



**AALBORG UNIVERSITY**  
DENMARK

**Aalborg Universitet**

## **The Wave Energy Challenge**

*the Wave Dragon case*

Christensen, L.; Friis-Madsen, E.; Kofoed, Jens Peter

*Published in:*  
Proceedings of the POWER-GEN 2005 Europe Conference

*Publication date:*  
2005

*Document Version*  
Early version, also known as pre-print

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*  
Christensen, L., Friis-Madsen, E., & Kofoed, J. P. (2005). The Wave Energy Challenge: the Wave Dragon case. In *Proceedings of the POWER-GEN 2005 Europe Conference: Milan, Italy, June 2005*

### **General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

### **Take down policy**

If you believe that this document breaches copyright please contact us at [vbn@aub.aau.dk](mailto:vbn@aub.aau.dk) providing details, and we will remove access to the work immediately and investigate your claim.

# **THE WAVE ENERGY CHALLENGE**

## **THE WAVE DRAGON CASE**

**BY**

**LARS CHRISTENSEN, WAVE DRAGON APS AND LTD, DENMARK  
ERIK FRIIS-MADSEN, WAVE DRAGON APS AND LTD, DENMARK  
JENS PETER KOFOED, AALBORG UNIVERSITY. DENMARK**

### **1. Introduction**

Wave Dragon marks a significant breakthrough towards commercial exploitation of the abundant energy concentrated in ocean waves. Whereas previous wave energy converters have either failed to operate or only provided limited potential for electricity generation, the seagoing trial of the Wave Dragon prototype has proven its offshore survivability for more than a year and verified the potential for commercial feasibility with large scale power generation below the costs of offshore wind power.

The global wave power potential is of the same order of magnitude as world electrical energy consumption. The best wave climates are found between 30-60 degrees latitude with annual average power levels between 20 -75 kW/m – orders of magnitude more powerful than solar and wind. For more that 100 years mankind has tried to capture and utilise this abundant energy, but until recently wave powered navigation buoys was the only practical result. In the last years a wide variety of promising wave energy converter concepts have however been developed and a handful of these have been or are now being tested. These concepts depict fundamental different energy absorption principles, for instance point absorbers, OWCs and overtopping devices. These concepts utilise very different power take off technologies such as direct drive, high pressure hydraulics, air turbines and low head hydro turbines.

Developers of wave energy converters face a series of major challenges. First of all they have to develop machinery that can operate and survive in this very rough environment. Secondly one has to optimise operation and maintenance systems to make wave power plants a viable solution. Wave energy converters have to compete with other renewable energy technologies, and it has now become obvious, that wave power can be much cheaper than for instance

photovoltaic power. There are good reasons to believe, that wave power in a few years will be a serious competitor to offshore wind power.

The Wave Dragon is an offshore wave energy converter of the overtopping type. The development work is to a large extent built on the concept: use proven technologies when going offshore. The plant consists of two wave reflectors focusing the incoming waves towards a ramp, a reservoir for collecting the overtopping water and a number of hydro turbines for converting the pressure head into power. Wave Dragon is by far the largest known wave energy converter known today. Each unit will have a rated power of 4-10 MW or more depending on how energetic the wave climate is at the deployment site. The utilization of the overtopping principle as opposed to power absorption via moving bodies means that the efficiency grows with the size of the converter. This means that only practical matters set limits for the size of this WEC. In addition to this Wave Dragon due to its large size can act as a floating foundation for MW wind turbines, thus adding a very significant contribution to annual power production at a marginal cost. This bust in profitability makes Wave Dragon an economical profitable investment with the prices for renewable electricity today in for example UK.

As part of the development activities towards a full size production plant in 2006 a grid connected prototype of the Wave Dragon in scale 1:4.5 has for the last two years been tested in a Danish fjord. The results of these more that 15,600 hours of continuously real sea tests validates annual power production estimates

## **2. Abundant wave energy resources available**

Wave energy ready for exploitation represents one of the largest renewable sources in the world, and is located near some of the world's major energy consumption centres.

### ***Total resource***

An estimate of the total wave energy resources that is available to be utilised in a short term perspective varies depending on how far offshore it will be technical feasible to deploy devices. As a conservative example IEA has estimated the potential world-wide wave energy contribution to the production of electricity to be between 10 and 50% of the world's yearly electricity demand of 15,000 TWh dependent of the expected load factor and wave regime.

In the table below another estimate is related to other renewable resources and as it is shown ocean energy (of which wave energy is the major part) outnumber major renewable sources like biomass, wind and hydro.

Table 1: Technical Potential of Renewable Energy (ExaJoules)

	Biomass	Hydro	Solar	Wind	Geothermal	Ocean	Total
World	283	50	1,570	580	1,401	730	4,614
Current use	50	10	0.2	0.2	2	0	62.4
Total primary energy supply							420

Source: Federal Ministry for Economic Cooperation and Development and Ministry for the Environment, Nature Conservation and Nuclear Safety: Conference Issue Paper, Renewables 2004 – International Conference for Renewables Energies, Bonn 2004, p.27.

A recent study by the Department of Trade and Industry (DTI) and The Carbon Trust in UK (Renewables Innovation Review, 2004) is stating some 200,000 MW installed wave and tidal energy power by 2050 which with a load factor of 0.35 is resulting in a power production of 6 TWh/y. Independent of the different estimates the potential for a pollution free energy generation is enormous.

### Distribution around the world

Wave Energy is not distributed evenly around the world. It is concentrated in northern and southern part of the globe. It is particularly interesting to note that the most wave energetic places are centred around some of the most energy consuming countries in northern Europe and northern US. Significant resources are found off UK, Ireland, North West US and Australia.

