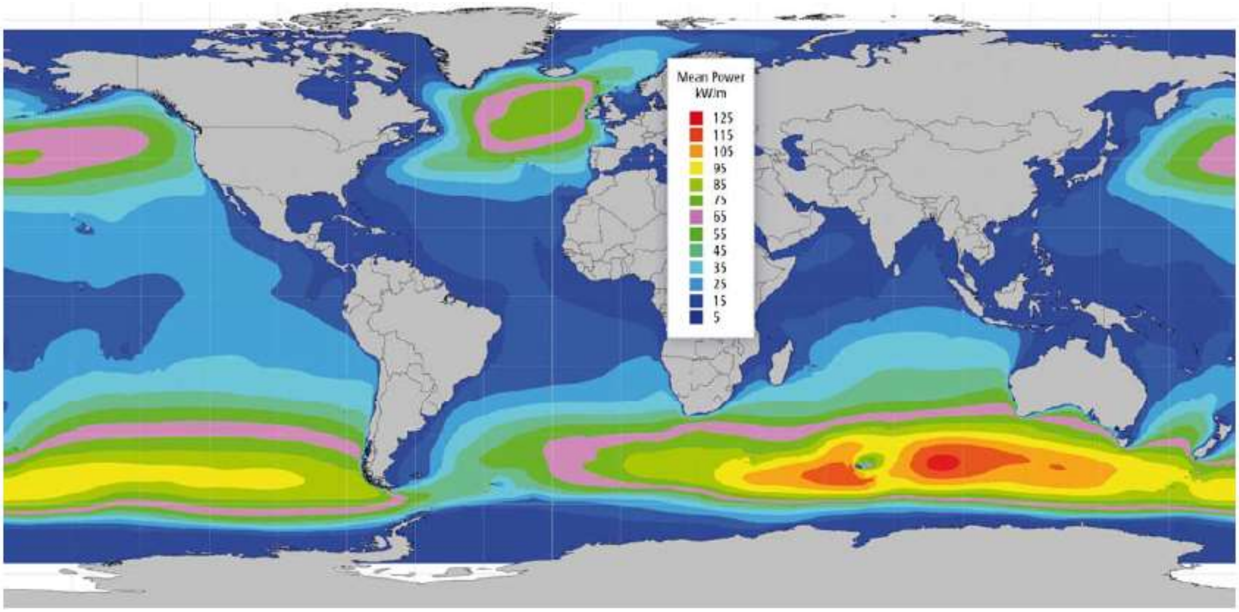


Figure 8.2: Global offshore annual wave power level distribution (Cornett, 2008).

"The theoretical global resource is estimated to be in the order of: 8,000 - 80,000 TWh/year. This has to be compared to the Worlds electricity consumption of 16,000 TWh/year. The total theoretical wave energy potential is estimated to be 32,000 TWh/yr (115 EJ/yr) (Mørk et al., 2010), roughly twice the global electricity supply in 2008 (16,800 TWh/yr or 54 EJ/yr). This figure is unconstrained by geography, technical or economic considerations. The regional distribution of the annual wave energy incident on the coasts of countries or regions has been obtained for areas where theoretical wave power P ≥ 5 kW/m and latitude ≤66.5° (Table 6.1). The theoretical wave energy potential listed in Table 6.1 (29,500 TWh/yr or 106 EJ/yr) represents a decrease of 8% from the total theoretical wave energy potential above (it excludes areas with less than 5 kW/m), but should still be considered an estimate of theoretical potential. The technical potential of wave energy will be substantially below this figure and will depend upon technical developments in wave energy devices. Sims et al. (2007) estimate a global technical potential of 500 GW for wave energy, assuming that offshore wave energy devices have an efficiency of 40% and are only installed near coastlines with wave climates of >30 kW/m, whereas Krewitt et al. (2009) report a wave energy potential of 20 EJ/yr. Potential changes in wind patterns, caused by climate change, are likely to affect the long-term wave climate distribution (Harrison and Wallace, 2005; MCCIP, 2008), though the impact of those changes is likely to have only a modest impact on the global technical potential for wave energy given the ability to relocate wave energy devices as needed over the course of decades."

Table 8.3 Regional theoretical potential of wave energy (Mørk et al., 2010).

REGION	Wave Energy TWh/yr (EJ/yr)
Western and Northern Europe	2,800 (10.1)
Mediterranean Sea and Atlantic Archipelagos (Azores, Cape Verde, Canaries)	1,300 (4.7)
North America and Greenland	4,000 (14.4)
Central America	1,500 (5.4)
South America	4,600 (16.6)
Africa	3,500 (12.6)
Asia	6,200 (22.3)
Australia, New Zealand and Pacific Islands	5,600 (20.2)
TOTAL	**29,500 (106.2)**

Note: The results presented in Mørk et al. (2010) regarding the overall theoretical global potential for wave energy are consistent with other studies (Cornett, 2008).

