ENERGY INNOVATION CLUSTER

Danmarks klyngeorganisation og innovationsnetværk for energiproduktion

Concrete for Wave Power

– Beton til Bølgeenergi

– B2B

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FINAL REPORT

PROJECT DETAILS

Project title	Concrete for Wave Power – Beton til Bølgeenergi – B2B
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Disclaimer: This report cannot substitute common sense and a good understanding of engineering. It is intended as a starting point for developers who wants to investigate the potential of using concrete for floating structures. But each developer must assess their own designs, carry out their own calculations etc. The authors take no responsibility for the results of using the report, but interested readers are welcome to contact them with questions regarding the use of concrete for floating structures.

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2. OBJECTIVES AND RESULTS (ENGLISH)

The objective of the project has been to investigate the use of concrete as construction material for floating Wave Energy Converters (WECs) to obtain lower structural costs and longer design lifetimes than 50 years without maintenance of the structures which can reduce the costs of energy significantly.

Several Danish wave energy developers are working on development of WECs. On the webpage www.wavepartnership.dk for the "Partnership for Wave Power" there is an overview of 11 Danish WECs under development. Of these *Wave Dragon* and *KNSwing* are large passive structures well suited to be built in concrete. Both systems absorb the wave energy with no moving parts outside of the turbines. The two WECs under investigation are both large multi MW converters for offshore deployment operating at water depths above 30 m at commercial scale.

The conclusion from the analysis are showing that following the state of the art of offshore concrete technology it is possible to establish wave farms of the size 100-1000 MW that can compete with floating offshore wind.

3. OBJECTIVES AND RESULTS (DANISH)

Formålet med projektet har været at undersøge anvendelsen af beton som byggemateriale til flydende bølgeenergimaskiner (WEC's) med henblik på at reducere strukturomkostninger og opnå en design levetid på 50+ år uden større vedligeholdelse af strukturerne, hvorved energiomkostningerne kan reduceres betydeligt.

Flere danske bølgeenergi udviklere arbejder på udvikling af WEC's. På hjemmesiden www.wavepartnership.dk for "Partnerskab for Bølgekraft" der er en oversigt af 11 Danske WECs under udvikling. Af disse er *Wave Dragon* og *KNSwing* store passive strukturer velegnet til at bygge i beton. Begge systemer absorberer bølgeenergi uden bevægelige dele udenfor turbinerne, og er begge multi-MW offshore maskiner beregnet for udlægning i kommerciel målestok på vanddybder over 30 m.

Konklusionen fra analysen viser, at det med dagens teknologi for offshore beton er muligt at fremstille de to anlægstyper i beton til konkurrencedygtige priser i forhold til flydende vindmøller, hvis produktionen sker i stor skala, dvs. i form af parker at størrelsen 100 til 1000 MW.

4. EXECUTIVE SUMMARY

Concrete is a perfect construction material for large wave energy devices.

The standards to be used can be difficult to identify. A recommended way is to use the DNV GL ST- C502 from 2018: *Offshore concrete structures* recommendation as basic document.

To increase lifetime – avoid corrosion of reinforcement, it is recommended to use light prestressing or fiber reinforcement in high stressed part of the construction. Special concrete like CRC can be optimal for special sections.

Huge price reductions are possible by mass production of concrete structures - reduction in mass production in the cost of fabrication facility is in the order 450€/kW to 250€/kW.

The LCOE for the *Wave Dragon* and the *KNSwing* technologies may be competitive with floating wind when used in wave farms. The cost of the concrete structure for the first 1 MW unit of *KNSwing* is 3600€/kW which for 100 units will be reduced to 3000€/kW. For *Wave Dragon* the 4 MW unit is reduced from 1125€/kW to 900€/kW.

In order to bring Wave Energy to commercial business it is therefore important that an incentive supporting structure is established to verify the design and performance for the first full size prototypes to minimize the financial risk in the development ahead.

5. PROJECT OBJECTIVES

Sand and gravel are readily available at most locations around the world and can be found on the seabed for harvesting by boats and delivery to the WEC manufacture sites thereby eliminating road transport of WEC structural materials. Furthermore, concrete is easily accessible, and the manufacturing expertise is available throughout the world. Another advantage is the fact that concrete prices are not as prone to fluctuations as steel.

The project is examining how concrete technology can be applied to typical large offshore wave energy devices in case Wave Dragon and KNSwing. A range of feasibility options will be examined to evaluate the design space for different concrete technologies, where they can be best applied. The study will examine solutions such as ordinary reinforced concrete, post-tensioned concrete, different reinforcement materials, different concrete mix technology, etc. different connection details will also be examined as part of this study.

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

Concrete is the preferred material for offshore structures if 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.

6. PROJECT RESULTS AND DISSEMINATION OF RESULTS

The overall coordination and management of the project has been carried out by Energy Innovation Cluster DK.

The project objectives have been obtained by focusing on the following 5 key objectives which also has been forming the 5 technical work packages in which the project has been divided:

- WP 2: Design basis, tools and standardization
- WP 3: Concrete formulation and cover layer thickness
- WP 4: Post- and pre-stressing methods and materials
- WP 5: Manufacturing methods: In situ and prefab methods
- WP 6: Design and LCOE evaluation

For each WP a detailed report has been produced. These reports are not suitable for publication as it is a mixture of Danish and English and include informative text sections in their entirety from many different articles and reports. A summary of each of these WP reports are forming the Technical Report which will be made available for all interested parties and published on the WEB page of EIC and the Partnership for Wave Power. The annexes reports can be obtained from the authors on request.

During the project the team has been interviewing and visiting key players in the field from several countries in Europe.

WP2 DESIGN BASIS, TOOLS AND STANDARDISATION

Applicable standards for the design of the structure and production methodology is identified. The project will seek to identify gaps in the currently available standardization and guidance.

THE DESIGN BASIS FOR MARINE STRUCTURES

The standard DS-IEC TS 62600-2-ED2 Marine energy – Wave, tidal and other water current converters – Part 2: Design requirements for marine energy systems, provides specifications easy to follow in the design of WEC's.

There are three stages of the WEC design process:

1. Design basis, in which the WEC design is specified and the of the site Metocean data presented, based on reviewed standards and specifications the Design load Cases are specified.
2. Concept design, using numerical models or experimental models the structural loads and energy production are presented, for the specified preliminary Design Load Cases.
3. Detailed design, in the detailed design the structural response to the load cases are calculated and the structural resistance and survivability verified.

The output of the *design basis* is the definition of design load cases (DLCs), on which basis the load and structural integrity assessment is conducted, for the *concept design* based on preliminary design conditions. During the detailed design the structural strength is verified against the ultimate and fatigue loads.