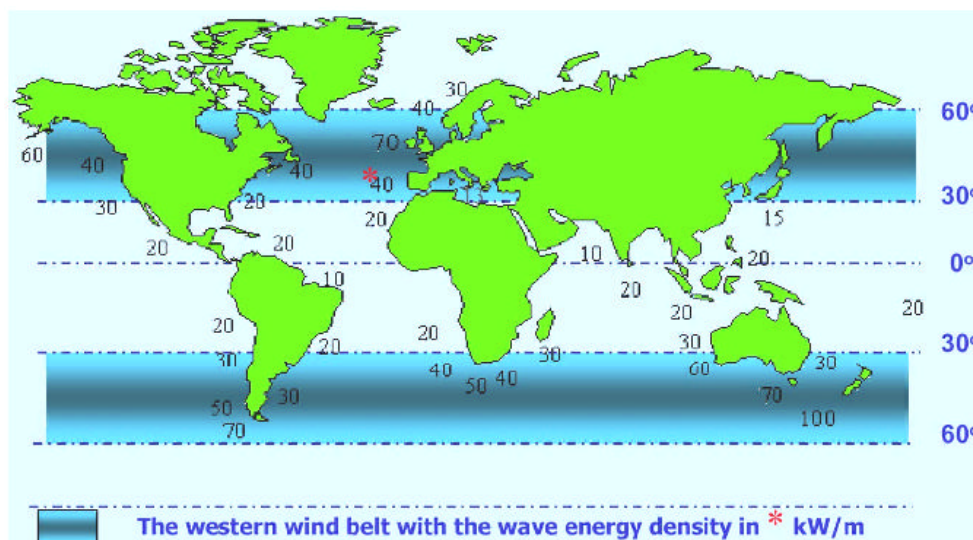


Figure 1: World distribution of average wave energy, European Thematic Network on Wave Energy, 2002.

### 3. Many different concepts

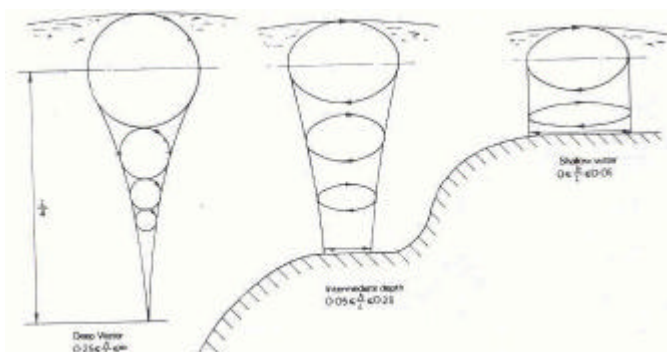
The development of wave energy converters are characterised by a wide variety of different absorptions and power-take-off techniques and in addition to this some technologies are designed for shoreline deployment, others for near shore deployment and again others for off-shore deployment. The text below gives a short introduction to the different technologies and some of the most promising technologies are presented.

#### *Wave Power Basics*

Winds generated by the differential heating of the earth pass over the open bodies of water, transferring some of their energy to the water in the form of waves. This energy transfer results in a concentration of the energy involved: the initial solar power level of about 1 kW/m<sup>2</sup> is concentrated to an average wave power level of 70 kW/m of crest length. This figure rises to an average of 170 kW/m of crest length during the winter and to more than 1 MW/m during storms.

An ocean wave in deep water appears to be a massive moving object - a crest of water travelling across the sea surface. But to understand wave energy it is important to realize that this is not the case; it represents a flow of motion or energy from its origin to its eventual break up. The water molecules in an ocean wave move in circles. The behaviour of waves depends largely on the relationship between a wave's size and the depth of water through which it is moving. The movement of water molecule changes from circular to ellipsoidal as a wave approaches the coast and water depths decrease. Eventually when the wave rolls up on a beach - and when most of us observe waves - the movement is mostly horizontal.

As wave's reaches shallow waters they dramatically loose their energy. The major part of wave energy resources is therefore located in areas with large water depths.



***The main challenges for wave energy concepts***

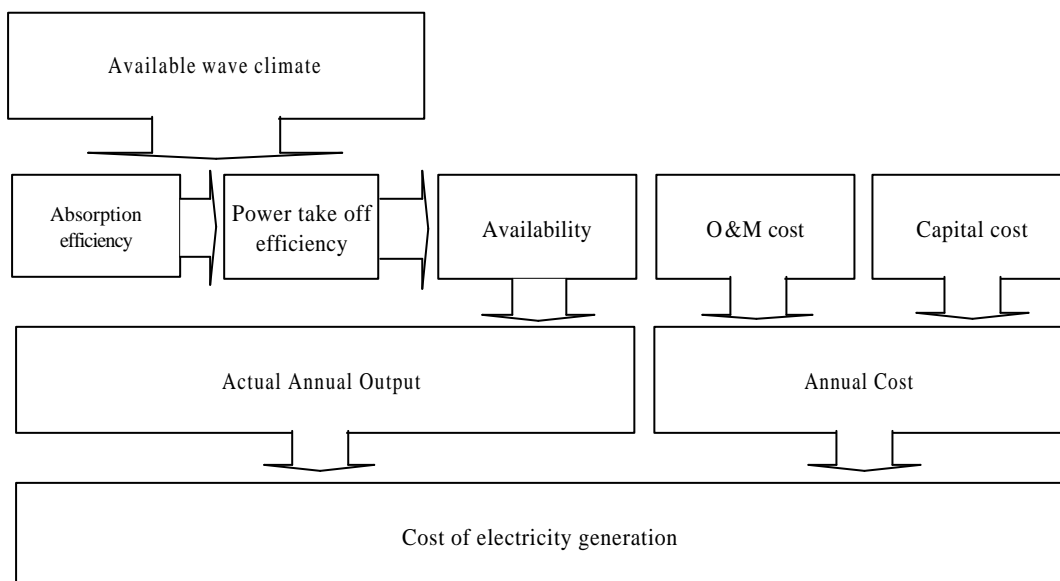
There can be no doubt that the major challenges for any developer of a WEC technology in their effort to demonstrate a economical viable technology, is

1. High survivability and availability
2. Low O&M costs
3. Unit scalability

Survivability is of course a vital aspect of any offshore construction and machinery. WEC's does not expose any real hazard to either the environment or humans, but if it cannot be proved that the technology will survive e.g. a 100 years wave, there is of course no future for this technology. Test standards from the oil & gas offshore sector can however be applied directly to predict devise survivability

Availability is also a key issue for any WEC. Although most device developers claims a 95% availability, it is most likely that significant differences in availabilities will be inherent in the WEC concept it selves, as a low availability can arise from limited access to the devise due to weather conditions or in the worst case from lacking possibilities to perform maintenance work on the device at all unless it is towed to a yard.