This wave energy potential is also quoted in the IEA Ocean Energy Systems booklet [59]

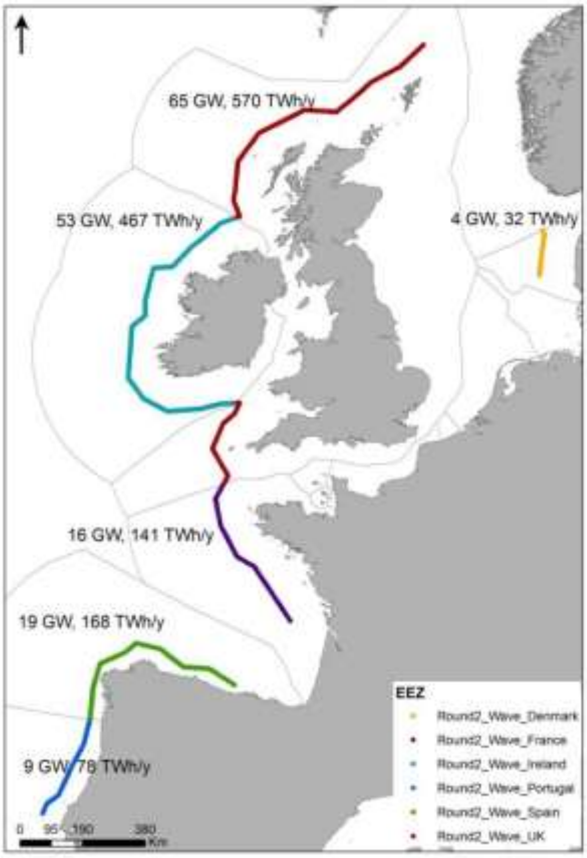
Figure 8.3: Front page IEA Ocean Energy Systems booklet

Pontes et.al. have in the article [38] estimated **3 TW** as the realistic potential.

Table 8.4 Global and regional theoretical wave power resource in GW, [38]

Global and regional theoretical wave power resource (in GW). Left column presents the gross power, the middle one the power excluding the areas where *P*<5 kW/m and the right column the net power (excluding areas where *P*<5 kW/m and potentially ice covered ones).			
REGION	*P* gross	P	P net
Europe (N and W)	381	371	286
Baltic Sea	15	4	1
European Russia	37	22	3
Mediterranean	75	37	37
North Atlantic Archipelagos	111	111	111
North America (E)	115	103	35
North America (W)	273	265	207
Greenland	103	99	3
Central America	180	171	171
South America (E)	206	203	202
South America (W)	325	324	324
North Africa	40	40	40
West and Middle Africa	77	77	77
Africa (S)	178	178	178
Africa(E)	133	133	127
Asia (E)	173	164	157
Asia (SE) and Melanesia	356	283	283
Asia (W and S)	100	90	84
Asiatic Russia	172	162	23
Australia and New Zealand	590	574	574
Polynesia	63	63	63
TOTAL	**3702**	**3475**	**2985**

The SI Ocean Resource Mapping [60] approach combines the wave and tidal energy potential in European waters focusing on the Atlantic arc region (UK, Ireland, Denmark, The Netherlands, Belgium, France, Spain and Portugal). Output from the resource assessment provides information regarding the areas with attractive wave and tidal resources in European waters, and which of these are most attractive when filtering layers are applied (water depth, distance to grid, shipping lanes, etc). The map below shows the accumulated wave energy resource for the Atlantic arc.



The technical potential is around one third of these numbers, which sums up to a total of 551 TWh/year (calculated for 5 rows of devices with a shadowing effect between rows of 15%)

For Denmark the technical resource has been found to 11.5 TWh [62], which is around 1/3 of the present Danish power consumption. In the SI Ocean study the technical energy for Denmark with 5 rows of WECs in the North Sea is found to 8 TWh.

A conclusion is rather easy to draw: the market is huge and more detailed market analyses have to deal with where to get started.

8.2. HOW TO MANUFACTURE THE DEVICE

The method for construction of the 6,500 tonne device will depend on the negotiation with contractors and the equipment available for the period of construction. The manufacturing of the reinforced concrete structure is straightforward using standard methods from the civil engineering field.

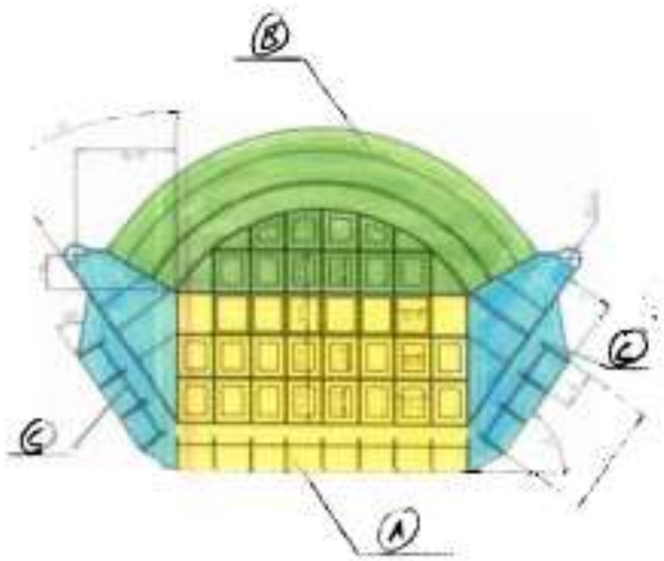


Figure 8.1 Selection of the main body for casting in small parts taken from a previous feasibility study of a 7 MW WD. The revised design is more modular and thus more flexible with regard to casting in small parts – see figure 6.2.

The actual construction process can be one of the following methods:

- Using an existing dry dock sufficient large (LORC) could be used.
- Using a floating barge of steel moored along the quayside in the harbor (50-100 meter industrial type). The barge will be submerged during construction and when Wave Dragon is of sufficient strength the barge can be removed as the Wave Dragon will then be able to float itself.
- Using existing building sites onshore to manufacture different components and finally bringing the components to the quayside where they will be connected using pre-stress techniques known from bridge and tunnel building.
- Building the whole unit on a slip way (50-100 m width) and launching the device into the water in the manner used for traditional shipbuilding.