The design basis is according to DNV "A document defining owner's requirements and conditions to be taken into account for design and in which any requirements in excess of this standard should be given."

The Design basis for WECs have some sections that will be WEC specific and some parts that will be similar across groups of WECs. In the case of this project the WECs are both large floating structures and share the same construction material: concrete.

The design life of the WEC structure is divided into five design phases as which can be different from one type of WEC to the other – but needs consideration and description:

Phase C – Construction	This phase includes construction in the graving dock or slipway and installation of equipment.
Phase T – Transportation	This phase includes transportation/towing of the structure from the graving dock to its final destination.
Phase I – Installation	This phase includes installation of the structure at its final location, i.e., the period from start of submerging from transport position, including offshore completion works, until the facility is ready for normal operation.
Phase O – Operation	This phase is the period from completed installation to decommissioning or removal from location.
Phase R – Removal	This phase includes decommissioning and removal of the structure.

THE STANDARDS

At present the IEC Technical Specification DS-IEC TS 62600-2-ED2 Marine energy – Wave, tidal and other water current converters – Part 2: Design requirements for marine energy systems, provides easy to follow specifications in the design of WEC's, and can potentially develop into a standard for the design of WECs .

Det Norske Veritas AS (DNV) Offshore Service Specification (OSS) 312 (DNVOSS-312, October 2008). This document overviews the principles and procedures associated with the certification of WECs, including an overview of relevant documentation.

The European Marine Energy Centre (EMEC) 'Guidelines for Design Basis of Marine Energy Conversion Systems', 2009 overviews general aspects behind design basis documentation, covering both wave and tidal energy converters.

Relevant standards from the maritime, oil & gas and offshore wind sectors have been reviewed. There are considerable similarities between the design of WECs and such structures / installations.

DNV GL ST- C502 from 2018 *Offshore concrete structures* is the most relevant standard when it comes to Concrete structures.

THE DESIGN TOOLS

From DNVGL-RP-C205 "Environmental conditions and environmental loads":

Design tools are typically numerical models used to calculate the response and loads on the structure of the wave energy converter and its moorings. The waves, tides, current and wind and possibly also ice causing the loads are depending on the site. The extreme waves that comes only a few times a year are extremely powerful and the drives of the cost of the structural design and the mooring design. The potential energy production and income from the electricity production depends on the annual energy production, which also can be calculated using numerical tools.

A review of tools suitable for WEC calculations are investigated in the IEA OES Task 10 project, supported by EUDP.

Simulations in focused wave groups should not replace longer simulations in random irregular waves to establish the ultimate loading resulting from continuous operation.

The sea states which lead to the maximum loading on the WEC during its design lifetime including wave height, wave period and directionality. Preliminary guidance on how to define the relevant environmental conditions is provided.

STRUCTURAL ANALYSIS PROCESS AND LIMIT STATES

Limit state design defines acceptable limits for safety and serviceability requirements of a structure:

1. Ultimate Limit State (ULS): resistance to ultimate loads[5],
2. Serviceability Limit State (SLS): criteria governing normal functional use.
3. Fatigue Limit State (FLS): resistance to the accumulated effect of repetitive action, described in
4. Accidental Limit State (ALS): resistance to loads during abnormal or accidental events.

Partial factors and their combinations form an important consideration within limit state design. Partial factors are used to allow for uncertainties and variability originating from materials and combinations of loads to gain enough reliability.

Partial factors applied to loads (typically referred to as action or load factors) are dependent on the limit state and the source of loading.

Partial factors applied to materials (resistance or material factors) are dependent on the limit state and the material classification.

This is all to ensure that reliable design values are obtained, the safety factor shall cover the uncertainties of the procedure and the accuracy of the load model.

For wave energy converters in general ***the wave induced load under extreme conditions*** can be considered the design driver concerning cost. This design situation is one of the first to consider evaluating the integrity of the structure.

Following Section 2 of the GL Rules and Guidelines IV-6-4 (2007) *Offshore Structures: Structural Design* for marine structures the loads to be considered includes:

G – Permanent loads:	E.g. dead weight of structure and external hydrostatic pressure permanent ballast, buoyancy, etc.
Q – Variable loads:	E.g. hydrostatic pressure, portable equipment, consumable liquids, removable parts, towing loads etc.
E – Environmental actions:	E.g. waves, wind, and ice loads.
D – Imposed deformations:	E.g. post-tensioning, temperature, creep and shrinkage.
A – Accidental actions:	E.g. vessel collision, explosion, fire and dropped objects, flooding of buoyant compartments, mooring line failures, inadequate lifting operations
P – Prestressing loads:	Loads from post-tensioned reinforcement.

Load safety factors must be looked up for the actual country.

Fatigue load is described in the detailed report

WP3 CONCRETE FORMULATION AND COVER LAYER THICKNESS

COVER LAYER THICKNESS

For relatively small devices the use of other reinforcement than unprotected black steel can reduce requirements to the concrete cover layer and thereby the plate thicknesses. This can reduce the weight of the device and thereby increase the buoyancy, which otherwise can be a problem. It is also possible to increase the buoyancy using light aggregates in the concrete – densities down to 1300 is possible, but values between 1800 – 2000 kg/m^3 are more commonly used. Economical optimization is not a straightforward exercise, as it is also dependent of local costs of materials and labor force. But in general, the more reinforcement per m^3 concrete the higher total cost per volume.

The necessary cover layer for various reinforcement materials in different parts of the structures can in some cases be smaller than the adequate values stated in the DS/IEC standard. The necessary cover depends not only on the reinforcement material, but also on the quality of the concrete and the design lifetime of the wave energy converter. For an offshore WEC it is usually not important if rust stains are visible, which means that steel fibers can be added to the concrete in order to improve the strength and/or the lifetime of the WEC. The primary goal when designing the structure next to obtaining the wanted lifetime is to ensure the lowest cost CAPEX plus OPEX over the WEC's lifetime.

With regard to reinforcement, the conclusion is that ordinary types of black steel reinforcement are always the most economical choice for projected lifetimes up to 50 years if at least cover layers as specified in the table below can be used.

It is always necessary to dimension cover layers based on knowledge of the expected concrete quality and reinforcement type. By using a non-corrosion-protected ordinary steel reinforcement, it can be justified to use smaller cover parts than specified in the DS/IEC for installations with a lifespan less than 20 years – e.g. prototypes in reduced scale or stand-alone demonstration facilities.