***The main factors on the road to reasonable market entry electricity generation costs:***



As can be seen from the model capital and O&M cost should be weighted against WEC efficiencies. The cost per kWh generated will to a large extent depend on which wave climate the device is deployed in, as the production grows to a power of 3.5 when scaling up the physical size in accordance with the wave climate. High wave climates will require relatively proven or mature WEC devices, as the ability to perform maintenance on WEC's in energetic climates is limited. One must expect early WEC deployment in relative low wave climates.

### ***Different technologies***

WEC concepts must be able to convert the slow, pulsing mechanical 0.1Hz motion of ocean waves to a reasonable steady electric output of 50-60Hz suitable to be fed into the grid. Most wave power devices can be built, deployed and maintained using available and tested technologies from marine, oil & gas and wind power industries.

More than 1000 wave power related patents have been filed over the past 50 years, but still only a few devices seem to have a technical and commercial potential. As opposed to modern wind turbines there are many different types of WEC's with regard to the absorption system and also in their choice of power take off system.

### ***Reactive systems***

A device of this type floats on or below the surface and converts the orbital motion of waves into electricity using an absorber system. The absorber is moored to the seabed either with a taut or slack mooring system. This moored system can then extract energy from its relative motion either between the buoy and the seabed or between two or more individual moving parts of the buoyant structures.

The most promising reactive technologies are the US based AquaBuoy system and the UK based OPD Pelamis system (EPRI assessment: Offshore Wave Energy Conversion Devices, 2004). Where AquaBuoy is a stand alone buoy device the Pelamis system is a "snake-like" system of hinged, partly submerged cylinders.

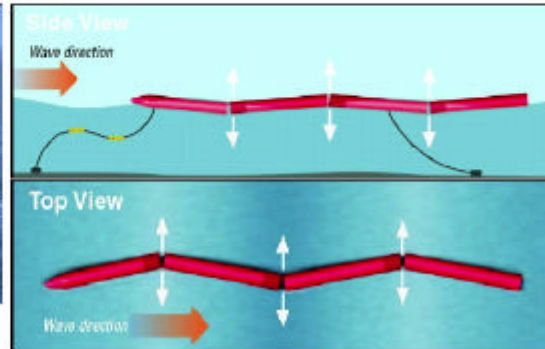
## Group1 - Ocean Power Delivery



Total Device Length: 150m  
 Device Diameter: 4.63m  
 Structural Steel Weight: 380tons  
 Average Power (24kW/m): 152kW  
 Water Depth: >50m



Video of prototype sea trials  
 Click on video image to play



EPRI

### AquaEnergy

Diameter: 15m  
 Structural Steel Weight: 40tons  
 Average Power (24kW/m): 20kW  
 Water Depth: > 50m

Figure 2: Pelamis and AquaBuoy illustrations from the EPRI report.



The central and challenging issue in developing these technologies is to tune the absorbing structures into resonance with the actual sea state in order to optimise absorption efficiency, and at the same time prevent fatal damage from extreme waves. Furthermore it is a prerequisite that very reliable mechanical and electrical systems are developed, as most service and maintenance work cannot be carried out offshore.

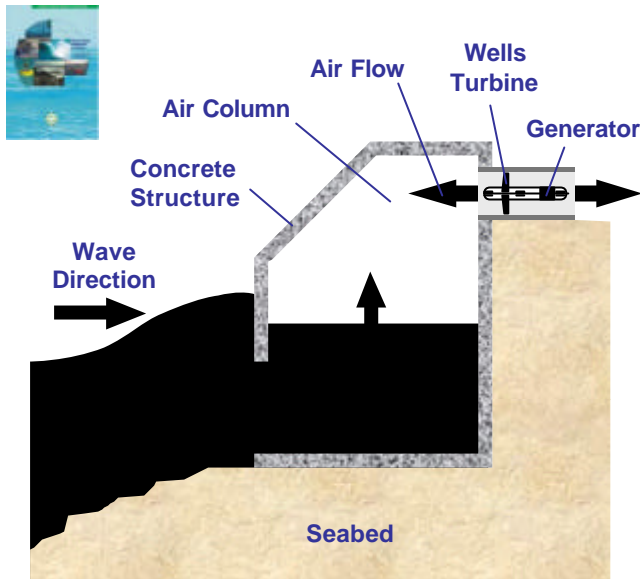
### Oscillating Water Column (OWC)

An oscillating water column utilises an enclosed column of water as a piston to pump air. These structures can float, be fixed to the seabed or be mounted on the shoreline. This type of wave energy devices have been working for several years in shoreline devices.

Also for these systems it is a central issue to get the oscillating bodies in resonance with the actual sea state and develop safety systems to prevent fatal damage from extreme waves.



## Oscillating Water Column



500 kW shoreline OWC (2000)  
Islay (Scotland)



400 kW (1998), Pico Island (Azores)  
Fully automated, full-scale testing facility

Figure 3: Limpet and Pico shoreline OWC's – brochure by European Thematic Network on Wave Energy

**OreCon**  
 Diameter: 32m  
 Structural Steel Weight: 1250tons  
 Average Power (24kW/m): 477kW  
 Water Depth: > 50m



Parabolic Width: 35m  
 Structural Steel Weight: 450tons  
 Average Power (24kW/m): 260kW  
 Water Depth: 10m to 50m



Figure 4: OreCon floating OWC and Energetec near shore bottom standing OWC - from the EPRI report.