For the Wave Dragon 1.5 MW device the dry dock has been prioritized as this method looks most feasible.

The gravity block anchors and reflectors will be manufactured at an existing building site (like quay side in Hanstholm) or on the same site as used for Wave Dragon. A tender will be essential.

Wave Dragon can, to a large extend, be deployed, operated and maintained by the use of subcontractors.

Most of the components are standard industrial components or can be manufactured by skilled workshops (e.g. turbines) with some know how transfer form an established turbine manufacturer. Installation works requires skilled electricians, metalworkers etc. To illustrate this: installation of generators, onboard cabling, and installation of hydraulic components etc. on the Danish prototype from 2003 were done by local companies found in the yellow-pages.

8.3. HOW TO GRID CONNECT WAVE DRAGON FARMS?

In contrast to most known types of wave energy converters Wave Dragon delivers a power output in line with offshore wind turbines. As a result of this grid connection will follow the same system as developed by the offshore wind sector. Dependent of the total rated power the following options exist:

<u>A farm less than 50 MW</u>

If the distance to shore (where a substation can be expected) is less than about 15 km a single cable can be used to one of the Wave Dragon units, where the power (AC) has been stepped up to 30/33/60/66 kV. Depending of the number of Wave Dragons and the figuration of the farm either 10 kV cables or 30/33 kV will be used between the individual devices and the Wave Dragon with the transmission cable substation.

If the power is lower than 15-20 MW a 10 kV AC connection can be used, depending of the distance to shore. At the DanWEC centre this solution can be used.

<u>A farm larger than 50 MW</u>

Here we are using the standard solutions for large offshore wind farms. A separate step up AC transformer – typically 110 kV or higher – is placed in connection with the Wave Dragon units like it can be seen at Anholt wind farm.

In the first projects Wave Dragon is only focusing on farms placed close to the shore with dominating waves from one direction. In this case the devices will be restricted from full weather-vaning to avoid twisting of the dynamical cable from the mooring buoy to the sea bed.

8.4. COSTS COMPONENT BY COMPONENT

A study utilizing the Danish developed COE tool, http://www.juliafchozas.com/projects/coe-calculation-tool/ has been performed by Julia F. Chozas (appendix).

Table 8.5 Cost of the **first unit** of a Wave Dragon 1.5 MW Demonstrator designed for a DanWEC wave climate.


JULIA F. CHOZAS
CONSULTING ENGINEER

Wave Dragon

Economic Feasibility Study

This section presents the input values and output results of the COE Calculation Tool for the Wave Dragon 1.5MW Demonstrator at DanWEC.

Wave Dragon 1.5 MW demonstrator

The Wave Dragon is a floating over-topping device designed for water depths of 20 meters or more. The central front face of the device is a curved ramp, up which incoming waves surge (as on a beach). Behind the crest of the ramp lies a reservoir that gathers the water as it spills over the top of the ramp. Energy is extracted as the water captured in the reservoir is allowed to drain back to the sea through a number of low-head hydroelectric turbines located within the reservoir. The amount of energy captured by the device is increased by the long reflector wings mounted on either side of the reservoir, which channel the waves towards the central ramp.

Costs (CapEx and OpEx)		Currency	EUR		
		Default	Enter	Used	
Engineering and management		0.0		0	€x1000
Planning and consenting		0.0		0	€x1000
Development		189.0	2000.0	**2000**	**€x1000**
Main material	Concrete	1290.0		1290	€x1000
Tons of Concrete		5200.0	6450.0	6450.0	ton
Other material	Steel	170.0		170	€x1000
Tons of Steel		50.0	50.0	50.0	ton
Access system and platform		0.0	20	20	€x1000
Machine housing		0.0	50	50	€x1000
50 ton glassfiber		0.0	460	460	€x1000
Total structure				**1990**	**€x1000**
PTO		0.0	1200.0	1200.0	€x1000
Generator		0.0		0	€x1000
Power electronics		0.0	600.0	600.0	€x1000
Control & safety system		0.0	200	200	€x1000
Air system & Hydraulics		0.0	300	300	€x1000
Total power take-off system		7500.0		**2300**	**€x1000**
Mooring system		0.0	**700**	**700**	**€x1000**
Pre-assembly and transport		100.0	400	400	€x1000
Installation on site		100.0	400	400	€x1000
Total installation				**800**	**€x1000**
Electrical connection		510		**510**	**€x1000**
Others		0.0		0	€x1000
Total Capital Expenditures (CapEx) before contingencies				**8300**	**€x1000**
Contingencies		10%		10%	
Total CapEx with 10% contingencies		9130		**9130**	**€x1000**
Operation & maintenance costs per year		498.0	400.0	400	€x1000
Site lease and insurance		166.0	150.0	150	€x1000
Others		0.0		0	€x1000
Annual Operational Expenditures (OpEx)				**550**	**€x1000**

The costs calculated by use of the DOE tool is in line with a feasibility study for 7 MW Welsh demonstrator project if the cost of the structure, PTO and auxiliary systems are scaled according to size:

Table 8.6 Cost taken from a 7 MW WD feasibility study

Item	GBP	Contingency	Cost with contingency
Structure	7,700,000	15.0%	8,855,000
Turbines and PMGs	3,000,000	15.0%	3,450,000
Low voltage installation	720,000	15.0%	828,000
High voltage installation	750,000	15.0%	862,500
Support systems	460,000	15.0%	529,000
Service systems	150,000	15.0%	172,500
Protection systems	140,000	15.0%	161,000
Navigational systems	40,000	15.0%	46,000
Control and instrumentation	170,000	15.0%	195,500
Floating Barge	2,800,000	15.0%	3,220,000
Mooring	2,300,000	15.0%	2,645,000
Total	18,230,000		20,964,500

It should be noted that the exchange rate between GBP and DKK has varied considerably in the since the mentioned 7MW feasibility study.