Proposed minimum cover layers:

Location:	Splash zone	Outside outside splash zone	Dry walls, bulkheads, etc.
Cover layer life 20 years	40 mm	30 mm	20 mm
Cover layer life 50 years	50 mm	40 mm	30 mm

Proposed minimum thickness of slabs:

Location:	Splash zone	Outside outside splash zone	Dry walls, bulkheads, etc.
Lifetime 20 years	120 mm	100 mm	80 mm
Lifetime 50 years	140 mm	120 mm	100 mm

Construction parts with two layers of reinforcement and/or tension reinforcement may be required in certain structural parts and will by nature have greater thicknesses – DS/IEC prescribes eczema-90 mm cover for stressed reinforcement, although this is probably not in all cases necessary – at least not for corrosion reasons.

The experience of up to 100 years with old American concrete ships and the Swedish company Pontona's pontoons shows that such modest concrete slab thicknesses can be sufficient. As mentioned above, the wall thicknesses can be further reduced using corrosion-resistant reinforcement, but it will probably only be topical for very small plants, where it can be difficult with large slab thicknesses to achieve the enough buoyancy. Furthermore, in terms of execution, it can be difficult to operate with such modest thicknesses when casting on site.

Choices to make for concrete constructions in general:

- Concrete formulation, i.e. aggregate and cement types, quality, where to find, prices.
- The use of pozzolans (eg flyash and silicafume), plasticisers, air entrainers and corrosion inhibitors
- Cover layer, lifetimes 20 to 50 years, considering reinforcement types and cathodic protection.

It should be noted that life cycle assessments may have a significant influence on the choices.

The durability of concrete structures with reduced cover thicknesses can be increased by replacing carbon steel reinforcement with corrosion resistant materials, including epoxy-coated, galvanized, MMFX type or stainless-steel bars. There is perhaps even more promising reinforcement being developed, which includes glass, basalt, aramid and carbon reinforcement. Corrosion resistance of reinforcement can result in reduced concrete cover requirements in ordinary reinforced concrete and hence thinner sections.

Rebars can also be supplemented by steel, polymer, and FRP fibres that can be included in the concrete mix. These ‘macro-fibres’ are typically 40 mm. Whilst they cannot replace the need for bar reinforcement, they can provide enhanced tensile strength, impact resistance, durability, and potentially fatigue resistance to the concrete. New technologies such as FRP reinforcement that can enhance the performance of offshore concrete in WECs seems very promising, but relevant durability and fatigue data for these materials is however not available today.

The Danish developed CRC-type concrete (commercialized by the project partner Hi-Con) can be used in thin walled elements replacing corrosion protected steel. It can be expected that CRC elements will be an economical solution for WECs with long lifetimes. The CRC material is also a very well documented solution in combination when “gluing” elements of ordinary concrete together to form a monolithic structure.

Due to the high durability of CRC there is no need to use special reinforcement as conventional reinforcement is perfectly adequate with a cover to the reinforcement of 10 mm. This cover layer was used in connection with drain covers (43,000 on total) on the Great Belt Link where there was a 100-year design-life.

Hi-Con has been involved in several research projects investigating the use of CRC for wind turbine towers, where the intention was to utilize the durability, fatigue resistance and crack control that can be achieved in CRC combined with relatively slender elements.

In the wind tower project Florida, the jointing technique was also used to connect individual segments to form a full tower ring.

CONCRETE FORMULATION

The main requirements for the material concrete is therefore that the aggregates must be durable to the environment to which the concrete is to be exposed, and the cement paste (the glue) must be, on the one hand, durable and the necessary strength, as for non-high-strength concrete it is primarily the strength of the cement paste, which determines the strength of the concrete.

Further, there are two additional requirements, namely that the aggregates must also be stable in the highly alkaline environment of the concrete, and the cement must normally be air-mixed in concrete exposed to frost to ensure frost resistance.

Embedded black steel reinforcement are rust-protected in concrete through the alkaline environment created by the cement's reaction with water, but if this corrosion protection is to be maintained over time, the concrete material is required to be so dense that carbon dioxide from the air (CO2) and chlorides (Cl-) from seawater does not reach the reinforcement in harmful quantities.

The cover layer is also necessary for the reinforcement to be anchored into the concrete.

UHPC HIGH-STRENGTH CONCRETE, SUCH AS CRC FROM HI-CON

The so-called UHPC materials are all very dense and with extremely good durability compared to ordinary concrete. The do not need “standard” cover layers thickness as normally specified for offshore applications. Many types of UHPC do not actually use traditional, slack reinforcement, but rely on fibers or on a combination of fibers and pretension.

For CRC – the type of UHPC used by Hi-Con – a combination of fibers and slack reinforcement is used. CRC also differs from other types of UHPC in applying relatively coarse aggregates in the matrix – typically sand/gravel up to 4 mm, but in some cases also up to 8 or 12 mm.

Since the durability of the CRC is very good, it is parameters other than chloride penetration or carbonation that determine the thickness of the cover layer. The cover layer is typically related to the maximum fiber length or the maximum grain size of the cover, and a compromise here is often chosen for 15 mm. Depending on a question of getting an appropriate casting – and not a durability requirement – it does not make much sense to look at alternative types of reinforcement (FRP, carbon, basalt, stainless steel) unless you can thus achieve better properties. In most cases, however, the other types of reinforcement that could be interesting are significantly more expensive than ordinary steel. The good durability of UHPC also means that no coating is needed as corrosion inhibitors, hardening membranes or sealers.

In some cases, for offshore structures slack reinforcement can be omitted and only fiber reinforcement used – e.g. for very slim constructions where bending moments are small. There will be no layer of cover at all, as corrosion of the fiber at the very surface does not affect either strength or durability. For this type of construction, a fiber mix can be used with a combination of long fibers with good anchorage to provide tensile strength, as well as small, thin fibers to protect against cracks.

UHPC is significantly more expensive than conventional concrete and density is slightly higher (up to 2700 kg/m^3 for elements with very strong reinforcement), so the use of UHPC will typically only be the choice if there are specific requirements for the construction. It may be a desire for a lower weight that can be achieved because elements of UHPC will typically have a thickness of 30-50% of what can be achieved with plain concrete. Other options are constructions that are heavily burdened by exhaustion or wear – or where you can replace steel with many welds with a monolithic construction in UHPC, where joints can be moulded out.

Finally, there is an option to simply use UHPC in particularly hard-pressed zones, such as in the anchor zone for a pre-tensioned concrete construction, or as a cover layer where water flows under high pressure.

