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Development of Wave Energy Devices – Past, Present and Future: The Danish Case

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1 Introduction

The Wave Energy Sector has come a long over the past decade, but has still quite some way to go and is still in an immature phase, characterized by a lot of new devices constantly appearing on the scene. An inventor will typically contact an energy utility or some possible investors claiming that his invention/device will be able to produce a lot of energy at a very low cost. In order to do a kind of comparison it is essential that a protocol exist so devices can be compared.

The Danish Government initiated in 1998 a special 'Wave Energy Program' with focus on economical support of new inventions. This program increased the need for a protocol to assess the devices. In 1999 a commission 'Bølgekraftudvalget' appointed by the Danish Government released a first protocol on testing/assessment of Ocean Energy Devices (Nielsen, 1999).

Aalborg University (AAU) has a long record of participation in the development of wave energy in Denmark during the last 10 years, and more than 60 projects have been carried out on approximately 30 different devices which have been tested or assessed.

The paper describes the best practice on assessment of wave energy devices being developed at Aalborg University based on the protocol from 1999, and it outlines current stage of development in this sector in Denmark, and some focus is put on the current efforts to develop best practices and/or standards both nationally and internationally. This work is taking place in various organizations – national subcommittee S-614 (lead by AAU) under Dansk Standard, I nternational Electrotechnical Commission (IEC) TC-114 (AAU member) and the EU FP7 project EquiMar (AAU partner).

2 Development level of devices

The assessments of the devices have been classified into 4 phases. The main idea is that each phase has to give some specific information to the inventor and his investors (including state support).

Secondary the idea is not to use too many resources before having an estimate on the potential.

The 4 phases used in Denmark are:

- Phase 1: Proof of Concept, Rough estimates of energy production in 5 specified wave states leading to an estimate of a yearly energy production, Suggestions for further development of the device. Typical small indicative laboratory tests followed by a ~10 page report. Cost ~10.000 euro.
- Phase 2 Detailed Laboratory tests in scale 1:50 to 1:20, Detailed Numerical calculations, Estimates on Cost, Feasibility studies, PTO design etc.. Typical intensive laboratory tests (optimizations) or intensive numerical modeling. This phase can consist of N (i.e. 10) detailed investigations followed by ~100 page reports. Cost N x 25-50.000 euro.
- Phase 3 Testing in real seas in scale 1:10 to 1:3. Normally Nissum Bredning (a "small" benign piece of inner sea, a part of the Limfjord in the northern part of Denmark, see figure 1 and 2) has been used for this purpose. Cost 0.5-5 mill euro.
- Phase 4 Demonstration in half or full scale. Cost 5-20 mill euro.

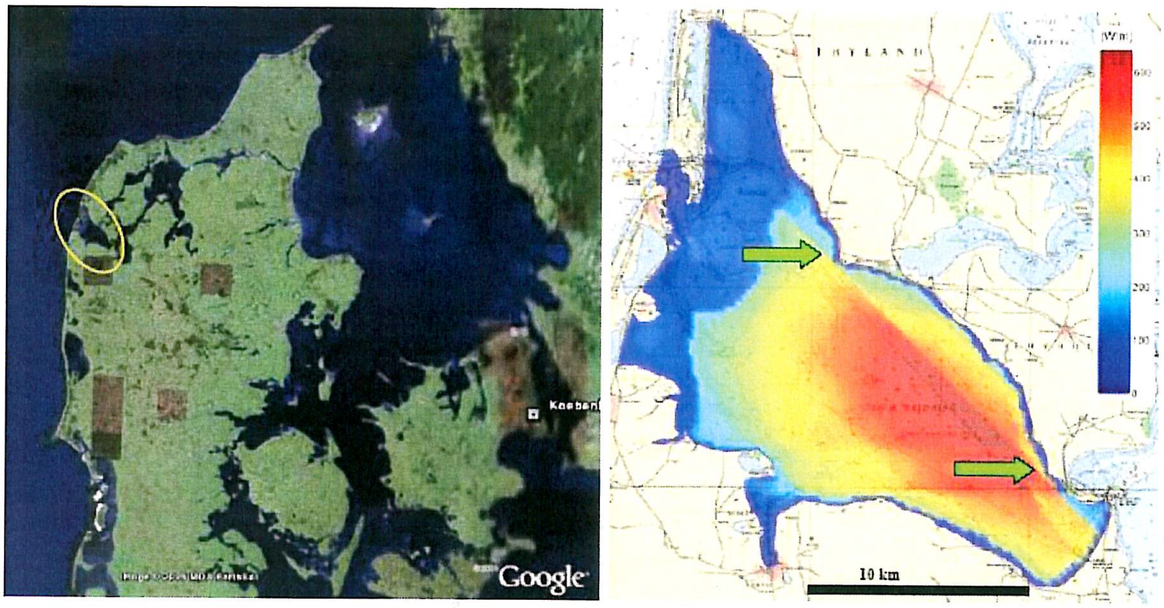

Figure 1*: Left: Location of Nissum Bredning in Denmark. Right: Detailed view of Nissum Bredning with indication of wave energy density (blue – low, red – high), and location where testing has been taking place. Upper green arrow indicates the location of the main wave energy test site in Nissum Bredning (see figure 2 below) where numerous small scale devices have been tested, and where the large scale Wave Dragon and the Wave Star prototypes have been undergoing long term real sea testing, delivering power to the grid. The lower green arrow indicates a more energetic location where the Wave Dragon prototype, as well as an AquaBuoy model, also has been tested.*