Table 8.7 The following CAPEX budget for the 1.5 MW demonstrator is primarily based on a feasibility study for 7 MW WD Welsh demonstrator

Item	Cost (DKK)
Structure	11,967,000
Turbines and PMGs	10,443,000
Hydraulic dampening and PMGs	2,000,000
Low voltage installation	2,780,000
High voltage installation	3,982,000
Support systems	2,205,000
Service systems	667,000
Protection systems	623,000
Navigational systems	291,000
Control and instrumentation	927,000
Mooring	11,600,000
Contingency (15%)	7,123,000
Device total	54,608,000
Construction yard preparation	2,000,000
Construction yard running costs	500,000
Insurance (15% per year)	4,000,000
Device construction total	61,108,000
Transmission sub sea (3km)	6,600,000
Onshore transmission	500.000
Mooring installation	600,000
Device installation	600,000
Wave Energy plant total	69,408,000

8.5. MARKET OPPORTUNITIES

The Wave Dragon product will be competing with other equipment suppliers to the general market for renewable electricity such as other newcomers within wave- and tidal devices as well as established RE technologies; PV, wind, biomass etc. Many countries have however established support schemes for these specific technologies thus offering initial individual financial support systems with the aim of promoting new technologies in the initial high-cost phase during market introduction. A separate market for marine energy and wave energy is therefore emerging.

This wave energy market can conveniently be segmented into:

- ≈ A market for bulk electricity generation into a central grid. This is a highly Wave Dragon-relevant market in which Wave Dragon will be competing with large solar plants, off- and onshore wind and biomass as well as other wave energy technologies
- ≈ Delivery of electricity to an isolated grid. This is also a highly relevant Wave Dragon market, in which the main competitive parameters will be the possibility for deep-water deployments;
- ≈ Remote communities and islands, in which the main competitive parameter is the avoided cost of energy from diesel generated electricity
- ≈ Offshore production facilities, in which the main competitive parameters are 1) availability, 2) scale of electricity supply and 3) avoided cost of energy from diesel generated electricity
- ≈ Powering stand-alone equipment.

The costumers for central grid connected Wave Dragons are expected to be identical with the present developers of offshore wind projects; i.e. small developer companies that develop projects to be sold to energy companies, and larger developers that plans, constructs and operates farms; among them the major energy companies.

Business case well defined:

Wave Dragon is particularly suited for the following purposes, which clearly defines three potential entry markets for the exploitation of the technology:

1. Utility-size renewable electricity generation: most wave energy converters aim at achieving resonance with the prevailing waves in order to maximise their power production. Although control systems can provide flexibility to some degree by widening the spectrum of the usable waves, the maximum size of these kinds of devices is defined by environmental conditions. Wave Dragon’s size is not limited by the dominant wavelength, but on the contrary its performances increase with size, which is therefore only limited by economic considerations (i.e. cost of the device). This brings many advantages, such as the ability to be deployed in parks with a relatively low number of

devices, thus limiting complications and costs related with e.g. power connection cables, mooring components and auxiliary systems. Rated power of Wave Dragon parks can therefore easily become comparable to those from traditional power plant: to provide the power of a medium size coal-fired plant, 700 MW, only 100 Wave Dragons deployed in a 36 kW/m average wave climate – such as can be found offshore at many North Atlantic locations – would be required, compared to the thousands required by devices of other types (see also Fig. 1.4).

Furthermore, by relying on a passive survivability strategy and allowing most of maintenance operations to be carried out on board of the platform, Wave Dragon can be safely deployed at the most energetic offshore locations.

2. Servicing remote/isolated communities: the reservoir of Wave Dragon provides energy storage capacity in the form of potential energy, while the PTO control strategy allows power production peaks to be smoothened out. Combined with the large size of the device, this is very attractive for remote communities (including offshore platforms) and islands, where weak grids require renewable electricity of high quality. In the latter case, it is particularly interesting the opportunity to combine Wave Dragon with two wind turbines, as it has been shown that wind and wave power have the potential to balance each other increasing the overall power quality. In many cases a few devices with significantly contribute to the energy requirements of remote islands, the cost of electricity being competitive even with limited support schemes (e.g. low feed-in tariffs) as in this case energy production is costly supported by importing raw non-renewable energy sources such as fossil fuels from the mainland.

3. Service platform for fish farming and algae production and floating foundation for wind turbines: the Wave Dragon platform is large (6,500 to 45,000 tonnes) in order to get out of resonance with the waves. Therefore the platform can form base for wind turbines or serve as platform for productions like fish farming or algae production.

The Wave Dragon concept is based on traditional technologies with many years of experience in different fields, such as concrete floating barges, catenary moorings, and low-head hydro-turbines. The innovative aspect of the technology lays in its design and the way it is operated. This has noticeable benefit of lowering risks and uncertainties related with the sub-systems performance, as well as the potential to create positive synergies with other industrial sectors such as the ship-building and concrete industry, or even facilitating the emergence a spin-off industry in serial low- head hydro-turbines production for wave energy application.