In the case of Wave Dragon, calculations show that UHPC can compete with steel and composite in the displayed parts of the plant:

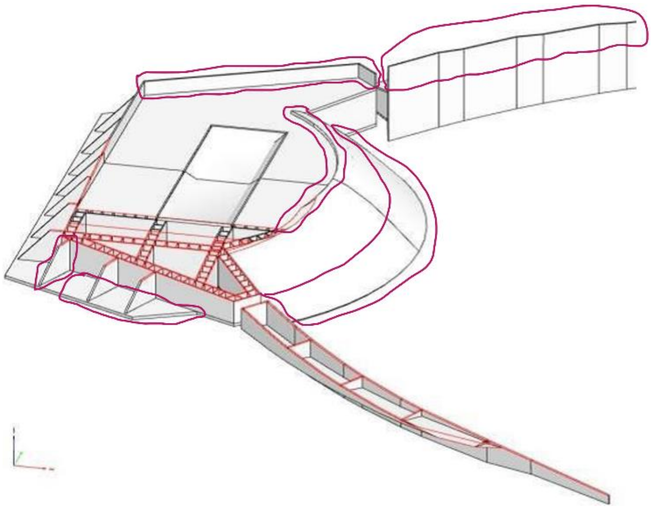


Figure 1 Parts of Wave Dragon where UHPC can replace steel

FIBER REINFORCEMENT ETC.

Corrosion free reinforcement is today significantly more expensive than normal black steel reinforcement. However, development in this area is continuing and it is possible that fibres and basalt reinforcement rods may become competitive in terms of price by use in relatively small concrete corrugated power plants if they are aimed at a life span greater than 20 years, but as it stands, it requires a significant scaling up the production of this new type of reinforcement material.

The same considerations apply when reinforcement containing glass fibers, carbon fibres and special synthetic fibres.

In terms of lifecycles the basalt reinforcement is a type of melted rock material – which at the end of its lifetime returns to nature – in a type of circular lifecycle.

WP4 POST- AND PRE-STRESSING METHODS AND MATERIALS

This chapter will describe steel and alternative corrosion resistant reinforcement bars. The different types methods will be described, and their typical applications and cost identified. It can be a very good solution for concrete built WECs to make use of precast elements eventually with pre-stressed reinforcement

It is almost always an advantage to combine the ordinary reinforcement in offshore concrete with pre- and/or post-stressed reinforcement. Both steel and alternative corrosion resistant reinforcement can be used, but black steel is still the most commonly used material. There is limited experience with most of the alternative materials when used as stressed reinforcement. The different pre- and post-stressed methods are described, and their typical applications identified.

CONCLUSION

It does not seem possible to draw general conclusions as to the optimal choice of pretension methods or to suppliers of materials and services. In practice, it would normally be the case that the system suppliers also participate in the performance and with their own equipment, tightening and controlling the pretensions and, where appropriate, injecting the cable channels. Tensioning must normally be done in several rounds, with the concrete having to reach the prescribed strength before full pretension is applied. In any case, there must be close cooperation between the concrete contractor and the pre-tensioning company.

In the case of corrugated power plants, the loads on the structures are inherently highly variable and, in terms of exhaustion, many millions of impacts in the life expectancy of the plant must be considered. Fortunately, well-designed pre-tensioned concrete structures are not very sensitive to fatigue fractures, but it must always be examined whether there is a risk.

In general, it should be stressed that both specifications including the placement of pretension cables and any pre-tension rods, as well as the device of the necessary additional slack reinforcement – if necessary in cooperation with batches of high-strength concrete such as CRC in anchorage zones requires quite a complicated detailed design, which should only be carried out by specialists with experience in the offshore field.

In the technical report there is a review of the historic development as well as a list of potential suppliers.

Pretension of concrete structures has been known since the end of the 19th century. In the 20th century, pretension was not commonly used until 1940, as the pretension will rapidly be reduced due to shrinkage, creep and relaxation. without special measures.

It was the French engineer *Eugène Freyssinet*, who developed and in 1928 patented pretension, which was practically applicable. He founded his company in 1943, which in 1976 changed its name to FREYSSINET.

There are two essential and fundamentally different methods for achieving pretension of concrete structures:

1. Pre-tensioning – pre-stressing – of the tension reinforcement and then the casting of the concrete. This method is used for practical reasons primarily for element production.
2. Clamped – post-stressing – of concrete, where cables or reinforcement rods are only tightened once the concrete has achieved some strength.

Below is an example of a 120 m long floating pier constructed of prefabricated modules that are first strung together into longer sections using reinforcing bars, after which the sections are towed to the final position and clamped using Cables.

Figure 2 Example of pre-tensioned float quay from Switzerland.

DYWIDAG also provides several types of pretension systems, both bonded and (unbonded), external systems that, for example, are not injected. can be used in cavities in bridges and wind turbine towers as well as clamping rods, where prototypes were tested as early as 1927:

- VSL International,
- CCL SCANDINAVIA (former Scandinavian Span concrete, established as early as 1947).
- Macalloy Company
- Swiss company BBR delivers, as is, for example, Dywidag

WP5 MANUFACTURING METHODS: IN SITU AND PREFAB METHODS

This chapter will address the cost including the establishment of the production facility for large scale manufacturing of wave energy converters. This will include describing the requirements for the location water depth infrastructure etc. Labour force and daily supply of sand and cement and reinforcement. In situ and prefab methods and optimal combinations of the methods.

Manufacturing techniques as used in the Fehmarn belt tunnel project could also be used to the production of low-cost high-performance wave energy converter structures. The proposed material and process technique are ready and can be adapted to wave energy manufacture within 3-5 years. Advantages of the process include continuous formation without joints or seals to almost any required length. It is well suited to the several elongated WEC designs that have been proposed to date.

The manufacturing process of tunnel segments can be adapted to the geometry required for wave energy converters such as the KNSwing with geometry alike the tunnel sections in its elongated shape with tubular buoyancy chambers, but the manufacturing techniques are also relevant to many other elongated WEC designs such as hinged barges like CrestWing and others.

Production facilities like the one proposed used at Fehmarn Belt fixed link (or other submerged tunnel projects) could perhaps, after completion of the tunnel, be used to continue building WEC structures. Alternative production sites such Ports along the North Sea as dry-docks that also can be utilized will be identified.

Although large quantities of concrete elements are produced today in many countries, in many cases it is preferable to continue to carry out concrete structures by casting on site. There are several things to take into account when choosing between embodiments:

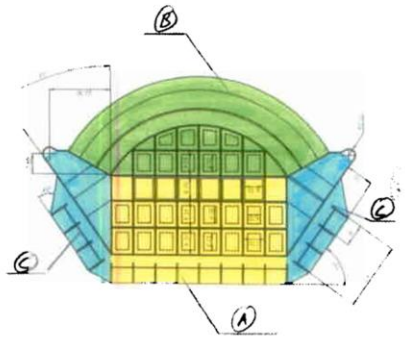
1. Price
2. Construction time
3. Durability
4. Aesthetics – usually not a problem with offshore constructions
5.