### ***Overtopping devices***

An overtopping device uses a ramp, up which waves can run and overtop into a reservoir located behind it. The reservoir then empties back into the ocean, driving a low-head turbine.

An overtopping device can be fixed to the shore or be deployed freely floating.

The performance of these WEC technologies are not dependant of resonance with the waves and can therefore be constructed very large. Central issues for floating overtopping WEC's are to control and stabilise the floating structure to optimise power output.

### ***Power take off systems***

Facts box

Power take off systems:	Efficiency	Maturity	Relevant to:
Direct Mechanical Systems (Gearbox or linear generator)	95%	Old & proven/ New & unproven	Reactive devices
Hydraulic Power Take off Systems	85%	Proven	Reactive devices
Air Turbines	60%	New & unproven	OWC
Low-head Hydro turbines	90%	Old and proven	Overtopping

## **4. Wave Dragon**

Wave Dragon (WD) is an offshore wave energy converter of the overtopping type where each unit will have a rated power of 4 -10 MW depending on how energetic the wave climate is at the deployment site. As part of the development activities towards a full size production plant in 2006 a grid connected prototype of the WD is presently being tested in a Danish fjord (a scale 1:4.5 of a North Sea production plant).

WD consists of three main elements:

- Two patented wave reflectors focusing the waves towards the ramp, linked to the main structure. The wave reflectors have the verified effect of increasing the significant wave height substantially and thereby increasing energy capture by 70 % in typical wave conditions.
- The main structure consisting of a patented doubly curved ramp and a water storage reservoir.
- A set of low head propeller turbines for converting the hydraulic head in the reservoir into electricity.

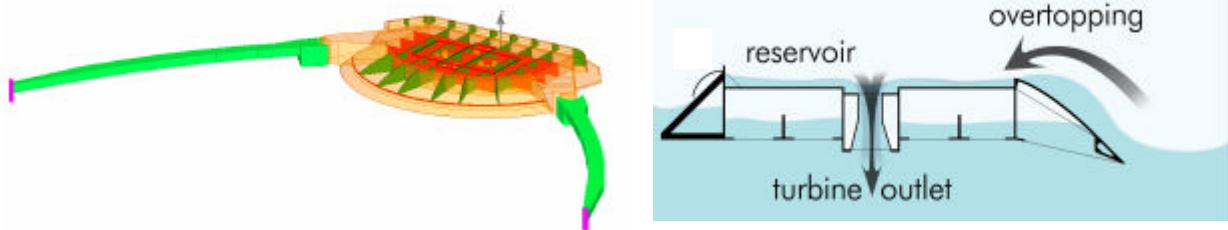


Figure 5: Left: Main components of the Wave Dragon. Right: The basic principle of the Wave Dragon, 1) waves overtopping a ramp, 2) water stored in a reservoir above sea level and 3) water discharged through hydro turbines. Wave Dragon floats on open air-chambers used to adjust floating level.



Figure 6: Wave Dragon prototype. Approaching waves are concentrated by the reflector towards the ramp.



Figure 7: Wave Dragon in good waves (left) and in smaller waves (right).

Compared to other WEC types the Wave Dragon is quite unique as it uses the energy in the water directly via water turbines, i.e. a one-step conversion system, which yields a very simple construction and has only one kind of moving parts: the turbines. But yet Wave Dragon represents a very complex design, where intensive efforts by universities and industry have been spent on designing, modelling and testing in order to:

- Optimise overtopping.
- Refine hydraulic response: anti-pitching and anti-rolling, buoyancy etc.
- Reduce (the effect of) forces on wave reflectors, mooring system etc.
- Develop efficient turbines for extremely low and varying head.
- Develop a turbine strategy to optimise power production.
- Reduce construction, maintenance and running costs.

All of this has been done with one goal: to produce as much electricity as possible at the lowest possible costs - and in an environmental friendly and reliable way.

### ***The power take off system***

Once the overtopping water has reached the reservoir, the potential energy is harvested by the installed low-head turbines. Early in the project it was concluded that the turbines had to be as simple and rugged as possible, with an absolute minimum of moving parts. Thus, a design with both fixed guide vanes and fixed runner blades has been chosen. The result has been a low head turbine specially developed by the Wave Dragon Team and tested at the Technical University of Munich. The resulting efficiency of the turbine is between 91 to 92 % in the relevant head and flow ranges. The operating conditions of the turbines on the Wave Dragon differ strongly from those in a normal river hydro power station:

- Firstly, the turbines have to operate at very low head values ranging from 0.4 m to 4.0 m, which is not only on the lower limit of existing hydro power experience, but also an extremely wide variation.
- Secondly, due to the stochastic time distribution of the wave overtopping and the limited storage capacity, the turbines have to be regulated from zero to full load very frequently.
- Lastly, they have to operate in a very hostile environment, with only a minimum of maintenance being possible on an unmanned offshore platform.

Efficient operation over the wide discharge range is ensured by using 16 relatively small turbines that can be switched on and off individually rather than a few large turbines. In order to grant a high efficiency throughout the wide head range, the turbines are operated at variable speed, using inverter-controlled and directly coupled synchronous permanent magnet generators. In order to keep the generator dimensions and cost low, the turbine design aimed at achieving a high specific speed; trying to attain a high unit discharge at the same time, which makes for a compact turbine.