Affordable, cost-effective, resource-efficient technologies (LCOE):

All of the above will drive down the cost of wave-generated electricity produced from Wave Dragon, to levels that are expected to be comparable with those from the offshore wind sector. LCOE is expected to converge to the goal of 0.04 €/kWh (+ capital costs) at locations with an average wave power climate of 36 kW/m such as the North Atlantic, some 10% higher in less energetic conditions such as found in the North Sea. This presents the case for a highly affordable and cost-effective (low maintenance) energy technology, comparable not only with other renewables but also with traditional technologies, especially (but not only) when externalities are taken into account.

Technological synergies

Being of the terminator-type of WEC, Wave Dragon offers sheltered waters for some wavelengths on its lee side. This may lead to positive synergies with applications such as fish farming and offshore platforms which need continuous serviceability. One of the most interesting technological synergies, as mentioned above, is with offshore wind power. Wave Dragon could provide a floating, stable platform for two wind turbines rated at 1/3 the device power each, a unique case in which a wave energy converter is of a power class comparable to the one reached by wind turbines. In this case the power production profile from wind and waves will balance providing high quality electricity, while other benefits will derive from sharing infrastructure such as power cable and substations, mooring system and auxiliary systems.

In some cases, Wave Dragon could even be used to limit erosion on sandy beaches, by being deployed in lines relatively close to the shore, thus acting as a floating barrier to the waves by acting on their transmission coefficient. In this case though the device would likely be over-dimensioned for its traditional aim of power production, as it would rather be used for the absorption of extreme waves, and thus economics viability will have to depend on complementary considerations. www.Theseusproject.eu - Wave energy converters as a coastal defense technique

Theseus report with detailed calc - Wave Dragon as coastal defence: http://tinyurl.com/k6qkr38

Wave Dragon has initiated the following activities:

UK and Ireland

Wave Dragon is developing a wave energy farm in the Celtic Sea. This project has an option to be linked to the planned Irish-Welsh DC inter-connector. A number of interested local counties and developers are being lined up.

Portugal

Wave Dragon has initiated a Wave Dragon project through a Portuguese company (TECDRAGON S.a.r.l.) to develop wave energy farms in Portugal and Portuguese speaking counties. This is done in cooperation with a Portuguese managed international investor group. Based on a favorable financial due diligence by Banco Espirito Santo Invest new investors among the major Portuguese contractors and energy companies are teaming up.

South Africa

Wave Dragon has been short-listed for an ESKOM wave energy project. An organizational set-up developed together with IFU is stand-by, ready to become operative if this lead turns out positive

Spain

Wave Dragon has been investigating project opportunities along the north coast as well as along the southern Atlantic coast. Without a Spanish support regime for wave energy it seems however at this time more reasonable to go for a demonstrator plant at the Canaries, where the wave climate is good and the power price high.

India and Greece

Wave Dragon has been in contact with several local developers of wave energy plants, but these projects are at this time on hold.

China

Wave Dragon has been working closely with a Chinese university for some years now, but public support seems to be needed to progress further at the time of writing.

We expect most major Oil & Gas companies with offshore production facilities to be relevant costumers. Wave Dragon has been in contact with PETROBRAS and CHEVRON concerning drafting possible combined wave- and diesel-generation power supply. PETROBRAS has short listed Wave Dragon for a possible demonstrator in Brazilian waters.

The geographic distribution of the Wave Dragon relevant markets are determined by:

- ≈ Available wave energy resources; the wave climate
- ≈ Cost of energy from competing sources
- ≈ Political climate; e.g. financial support and regulatory framework

This means that the entry markets for Wave Dragon are considered to be UK, Ireland and Portugal; which have attractive wave climates as well as attractive support system and regulative framework about to be in place. In the UK the favorable ROC system is now being replaced by a CFD system. It is not clear how favorable the new support regime will be for wave energy, but considering the attractive wave climate we are still quite optimistic with regard to a Welsh project. In Portugal a demonstration zone has been established; expected feed-in tariffs in the level of 0.17 €/kWh to 0.22 €/kWh.

In Ireland a national target of 500 MW by 2020 has been declared; the regulatory framework is being developed and wave resources are abundant; feed-in tariffs in the level of 0.22 €/kWh.

Countries like Denmark and other countries with a moderate wave climate will also be relevant. This is even more true when scale in manufacturing can reduce cost. An early market entry in these countries will be possible when the Wave Dragon is combined with wind turbines.

The size of the "central grid" market are expected to be in line with the present and expected future offshore wind markets i.e. slowly developing but generally expected to be large. Markets not seen as relevant offshore wind markets like west coast US, Scotland, Spain and Ireland can develop into very attractive offshore wave energy markets.

Wave Dragon expects to achieve capital costs per installed unit capacity and total electricity generation costs which are competitive with existing renewable technologies that are being built at present (e.g., offshore wind).

Compared with other ocean wave energy technologies, Wave Dragon has the scale to be truly commercial for bulk electricity generation. It is designed to be robust in operation and easy to maintain and operate in a real offshore environment.

The Wave Dragon prototype was as mentioned the world's first floating grid connected wave energy converter. With 20,000 hours of real-sea grid connected experience, reliance on existing proven marine technologies, an industry standard mature power take off system, and an outstanding network of partner companies; technical and scale-up risks are reduced to a minimum.

The design life time of the structural parts is more than 50 years; in line with offshore concrete oil platforms. The design lifetime of the water turbines and most of the auxiliary systems is 25 years.