WAVE DRAGON

Wave Dragon has considered two different method for production:

- Produced in a dry dock.
- Produced on a floating barge there can be submerged and reused.

The following text and drawings are taken from a feasibility study conducted by MT Højgaard for Wave Dragon:



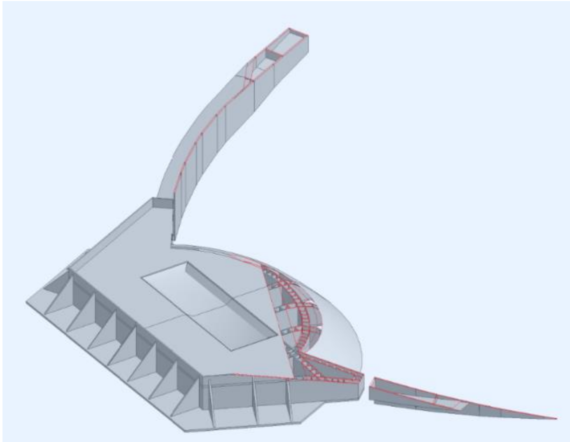


Figure 5 Sectioning of the main body for casting in small parts

As indicated on figure 5 the Wave Dragon could be divided into a main body (A) of 61,6m x 27,9m x 8-9m high, one front unit (B) and two side units (C).

The launching operation of each unit will be carried out off-shore with waterdepths that allow the nose of the barge to touch down on the seabed in a gentle way not to damage the barge and the structure. Tugboats assistance and temporary mooring will be required.

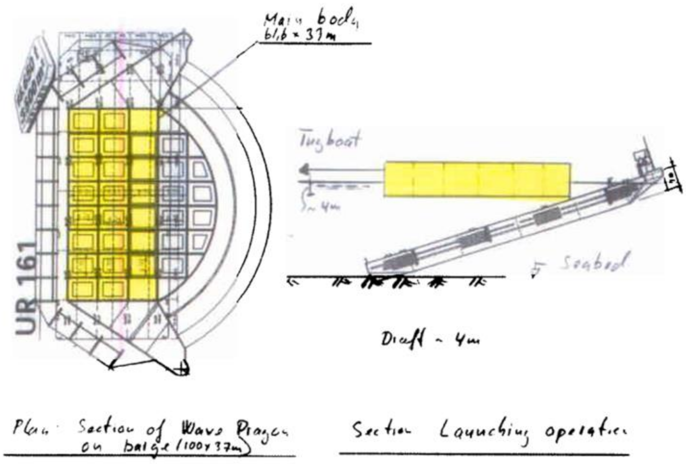


Figure 3 Construction of the Wave Dragon on a flat Barge

The aim of the study was to identify the different possibilities for how such a large and heavy structure as a 4 MW Wave Dragon could be constructed. The 3D drawing shows Wave Dragon in a more recent optimized design. The design allows both the central platform and the wave reflectors to be constructed in prefabricated elements of relatively easily manageable sizes:

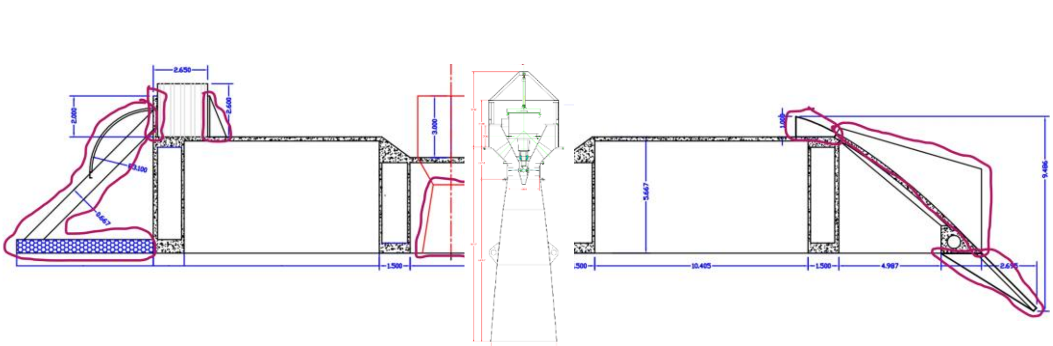


Figure 4 Cross section of Wave dragon –the water reservoir is lifted above the sea surface by the buoyancy of the hull.

The present project has examined whether certain parts of the plant could be successfully carried out in high-strength concrete. In the drawing, these parts are marked in red. This applies primarily to wave screens and stabilizers, as well as outlet tubes, draft tubes, from the water turbines. These parts to be fitted to the concrete structures can also be manufactured in corrosion-protected steel or in a composite sandwich structure. In certain cases (depending on the construction dock) the lower single-curved part of the overtopping ramp must be installed after the platform has been launched and should therefore be of relatively light construction. When maintenance costs are considered, high-strength concrete in many cases will be cheapest.

KNSWING

The production of KNSwing can be carried out like the production of the tunnel elements to the Øresunds Bridge, i.e. a dry dock solution.

The facility used for production of tunnel elements that was used in connection with the Øresund link and proposed for the Fehmarn Belt could be considered for the production of elongated concrete structures, such as barges or ship shaped floating structures.