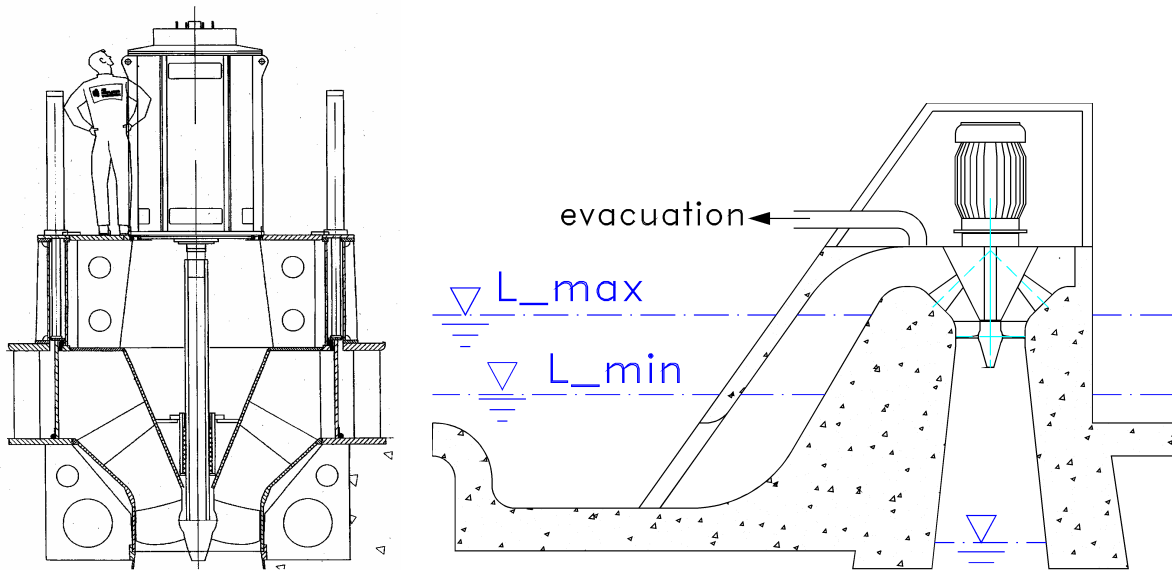


Figure 8: Left: A full scale WD cylinder gate turbine. Right: The principle of the siphon type WD turbine.

A comprehensive software package has been devised, enabling the overtopping of the individual waves and the operation of the turbines to be simulated. With the aid of this simulation software, optimum turbine operating strategies have been conceived. It has been found that for maximum energy production the turbines need to be switched on and off very frequently. In order to make this viable, two alternative solutions have been devised: A hydraulically operated cylinder gate upstream of the guide vanes and a siphon intake. Both designs have been considered worth pursuing and are at the present time being tested on the small scale prototype.



Figure 9: The six axial propeller turbines being assembled at Kössler GmbH (left) and one of the turbines being installed on the prototype in open sea

**The control system**

The Wave Dragon is equipped with a SCADA system allowing remote control and standard power plant operation