Wave Dragon has published expected production cost during the whole development period based on cost calculations by several large offshore contractors. The price level has been verified through extensive testing of models and the 1:3 scale (of the 1.5 MW device) prototype. Several feasibility studies have been performed, and even if some of which are rather old the main findings are still valid .The expected price level for Wave Dragon has been studied in detail both in a EC framework program supported project and also in the UK Carbon Trust Marine Energy Challenge project. Without financial costs the findings were:

Table 8.8 Wave Dragon expected cost in €/kWh

Wave climate	Device capacity	First device	After deployment of 100’s
24 kW/m	4 MW	0.11 €/kWh	0.054 €/kWh
36 kW/m	7 MW	0.083 €/kWh	0.040 €/kWh
48 kW/m	12 MW	0.061 €/kWh	0.030 €/kWh

Table 8.9 Wave Dragon expected capital cost in €/kW

Wave climate	Device capacity	First device	After deployment of 100’s
24 kW/m	4 MW	4,000 €/kW	2,300 €/kW
36 kW/m	7 MW	3,200 €/kW	1,875 €/kW
48 kW/m	12 MW	2,700 €/kW	1,575 €/kW

Due to inflation and quite volatile raw material cost these prices needs some adjustments. The price level is nevertheless seen to be competitive with offshore wind when getting up in scale.

8.6. STATE OF THE ART REVIEW

The state of the art within wave power is in many ways comparable to the state of the art within wind power around 1980. A vast number of different technologies are being promoted, and it is not currently established which technology will be “the winner” in the long run. Also, very few of these technologies have gone through sea trials.

Apart from a few onshore or near-shore systems being developed for small special markets, govern-ments and technology developers are focusing on offshore systems. All offshore competitors to Wave Dragon are developing resonant systems, i.e. buoy-based, oscillating water columns (OWCs) or systems like Pelamis. As a consequence their systems are limited in size due to the requirement to be in resonance with the waves.

The field of wave energy competitors is well described in the United States “EPRI wave energy evaluation program”, the UK “CT Marine Energy Programme” and in the reports of the European project “Waveplam”. Wave Dragon is constantly listed among the top 3-5 systems with regard to commercial and technological perspectives; none of these top 5 companies has published scientific data or results openly - except Wave Dragon.

Wave energy converters can be classified as follows:

Attenuator: Pelamis is a wave energy device which extracts energy from the pitching motion of the waves through quite a complex series of hydraulic rams. It has raised more than £70m for its development and has won three commercial contracts (Portugal, Orkneys, Cornwall) for multiples of its 0.75 MW device. The reported maximum power production has been 280 kW in average over a 30 minutes period. There have been persistent rumors of technical and maintenance problems. The company was closed ultimo 2014.

Point absorber: These smallish devices heave under the action of the oncoming wave. Typically they react against another part of their structure, or the anchoring lines, with some generator extracting power from the relative motion. For optimal design they must be small compared to the waves, and are therefore usually limited to a power of 150 – 250 kW. Some developers claim very high rated power, but this comes of course with a low capacity factor. The OPT PowerBuoy is the best known buoy-based technology. OPT planned to deliver wave farms based on arrays of buoys each rated at either 40 kW or 150 kW. OPT achieved an AIM listing in 2003, followed by a NASDAQ listing in 2007 (net $90m). Until today the reported maximum power production has been 45 kW from test with a non-grid connected 150 kW buoy - specifications can be found at www.oceanpowertechnologies.com
OPT now concentrates about developing their small buoys with peak power up to 50 kW

Seabased is another point absorber, but of the tight-moored type as opposed to OPT. The company is developing a €29m, 10 MW project in Sweden, with €15m public grant support.

The plant consists of 340 devices i.e. each buoy has a power below 30 kW (http://www.seabased.com/).

Oscillating water column: Very few floating OWC's have been tested in real seas. Oceanlinx have in rather short periods of time tested two quite different designs of scaled floating prototypes. No test results have been published - http://oceanlinx.com

Ocean Energy has tested a fourth scale prototype for a prolonged period of time, but no more than 816 hours of data were collected with the new developed type of air turbine – of which only 192 hours with a wave height more than 0.8 m - http://www.oceanenergy.ie/

Other types of floating WEC's exist, but until today no significant large scale tests have been performed.

Innovation potential of Wave Dragon beyond the state of the art

The State of the Art of any Industry is often hard to clearly define; in the case of Wave Dragon particularly, and Renewable Energy in general, this is especially difficult. Wave Dragon has, in the past, been criticised for being a 'low-tech' option. We do not think of this as a criticism at all. Wave Dragon is simple, tried and tested; its major component parts are drawn from industries that are equally tried and tested. We know our turbines will be state of the art in 50 years, because their design was state of the art more than 50 years ago and has changed little since; in fact Wave Dragon have simplified the old turbine design rather than complicated it.

Wave Dragon is a State of the Art Wave Energy technology, but due to its innovative application of existing technology. Should the potential, of this technology, be maximised through a project such as this, the resulting wave energy development will benefit energy supply, security and a low carbon European economy.

The most important technical differences between Wave Dragon and its competitors are addressed below:

- ≈ Bulk energy production, in the multi-MW range: The size of Wave Dragon gives it a head start with regard to capital and maintenance cost. In a 100 MW wave energy farm only 14 Wave Dragon devices are needed compared to 400 or more buoys and 133 Pelamis (see Fig. 1.8). With regard to offshore transmission capital cost this means a cost advantage in the range of €200 to €90 per installed kW for Wave Dragon. There is a similar cost advantage with regard to mooring costs. In the "All Island Grid Study" by the Irish grid operator ESB it is stated: "Pelamis (750kWe) was used as the reference machine in the Irish Wave Atlas while Wave Dragon (7 MW) has been used in this study because of its potential economy of scale from a utility perspective."

- Simply scalable from 1.5 to 12 MW in accordance with the local wave climate.