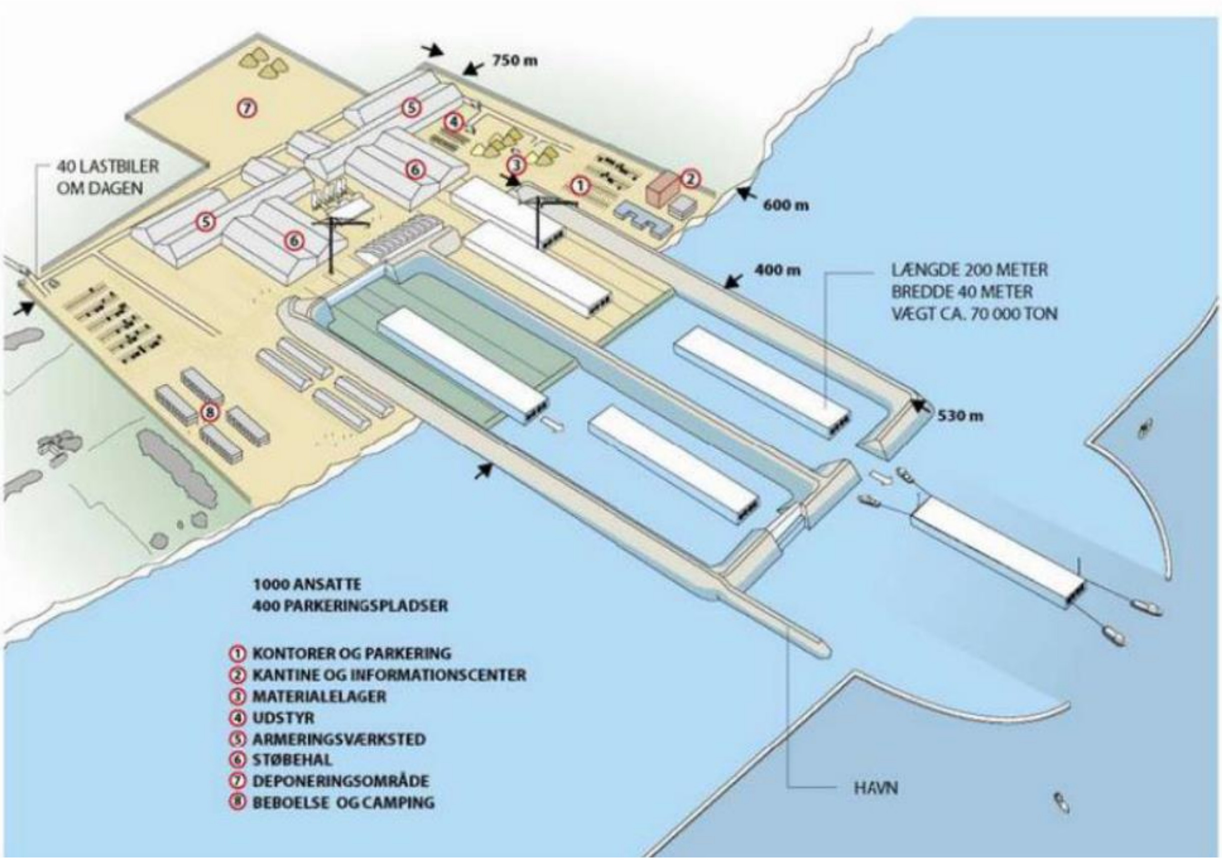


Figure 5 The Fehmarn Tunnel production facility is an example of a dedicated mass production of large concrete structures

The KNSWING:

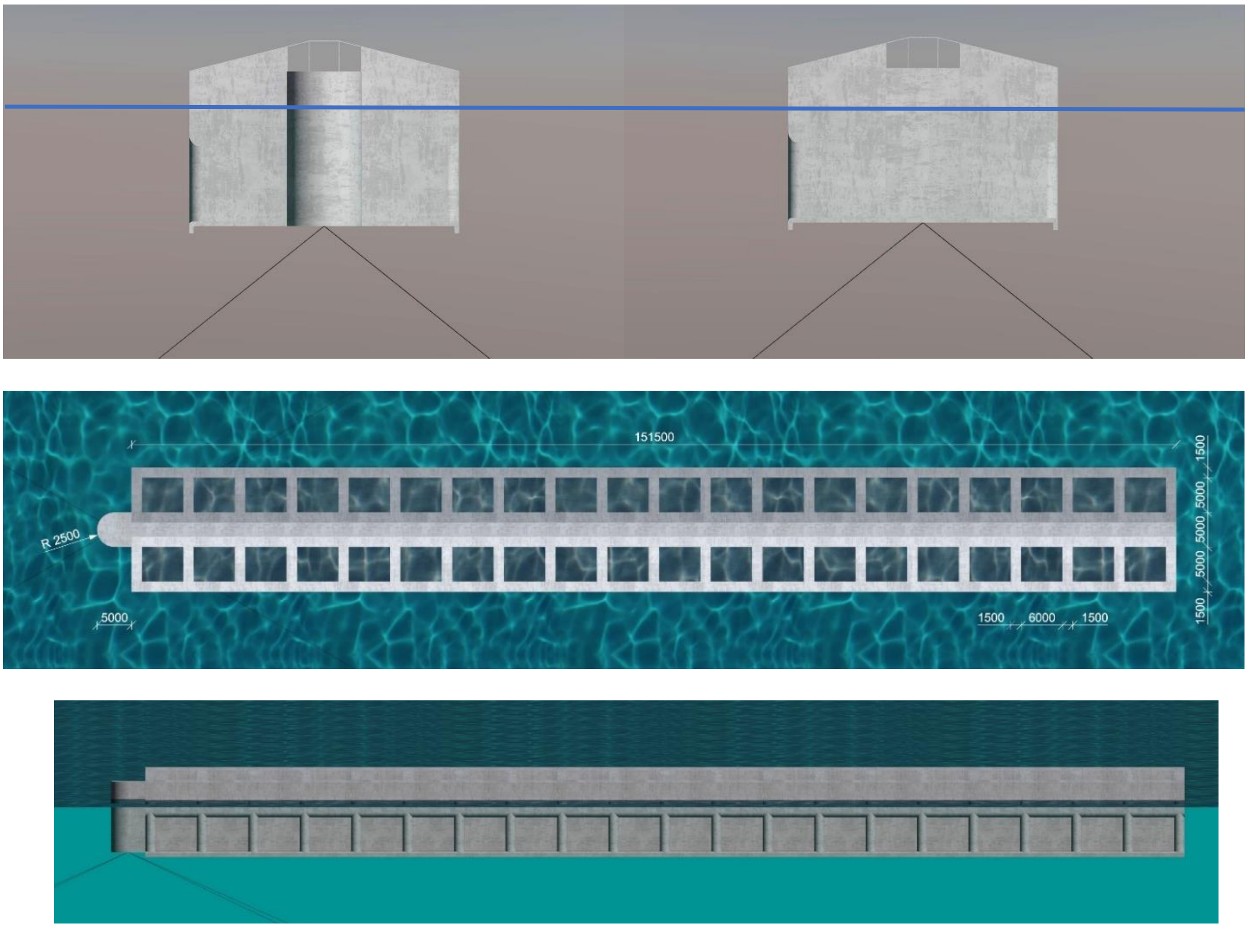


Figure 6 Conceptual design of the KNSwing

But also, the method used by the Swedish company Pontona (delivering floating pontoons for minor harbors or support for buildings in a harbor like Nordhavn) can be used.

Figure 7 The 190 tons heavy wave breaker from Pontona (august 2019).