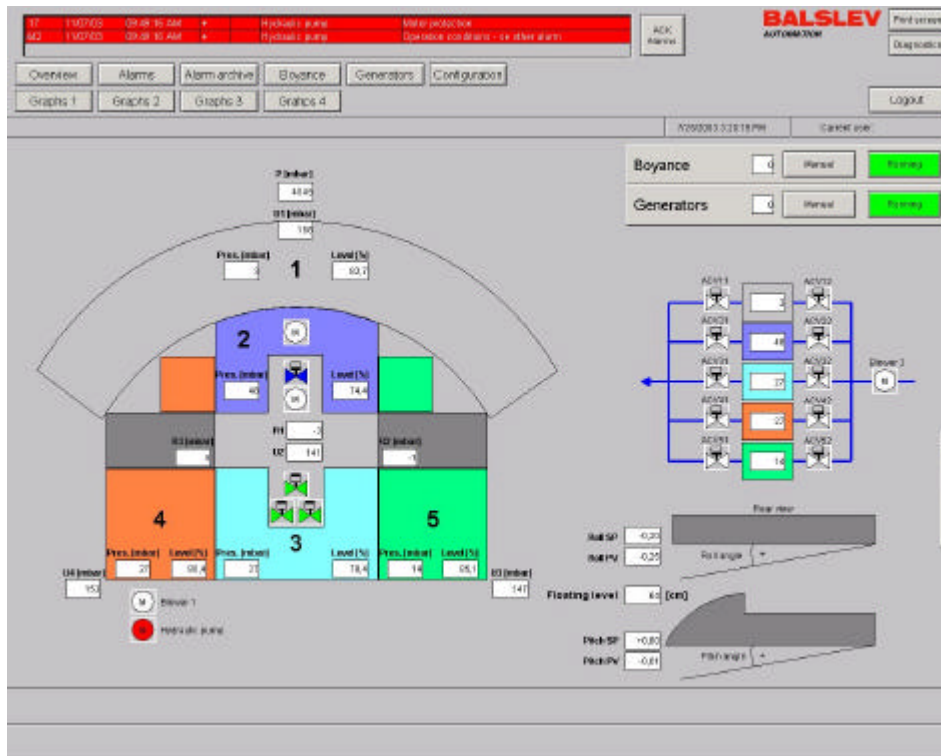


Figure 10: The main SCADA screen

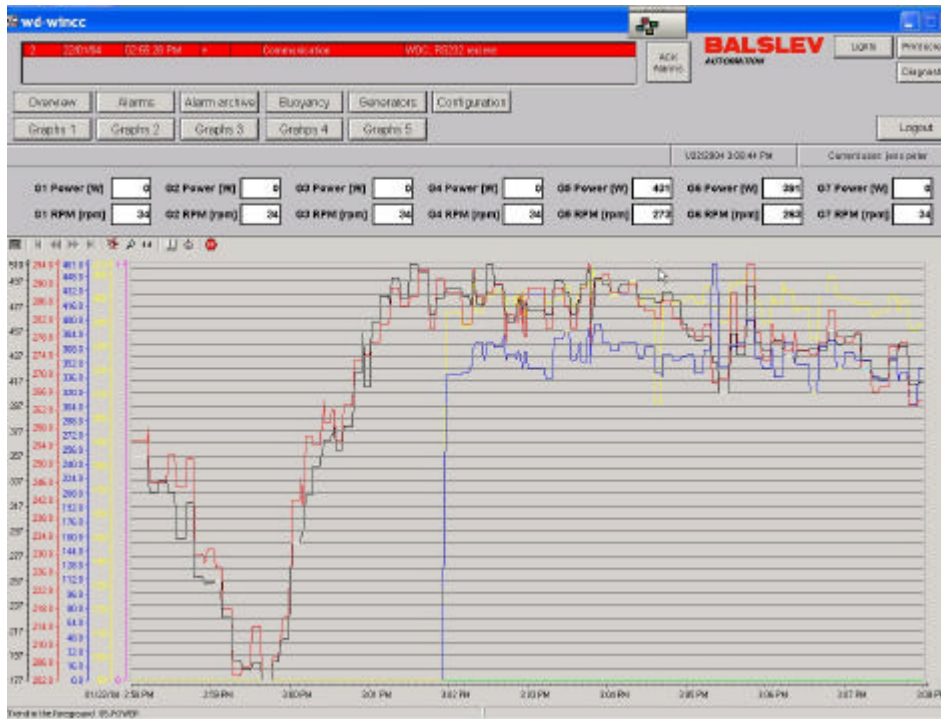


Figure 11: This SCADA screen dump illustrates rpm and power during start up of two turbines.

## **5. The Wave Dragon path to bulk generation**

The development of the project was initiated in the late 1980's by the inventor M.Sc. Erik Friis-Madsen. Since then, the work on the project has involved a wide variety of universities and industrial partners. The WD development costs to date amounts up to 8 mill. € Half of this has been funded by the participating partners and sponsors, the rest from public and other funds (primarily from the Danish Energy Authority and the European Commission). WD has been subject to thorough testing in scale 1:50 carried out in wave tanks at Aalborg University and University College Cork, and a highly efficient power take-off in the form of an axial turbine in scale 1:3.5 has been developed. The turbine has been tested in the acknowledged turbine test stand at Technical University Munich. Furthermore, a significant development and design optimisation program has been carried out in a fruitful cooperation among a number of European companies.

The Wave Dragon device has been in constant development over the last ten years and is now generally considered to be one of the most well developed offshore wave energy devices in the world.

Erik Friis-Madsen first outlined the concept in 1987, with the design intention of using mainly standard equipment. In particular, simple turbines as normally used for hydropower can be used to convert a low head from a reservoir into electrical power avoiding the use of new invented air turbines or complicated mechanic power take off systems. Substantial development of the device using EC and Danish Government funding has been going on since 1997, and the initial concept from 1987 has been much refined. Design improvements include the installation of reflector arms to help concentrate the waves and increase the amount of water overtopping the device, the refinement of the curved ramp in front of the reservoir to maximise overtopping and the development of a very efficient yet robust refinement of the well known Kaplan type turbine.

A fundamental design aim for dikes and harbour walls is to avoid overtopping. With its doubly curved ramp and wave reflectors Wave Dragon is deliberately designed to maximise the amount of water that overtops the ramp crest. The deflection of the waves towards the ramp by the reflectors results in a large increase in wave height in front of the ramp. The Wave Dragon ramp is by comparison to a beach short and relatively steep to minimise the energy loss from wave breaking. A beach causes the wave to change its form and to elevate. The spe-

cial curved shape of the ramp optimises this effect, and tests have shown that this increases overtopping significantly. The doubly curved ramp and the wave reflectors have been patented.

Wave Dragon is constructed with a number of open-bottom floodable compartments and a pressurised air system is used to adjust the freeboard of the device. This is used to maximise the energy production by optimising the amount of water collected and the head on the turbines. There are quite complex physical relationships between wave height, the geometry of the ramp and wave reflectors, the floating height of the Wave Dragon and the amount of water that overtops into the reservoir. The development programme has led to a thorough understanding of the performance of the device in different wave climates, and the likely construction costs and operation & maintenance costs. Wave Dragon is now well set for testing a commercial size prototype.

<b>Date</b>	<b>Activity</b>
1987	Erik Friis -Madsen develops the concept of the Wave Dragon wave energy converter
1994	Patent application submitted. Danish patent granted in 1999 and European patents granted in 2001.
1995-1999	Preliminary studies of structural layout, economic aspects, geometry, optimal choice of turbine configuration and Wave Dragon movement carried out
1998-2000	Floating 1:50 scale model built by the Danish Maritime Institute and tested at Aalborg University and University College Cork. Funding from the Danish Wave Energy program.
1998-2000	Work carried out using EC funding to develop low-pressure turbine and control equipment.
2001-2005	Development and testing of a 1:4.5 (20 kW) prototype at the Danish Wave Energy testing site at Nissum Bredning. Supported by EC and Danish funding (Danish Energy Agency, PSO)
2005	Development and testing of new platform/reflector design and secondary power-take-off in scale 1:50 wave tank tests and on the 1:4.5 prototype in Nissum Bredning Denmark. Supported by Danish funding.

## **6. Promising results from 2 year continuous real sea prototype testing**

The hydraulic performance of the WD has been optimised through numerical modelling and the use of small scale models tested in wave tanks. The optimisations includes overall structural geometry, focusing especially on reflector design and the cross section of the ramp, and has almost doubled the energy capture compared to the 1st generation design. This has lead to the overtopping expression below by Hald & Frigaard, 2001 based on 1:50 scale model tests.



$Q^* = 0.025 \exp(-40R^*)$  where

$$Q^* = \frac{q\sqrt{s_{op}/2p}}{\sqrt{gH_s^3 L}}$$

$$R^* = \frac{R_c}{H_s} \sqrt{\frac{s_{op}}{2p}}$$

$q$ =discharge due overtopping

$H_s$ =significant wave height

$L$ =ramp width

$s_{op}$ =wave steepness,  $s_{op} = H_s/L_{op}$

$L_{op}$ =deep water wave length,  $L_{op} = \frac{g}{2p} T_p^2$

$T_p$ =Peak period

$R_c$ =Crest freeboard relative to MWL

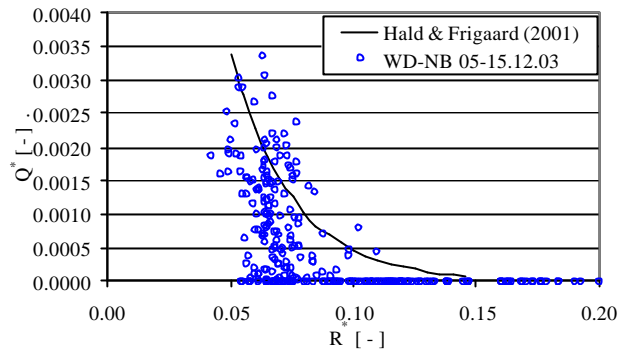


Figure 3. Comparison of preliminary prototype data and overtopping expression.