- High survivability, storm protection mode is passively achieved [5: The survivability of the Wave Dragon is rendered unquestionable through validation by wave tank tests and structural analyses performed by experienced contractors within offshore wind power and oil & gas industry. Experiences from the more than 20,000 hours of sea trials have verified the survival capabilities.

- Standard mooring system, absorbing peak load without affecting PTO system. Also, the fact that Wave Dragon is a slack moored device means that tide has no influence on the power production, as opposed to coastal-based devices and devices that utilize the ocean bed to resist heave movements. The potential for this type of device is huge – the main request to the deployment site is water depth of minimum 20 meters.

- Installed power easily adaptable to local grid demands.

- Smooth power output ensured by onboard energy storage and set of turbines (see Fig. 2.1): The reservoir has a volume large enough to accommodate the overtopping from 3 consecutive waves in the dimensioning sea state (5 meter significant wave height). A high number of the fast operating variable speed on/off turbines provide for a smooth ramping of power production from wave group to wave group ensuring a high quality power production.

- No new mechanical equipment, PTO by proven hydro turbine technology: The Wave Dragon utilizes a mature and highly efficient power conversion technology with low maintenance requirements. Whereas most wave energy converters utilize novel and complex air turbines or complex hydraulic engine systems, a low-head axial propeller turbine has been developed and tested for the Wave Dragon with peak efficiencies above 90%. Turbines of this type have been in operation for 80 years and are still running, with very low maintenance requirements.

- Few moving parts (only turbine rotor) allowing low maintenance and high reliability.

- High availability, producing even in very low waves and having no upper-production limit: The turbines utilise permanently magnetized synchronous generators controlled by frequency converters, allowing the turbines to be operated at variable speed, which secures that the efficiency stays very close to the peak value in the whole pressure head range between 0.7 and 4.0 meters.
- Vast real sea experience, with 20.000+ hours of prototype operation. It was the World first floating WEC delivering electricity to the grid (May 2003).

- Low O&M costs, only the turbines will be brought to shore for major overhaul: The competing technologies need to be towed to a harbor for necessary maintenance (e.g. Pelamis is expected to need planned maintenance once a year). In Wave Dragon, planned overhaul of turbines will be done in a workshop (every 5 years) and do not reduce the yearly power production. This is due to the redundancy of Wave Dragon's power take off system. Planned maintenance will be performed during the summer period where the wave power is low, which means that there is no need to operate the full set of turbines to handle the overtopping water. All other maintenance work than major turbine overhaul can easily be performed at sea. This well-structured maintenance operation plan ensures much lower O&M cost for Wave Dragon compared to all competing offshore wave energy converters.

- Long certified lifetime: The offshore competitors to Wave Dragon are built in steel, which makes them vulnerable not only to corrosion but also to rather unpredictable steel prices. Wave Dragon is primarily constructed in reinforced concrete, which is a much more price stable material. Offshore concrete constructions like Wave Dragon have a certified life time of more than 50 years even without maintenance. The Wave Dragon water turbines are - as opposed to the power take off systems of the competitors – a well proven technology with 90 years track record. The expected economic lifetime of Wave Dragons power take off system is 25 years – much higher than can be expected for unproven technology such as the air turbines, high pressure hydraulics and linear generators as proposed for the competing wave energy devices.

- Low environmental impact even compared to other renewable energy technologies. Wave Dragon was the WEC to deliver an Environmental Impact Assessment (EIA) in April 2007 [8].

- Enables industrial synergies, as it can host 1 or 2 wind turbines, boosting the power production more than 50%. Due to the large rated wave power, it is perhaps the only WEC for which a combination with offshore wind turbines makes sense today.

- IP Protected: Both the Wave Dragon technology and some of its unique features are patented. The patented doubly curved ramp profile has been verified as the optimal overtopping ramp profile among 20+ different profiles tested. The patented wave reflectors have been verified to increase energy capture by 30 to 70%.
- Proprietary control strategy ensures constant high conversion efficiency, thanks to the unique operational knowledge acquired during the almost 20 year of continuous development.

8.7. BUSINES PLAN

This chapter is taken from the Summary of a Wave Dragon short version[1] Business Plan.

Wave Dragon is a state-of-the-art solution for large scale exploitation of wave energy, with production capacity directly comparable to traditional power plants.

Wave Dragon was the first floating wave energy converter in the world to be connected to the grid. This was in 2003, and since then Wave Dragon has accumulated more than 20,000 hours of operational data.

The Wave Dragon Prototype in Denmark, 2003 to 2011

Wave Dragon clearly stands out as the most promising solution within exploitation of wave energy – especially supported by three key facts:

1) **A flexible modular solution with unit sizes from 1.5 MW to 12 MW, offering power plant capacity of 500+ MW.**

2) **A long term perspective of being commercially viable on market terms with a cost of down to 4 pence per kWh (ex. finance).**

3) **Today; offering power plant operators and investors a profitable wave energy solution, with IRR's in excess of 10%, given the current favorable subsidy schemes.**

Wave Dragon is an attractive opportunity to invest in the development of a wave energy solution, which has the potential to be a globally leading player within renewable energy prodution – and even further; not just within renewable energy, but across a whole range of traditional power producing facilities.

[1] Full versions of WD Business Plans not to be released without signed NDAs.

Wave Dragon is looking for funding to:

1) **Construct and deploy the first full size power plant unit**

2) **Develop Wave Dragon into a business selling power plants globally**

Re 1) The first full size power plant unit can be 1.5MW, 4MW or 7MW, subject to investor preference for location of deployment, size of investment and easy of selling the unit on to an actual power plant project. The funding required will accordingly be £8M, £16M or £22M. If the first unit is sold on to an actual power plant project, a significant part of the investment can be recouped.