WP6 DESIGN AND LCOE EVALUATION

TWP6 integrate cost data associated with selected design solution to guide the development of each concept toward optimal solutions. The Cost of Energy Tool [1] is used. The tool has previously been tested as part of the MSLWEC Mooring project at AAU. In this way each concept presented their WEC using a similar cost breakdown structure. The work will focus on documenting of the LCOE for different structural design solutions and manufacturing methodologies. A major part of the cost associated with the concrete WECs is the cost of the WEC structure, and therefore the cost unit cost of concrete is investigated.

A preliminary she structural design has been carried out on the KNSwing in order to predict the structural bending moment of the ship like structure and the required amount of reinforcement.

The cost reductions using learning curves has been used to predict the effect of mass production.

SUMMARY AND CONCLUSIONS

The two WEC systems Wave Dragon and KNSwing are both suitable to be built in concrete. Both systems are passive structures with few moving parts. Because of the substantial structural weight, the unit cost of concrete is important, and a future low cost will require mass production.

Huge price reductions are possible by mass production of concrete structures – perhaps even bigger than Ford showed with the car. The differences include a significant reduction in mass production in the cost of fabrication facility in the order 450€/kW to 250€/kW– as this cost will be shared on many concrete WEC's which also result in a reduction of the unit cost of concrete from approx. 410 €/ton for first unit plant to 240€/ton for mass production of WECs. These conclusions are based on previous studies (DWP, AARUP, Skaska) and CG Jensen contractors. Relevant examples of building concrete structures in large quantities on dedicated facilities is the great belt bridge, the tunnel project in Øresund and the proposed tunnel project in Fehmarn. The conclusion is that in order to get the price down, it is important to industrialize and use a modular principle when building wave energy plants. The first demonstration project will yield a very high energy price – but the potential for price reduction is great.

Based on these fabrication methods and cost assumptions both Wave Dragon and KNSwing can be developed following the steps in the Danish Strategy for Wave Energy 2012 [2] in which the incentives to achieve successful development of the Wave Energy sector are described.

The benefits from placing the Wave Energy Converters in combination with an offshore wind farm are:

- Better use of sea space
- Better use of infrastructure such as grid connection
- Better use of O&M equipment
- Possibly the WEC can be used as a floating foundation for the windmills

Additional benefits using wave energy can be the reduction of wave heights after the wave farm – which can lead to more days pr. year to carry out O&M.

CHOICE OF LCOE PRINCIPLES

Each Developer has filled in their cost estimate of fist prototype in the Cost Spread sheet the tool developed by Julia F. Chozas and annual energy production for both WEC system is calculated and the capacity factor CF calculated on a common site. The LCOE estimate of the fist-built No. 1 demonstration unit of the Wave Energy Converters are based on the following assumptions, that the WEC is:

1. is built on a temporary fabrication site close to the sea.
2. can be towed to a position in which its anchored in soft sand and clay
3. is grid connected to a Offshore Windmill, Oil & Gas platform or a test site connecting point
4. is placed in a wave climate like point 3 in the North Sea 21 kW/m
5. KNswing is at TRL 3 and Wave Dragon TRL 5

The LCOE reduces when mass-production and deployment is applied. This is illustrated by assuming the building of a wave farm of 100 MW at a generic location. The site assumed located 20 km from the shoreline grid – and 30 km from the production site on 30 – 40-meter water depth. The wave climate is also here assumed 21 kW/m (like point 3 in the North Sea).

Operation and Maintenance costs (OPEX) is assumed potentially to become very low because both systems have very few moving parts. However, the lifetime of the mooring lines is at this stage very uncertain and can have an important impact on OPEX.

The cost data from the device specific cost data are shown in the Table 2 below and the potential for cost reduction and improved CF from learning used to estimate the cost of 100 units built.

Tabel 1 Cost Estimates at a common generic site with 22 kW/m

	Wave Dragon 4MW estimates No 1	Wave Dragon 4MW Unit 100	KNSwing 1 MW Estimates No 1	KNSwing 1 MW Estimates Unit 100
1. Development & Infrastructure (€/kW)	500	200	500	200
2. Structure and prime mover (€/kW)	1125	900	3600	3000
3. Power Take-off (€/kW)	1000	600	600	300
4. Moorings and Foundations (€/kW)	500	300	500	300
5. Installation (€/kW)	250	250	250	200
6. Grid Connection (€/kW)[1]	200	200	200	200
Total Capex (€/kW)	3575	2450	5650	4200
Capacity Factor (CF)	16%	29%	21%	29%
FCR (see annex III)	9%	7%	9%	7%
OPEX per year (€/kW)/ Capex (€/kW)	8%	2%	8%	2%
LCOE (€/MWh)	435	87	524	149

[1]Grid connection only includes cable from WEC to offshore platform The total grid connection cost from WEC to shore is estimated to 514€/kW and the offshore transformer platform of 20M€ (200€/kW) is 614€/kW. These costs are not included in the table1 above.

THE COST OF THE CONCRETE STRUCTURES OF THE CONSIDERED WECS

A methodology to estimate the Concrete structure based on its weight, amount of reinforcement and formwork is described in the WP. Also the cost reductions that can be achived from mass production are outlined. Based on these consideration the estimated weight of Wave Dragon and KNSwing as well as their Rated Power provided by the developers are shown in the table below.

The amount of concrete involved the KNSwing in its present 150 m design it is 12.000 ton rated at 1MW and the amount of reinforcement 0.2 ton/m^3

The 160 m wide Wave Dragon of 4MW weigh 18.000ton of which 100 ton is permanent steel. The amount of reinforcement is 0.1 ton/m^3.

	KNSwing 150 1MW 1st unit	KNSwing 150 1MW Unit 100	Wave Dragon 4MW 1st unit	Wave Dragon 4MW Unit 100
Rated El-Power MW	1	1	4	4
Weight estimated (ton)	12000	12000	18000	18000
Cost of Concrete €/ton	300	250	250	200
Total Cost (€)	3600000	3000000	4500000	3600000
Structural Cost (€/kW)	3600	3000	1125	900

Comparing Wave Dragon with KNSwing in terms of structural cost per kW it is clear that the KNSwing needs to improve the amount of power that the structure can produce or find ways to reduce the amount of concrete in order to reach a similar low cost per kW as Wavedragon. The KNSwing is however at a relatively early TRL 3 compared to Wavedragon TRL 5.

THE COST OF POWER TAKE-OFF, GRID, GRID AND INSTALLATION

The Power take-off of the WEC includes turbines, generators, power electronics, control, onboard cabling, storage and transformation to 330 kV AC. In the case of the 4MW Wave Dragon, it includes 16 low-head water turbines of rated power 250 kW estimated at a unit cost of 1.000 €/kW. This unit cost is based on estimates from conventional low head water turbines confirmed by industry, it is estimated to reduce when produced in mass production supplied in large quantities. A 1MW KNSwing includes 40 air turbine-generator units of 25 kW. The unit price of 333 €/kW is an estimate like the cost of the DWP submersible 45 kW turbine generator unit. The PTO is assumed to be mass-produced and fitted onto the structure.