*Figure: 12 measured prototype data compared to expression based on laboratory tests.*

The reasons for the general scatter and the data points falling below the prediction line:

- Ideally, the buoyancy control system on board should keep the reservoir level at all time. This has not been the case during all the test runs. The regulation of the buoyancy system is under continuous optimisation in order to obtain more stability.
- When the crest freeboard has been low compared to the wave height the limited capacity of the turbines and reservoir occasionally lead to spilling of overtopped water.
- Due to the current mooring configuration at the test site WD has not been able to align it self up against the waves at all times, and misalignment with the wave direction decreases the overtopping rate.
- Measuring uncertainties, especially on the measurement of the floating level and thereby the crest freeboard, are of importance. Some drifting of the pressure measurements has been experienced, mainly due to marine growth on the transducers.

However, it is reassuring that there are points above the prediction line, as this indicates that the overtopping expression can be exceeded under certain circumstances. Thus, the overall picture is that the overtopping expression is realistic in normal operation, i.e. when the reservoir is level and not overflowed and WD is fairly aligned towards the waves..

### ***Experience with the turbines***

The turbines were dismantled for inspection and maintenance after one year of tests, as the bearings showed signs of corrosion due to inadequate protection against intrusion of salt water. The inspection showed also, that marine growth is a factor that may not be taken lightly.

The draft tubes of the turbines was made from different materials: uncoated stainless steel, black steel protected with conventional epoxy paint and black steel protected with a special silicone-based antifouling paint. The draft tubes painted with the conventional paint system were found heavily overgrown with a wide variety of flora and fauna, which was almost impossible to remove. The stainless steel tubes as well as the ones coated with the silicone paint had only a few mussels on them which could be swept off very easily. The effect of the antifouling paint is very convincing, therefore all the cylinder gate turbines have now been treated with this paint system. The Wave Dragon is not sensitive to fouling on the structure it self in contrast to small WEC's, thus it can be concluded that bio fouling will not be a problem in the future development.

### ***Stranding***

Denmark was, as the rest of Northern Europe, hit by a severe storm January 8<sup>th</sup> 2004. WD is deployed in the part of Denmark that experienced the highest wind speeds exceeding more than 33 m/s in 10 min. average. During the storm the main mooring connection broke and the platform drifted towards the shore where it stranded close to the beach.



*Figure 13: The WD stranded at the beach (left) after failure of the force transducer in the main mooring line (right).*

The structure proved to be very robust as no damages have been observed. A broken force transducer, which connects the main mooring lines and the anchor block, caused the failure. The transducer broke at a load lower than the guaranteed break load. The 15,600 operating hours track record have provided a thorough insight in the hydraulic behaviour of the WD device and a number of specific suggestions for improvement of the wave energy absorption system (i.e. structural elements) have evolved based on this experience. The prototype will be deployed in a more energetic wave climate this summer.

### 7 The lesson of wind power

Wave energy can be expected to develop in a similar way as have been seen for the wind energy industry, which has shown us a remarkable learning curve:

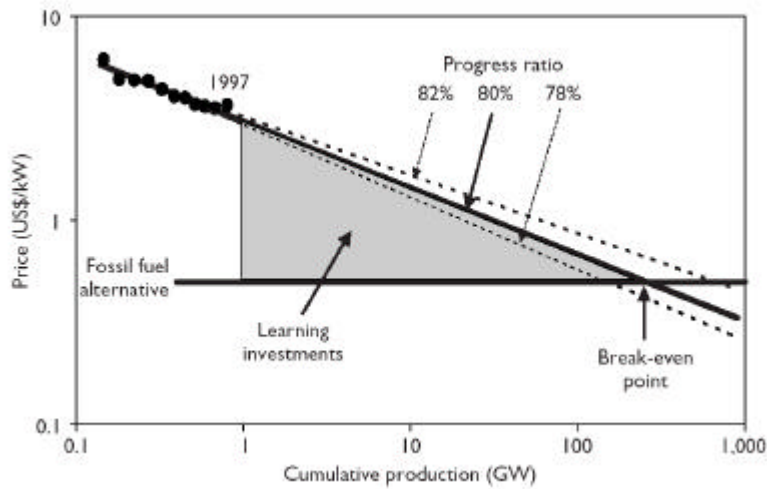


Figure 14: The learning curves for wind turbines

One of the main advantages of the Wave Dragon technology is that it can be scaled up freely in size. Wave Dragon is therefore among the technologies being developed to day the only one that holds the possibility to experience an industrial development like the wind power industry. The constant development towards still larger and more powerful and efficient machinery from the early days of wind power is illustrated in the figure below.