Re 2) Funding of up to £8M is required to engage in developing and selling power plants globally, and funding the business until it is cash flow positive.
This investment will over the next 5-7 years enable Wave Dragon to sell power plants of around £500M per year with EBITDA > 20%. This could value Wave Dragon of more than £600 million offering an investor a very attractive return, via either an IPO or a trade sale.

Wave Dragon Wales – 28MW Power Plant
Wave Dragon is currently well progressed with developing a 28MW power plant to be deployed off the Welsh coast. This is a £98M investment which, when in full operation, will generate electricity sales of more than £20M per year with EBITDA > 80%. A first 4MW or 7MW unit could be sold on to this power plant project.

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Power generating estimates, based on the existing research and knowledge, are given below in expected GWh per year based on the wave climate.

Power Production				
Wave climate in kW/m	**<12**	**12-24**	**24-36**	**36-48**
Unit size / MW capacity	**1.5**	**4**	**7**	**12**
Max. power production-GWh/year	**4**	**12**	**20**	**35**

Wave Dragon will have the capacity to operate in sea environments of up to 60-70 kW/m.

Technologically, Wave Dragon is made up of proven technologies. Establishing large offshore Wave Dragon farms does therefore not present technical challenges which have not been solved within other industries. Wave Dragon utilise mature technology. One significant innovation is the design of the wave concentrating flume. Wave Dragon have through the many years of focused work identified and developed several IP protectable solutions which minimise the cost per kWh produced.

Additional Technical Information and detailed descriptions of functionality, research data and verifications are available.

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9. DISSEMINATION

This chapter describes the dissemination of the project results.

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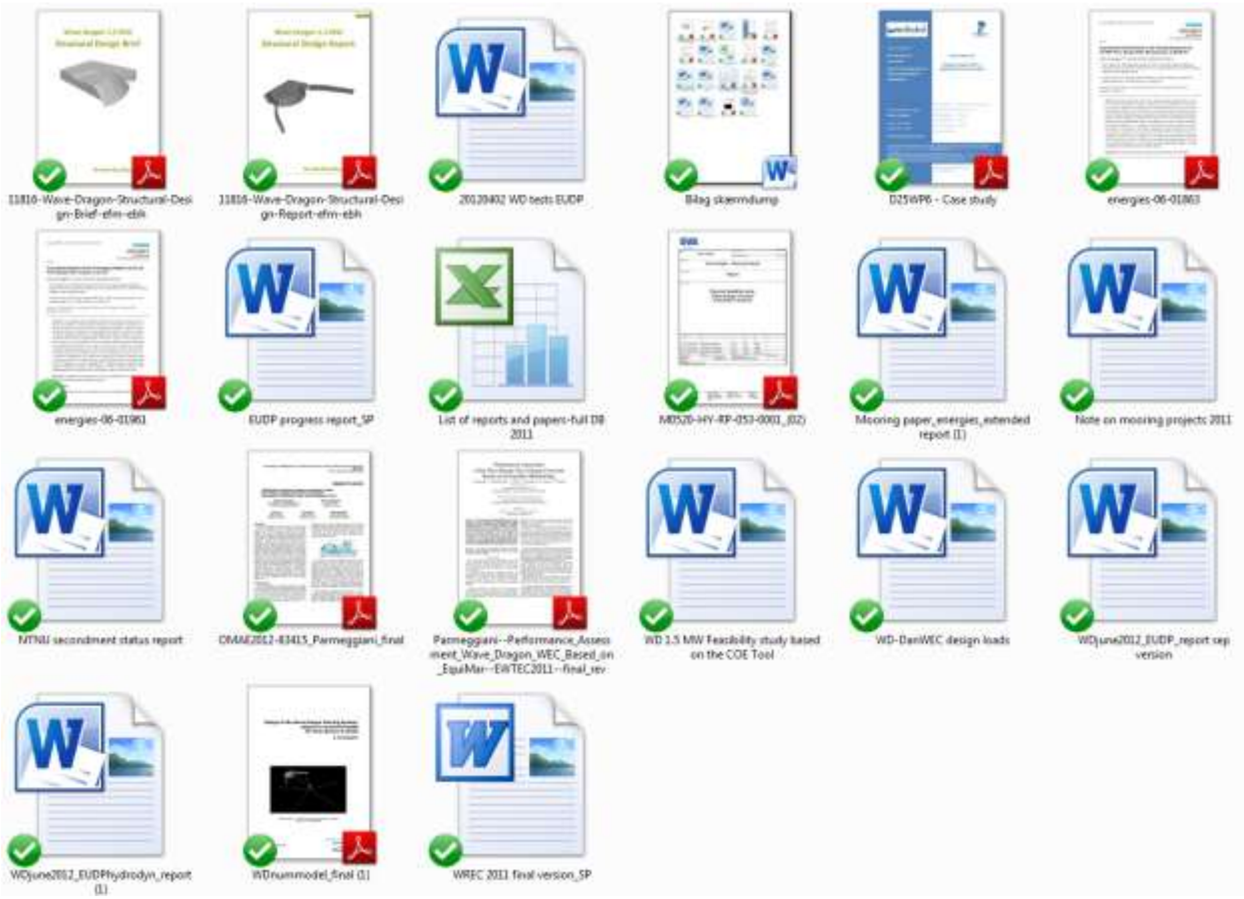
11. APPENDIX



+ DNV GL reports

+ WD leaflets

+ Figures from previous feasibility studies