	KNSwing 150 1st unit	KNSwing 150 100 unit	Wave Dragon 1st unit	Wave Dragon 100 unit
Rated Abs. Power MW	2.5	2.5	5	5
Rated El-Power MW	1	1	4	4.1
Efficiency	44%	44%	80%	82%
Unit Cost of PTO €/kW	500	300	1.000	600

The PTO cost in general dependent on turbine and generator type, the rotational speed and type of control required.

The cost of the mooring system includes anchors, mooring lines and chains. The main structure is connected to the moorings at connections points. Mooring system costs were investigated and optimized for large wave energy converters such as Wave Dragon and KNSwing as part of the project MSLWEC [3]. Mooring costs were studied, and cost estimates were provided by the commercial partner. For This study the unit cost of moorings including installation is estimated in the range of 500 €/kW for both concepts including installation. The unit cost is expected to reduce following learning curves to 300€/kW.

The installation includes the cost of towing the WEC from the fabrication to the site. For the initial unit the cost is estimated to 250 €/kW. In large scale a dedicated vessel is assumed to available to tow and connect the WECs to their moorings any day with suitable weather conditions. Installation at the generic site 40 km offshore it is assumed to cost 200 €/kW in mass production.

The Installation of the electrical power cables are included under the grid installation. Installation of the mooring system 30-40 m depth is included in the mooring cost estimate.

The initial cost of grid connection is estimated as the cost of connecting the WEC to a Windmill tower, a test site platform or an Oil & Gas rig located at say 5 km from the WEC. The umbilical is flexible as shown on figure 1, the flexibility provided by the curved shape of the cable. This allows the WEC to move horizontally while the connection point on the seabed remains fixed.

The umbilical is then continued as inter-array cable on the seabed. The inter array cable is laid on the seabed and the cost of laying it is estimated by Dalton [4] to 100.000€/m. The cable itself is estimated 60.000 €/m. This gives a cost of 200€/kW

For the large WEC farm the estimate is based on a 100 MW wave farm, and a rough estimate of the cable types and connections are described. The layout can be compared to that of an offshore wind farm as indicated on figure below.

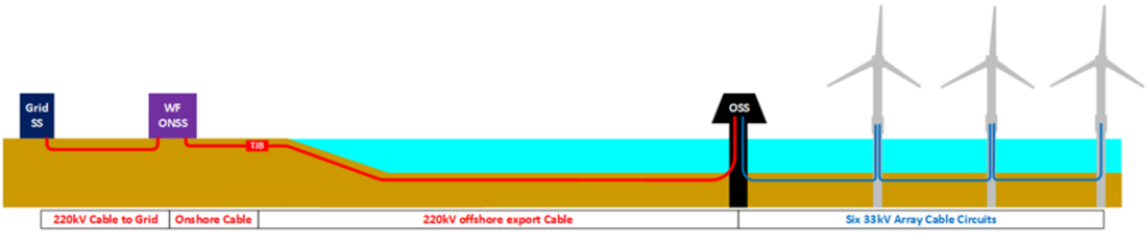


Figure 1 Typical connection to shore from a wind farm

The grid connection cost estimates of 514€/kW and the trafo platform of 20M€ (200€/kW) is 614€/kW. These costs are not included in the table 1.

5. UTILIZATION OF PROJECT RESULTS

The project results are establishing a more solid knowledge base for the future development of large passive MW size wave energy devices. Some of the data can directly be used in revision of existing Business Plans.

The more detailed WP reports will give other than the project partners access to useful knowledge for them to assess if concrete can be used in their design and to give useful guides for the design. Therefor the results will be presented for the Danish group of wave device developers at their regular meetings under the Partnership for Wave Energy.

The project has fostered many new ideas and inspirations, with guidance from Hicon and AAU – with respect to investigate prefabricated structural parts that could potentially be lighter and thinner.

The idea to integrate OWC chambers from the KNSwing into existing floating harbor breakwaters and the Swedish company Pontona's is a significant result which can lead to further co-operation and new business under the blue economy.

One or two articles about the two developers design is expected to be published international reports.

6. PROJECT CONCLUSION AND PERSPECTIVE

The two WEC systems Wave Dragon and KNSwing are both suitable to be built in concrete. Both systems are passive structures with few moving parts. Because of the substantial structural weight, the unit cost of concrete is important, and a future low cost will require mass production.

The project has given the two developers and companies involved the opportunity to co-operate and identify areas where additional improvements in their design can be obtained.

The standards to be used can be difficult to identify. A recommended way is to use the DNV GL ST- C502 from 2018: Offshore concrete structures recommendation as basic document.

For relatively small devices the use of other reinforcement than unprotected black steel can reduce requirements to the concrete cover layer and plate thicknesses. It is also possible to increase the buoyancy using light aggregates in the concrete – densities down to 1300 is possible, but values between 1800 – 2000 kg/m^3 is more commonly used.

Pre-tensioning reduce the risk of cracks in the concrete and reduce the amount of slack reinforcement required – it is quite a complicated design, which must be carried out by specialists with experience in the offshore engineering.

To increase lifetime by avoiding corrosion of reinforcement, it is recommended to use prestressing or fiber reinforcement in high stressed part of the construction. Special concrete like CRC can be optimal for special sections.

Mass production of concrete structures – can give large benefits in the cost of fabrication facility per WEC it is in the order of 450€/kW for the production of one unit to 250€/kW for the production of a large wave farm. Based on the cost assumptions presented in WP6 the LCOE for the Wave Dragon and the KNSwing technologies are competitive with floating wind when used in wave farms if the cost of grid connection is not included. The cost of the concrete structure alone for the first 12.000t 1 MW unit of KNSwing is 3600€/kW which for unit no. 100 units will be reduced to 3000€/kW. For the 4 MW Wave Dragon the first 18.000t unit is 1125€/kW expected to reduce to 900€/kW.

In order to bring Wave Energy to commercial business it is therefore important that an incentive supporting structure is established to verify the design and performance for the first full size prototypes to minimize the financial risk in the development ahead.

Wave energy has the potential to cover 15% of the Danish electricity production. Further it is shown that a combination of wave and offshore wind in the North Sea has large economic synergies.

The results will be used of the developers in the fund raising for establishing the detailed design and optimization following the principles and guidelines presented in the projects WP reports. One or more MW devices needs to be demonstrated in larger scale to start the development and tap into this potential new industry.

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