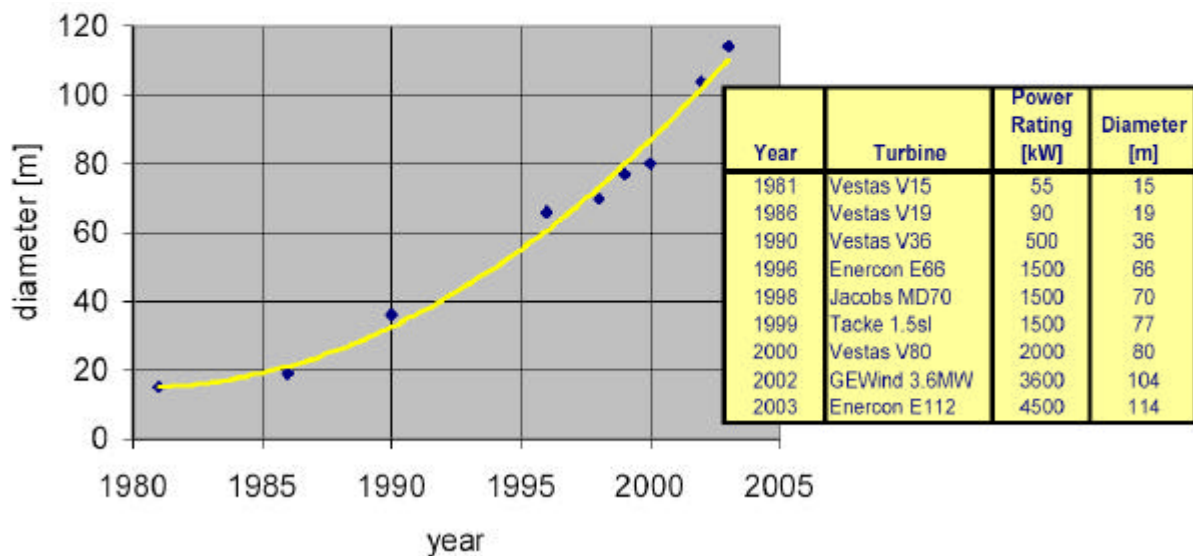


Figure 15: The steady growth in size for wind turbines.

Wave Dragon has been developed towards long term profitability in a fairly low 24 kW/m wave climate; a wave climate that can be found at most western European coast lines. The profitability will however increase significantly when deployed in more energetic wave climates.

## 7. Scaling up – the way to profitability

Wave Dragon can be constructed in any size. The optimal size - based on the present efficiency and the calculated construction costs - are in different wave energy climates as shown in this table:

Unit size	Prototype	24 kW/m	36 kW/m	48 kW/m	60 kW/m
Width (between reflector tips), m	57	260	300	390	390
Weight incl. ballast, t	237	22,000	33,000	54,000	54,000
Reservoir, m <sup>3</sup>	55	5,000	8,000	14,000	14,000
Number of turbines	1+3+6	16	16-20	16-20	16-24
Annual power production, GWh/year	0.06	12	20	35	43
Generators (PMG), kW	2.5	250	350-450	460-700	625-940

*Table 2. Dimension of Wave Dragon prototype and Wave Dragons for different wave climates.*

There is no upwards restriction in Wave Dragon unit size as the efficiency steadily increases with the physical size. The chosen size at an actual wave climate is solely a result of a cost benefit calculation. The Wave Dragon technology is in the short term expected to be economical competitive with offshore wind power in wave climates above 33 kW/m. Very significant profit potential exists in higher wave climates. Taking moderate cost savings and power efficiency increases into account, Wave Dragon power price will eventually be in line with the costs of fossil fuel generation.

### *The ongoing work towards commercialisation of Wave Dragon*

Power production will be increased by:

- Optimising overtopping.
- Reducing spill from the reservoir by intelligent trim and heel control.
- Refining the turbine-generator technology and the turbine control strategy.
- Increasing the availability

The calculated annual cost will be lowered by:

- Reductions in construction costs due to an optimised, composite built structure.
- Optimising the planned operation and maintenance work.

## 8. Status and conclusion

A prototype of the WD is, as part of the preparations towards a full size multi MW production plant, undergoing real sea testing in Nissum Bredning, Denmark. So far the preliminary test-

ing has supported the data earlier achieved from the laboratory tests. Furthermore, invaluable experience has been obtained in most operational aspects, such as regulation strategies for crest freeboard and turbines, remote control of operation and testing, etc. The experiences from the almost two years test program, which primarily is supported by the European Commission and the Danish Energy Authority, will establish the necessary background for an optimal design of the structure and the power take off system. Planning for deployment of a 7 MW power production unit in the Atlantic within the next 1-2 years is in progress and basin tests of a second generation WD with secondary hydraulic power take off systems is ongoing. A multi MW second generation WD prototype project has recently been approved by EC's framework programme.

The profitability of the Wave Dragon technology will - as outlined above - improve due to continuous technological development of the WD technology; and WD will in the longer perspective be scaled the up for more energetic wave climates. Due to the fact that the WD platform is very stable even in storm waves, it is also not unlikely that MW wind turbines will be installed on WD platforms when the two renewable offshore technologies have matured.

For further information, please visit:

[www.wavedragon.net](http://www.wavedragon.net) and [www.civil.auc.dk/~i5jpk/wd/wdnb.htm](http://www.civil.auc.dk/~i5jpk/wd/wdnb.htm).

## REFERENCES

Hald, T. and Frigaard, P.: *Forces and Overtopping on 2. generation WD for Nissum Bredning*. Phase 3 project, Danish Energy Agency. Project No. ENS-51191/00-0067. Hydraulics & Coastal Engineering Laboratory, Aalborg University, Denmark, 2001.

IEA (2001): *IEA Learning Curves RES 2001*, Paris.

European Thematic Network on Wave Energy (2002): *Wave energy Utilization in Europe, Current Status and Perspective*, EU, [www.wave-energy.net](http://www.wave-energy.net)

Soerensen, H.C., et al (2003): *Development of Wave Dragon from scale 1:50 to prototype*, Proceedings from the 5th European Wave Energy Conference, Cork, Ireland 2003.

Knapp, W., Holmen, E. et. al. (2003): *Turbine development for the Wave Dragon wave energy converter*, Paper presented at the Hydro 2003 conference in Croatia, November 2003.

EPRI (2004): *Offshore Wave Power Feasibility Demonstration Project*, Palo Alto, CA, USA, [www.epri.com](http://www.epri.com)

Kofoed, J. P., Frigaard, P., Friis-Madsen, E. and Sørensen, H. C.: *Prototype testing of the wave energy converter Wave Dragon*. 8th. World Renewable Energy Congress, Denver, USA, Sept. 2004.