Figure 2*: The main wave energy test site in Nissum Bredning. To the left in the picture the Wave Dragon prototype can be seen.*

3 Laboratory Testing

The main instrument used under phase 1 and phase 2 to assess the Wave Energy Devices is small scale testing in a hydraulic laboratory. These tests are performed in order to gain knowledge on the devices before they actually are being built in full scale in the sea. The laboratory tests will give information on:

- Loads on the device
- Movements of the device
- Run-up / Over topping of the device
- Energy Production

In a phase 1 assessment the test will give rough estimates (± 20%) on energy production, and knowledge from the tests will help to estimate costs.

In a phase 2 assessment the test will give more detailed estimates (±5%) on the expected energy production. A phase 2 test could further include a parametric study making it possible to optimize the device.

The far most used model low in relation to laboratory tests is Froudes Model Low, which require:

- Inertia forces to dominate the physics. Friction forces must be neglect able relative to the inertia forces. Inertia forces are forces proportional to the volume/mass of the device.
- The model must be geometrically similar to the full scale device

The constrain requiring friction forces to be small relative to the inertia forces will typically lead to a maximum scale in the order of 1:50 for the hydraulic part and 1:10 for the power take off part.

Wave basins are normally designed for hydraulic tests with marine constructions, ships or coastal structures. In order to keep costs down such tests are traditionally performed in scale 1:20 to scale 1:100. If a design wave height is 15 meter with a period of 12 seconds, a model test in scale 1:100 will be performed with a wave height of 15 cm and a period of 1.2 second.

The wave energy sector wants to perform tests in i.e. scale 1:10. For the previous example that would give a wave height equal to 1.5 meter with a period of 3.8 seconds. Model tests with so large waves can only be performed in very few laboratories around the world, and costs are enormous. Therefore model tests are performed in i.e. scale 1:40, which leads to scale effects on the modeling of the power take off.

Consequently the power take off is modeled to perform in accordance with pre-specified characteristics. This is not a serious problem because one of the requirements to the outcome of the model tests often is a specification on the loading of the power take off. One should just always remember that the dimensions of the power take off system can not just be scaled up. It is the performance which can be scaled up.

Transferring measured data to full scale values follows the Froudes Model Law:

Parameter	Model	Full Scale	Example 1:100
Length	1	S	100
Area	1	S^2	10000
Volume	1	S^3	1000000
Time	1	$S^{0.5}$	10
Velocity	1	$S^{0.5}$	10
Force	1	S^3	1000000
Power	1	$S^{3.5}$	10000000

Table 1*: Up scaling of measured parameters from model in scale S (S=100 in example) to full scale.*

It is often difficult for the public to understand the figures given in table 1. A few examples are: In the laboratory we measure a maximum load equal to 20 kg on a model in scale 1:30. In full scale this load will be 54 tones.

Another example is: In Nissum Bredning the 1:4.5 scale model of Wave Dragon is equipped with 20 kW. In full scale this corresponds to almost 4 MW.

4 Modeling the Sea

Waves are by nature irregular, short crested and non-linear. The question is: How accurate is it necessary to model the sea.

The energy content in the seas around Denmark varies from location to location. Excluding the very extremes the Danish seas have areas with average energy levels ranging from 5 to 22 kW/meter wave crest. Scatter diagrams exist for many parts of the Danish Seas. It is obviously that a detailed design/optimization must take into account the actual waves existing on the proposed location for the wave energy device but in order to make some comparison possible for devices being tested under phase 1 (and phase 2) devices are normally tested against some pre-defined wave states:

- 5 wave states describing energy content of the sea.
- 3 wave states describing design wave heights.
- wave states to describe fatigue loads.

In phase 1 the sea is always modeled as linear irregular long crested waves using JONSWAP spectra with a peak enhance factor equal to 3.3.

Hs is wave height as defined by IAHR, and Tz is average wave period and Tp is peak period of the wave spectrum.

Wave State	Hs	Tz	Tp	Energy flux	Prob. Occur.
	m	*sec*	*sec*	*kW/m*	%
1	1.0	4.0	5.6	2.1	46.8
2	2.0	5.0	7.0	11.6	22.6
3	3.0	6.0	8.4	32.0	10.8
4	4.0	7.0	9.8	65.6	5.1
5	5.0	8.0	11.2	114.0	2.4

Table 2: *Standardized wave states describing energy in the Danish seas.*

For tests to assess the energy production, the minimum duration of the test in each irregular wave state is 500 waves.

5 Design Waves

The Danish tradition on required safety levels for offshore structures corresponds to 2% exceedence of the load per year. This is equal to operate with a wave states with a 50 years return period (a 50 years wave). Many other countries use the 100 years wave for design. Since most wave energy devices will be unmanned it is possible that the required design wave will be lower than these waves. It is believed that the future will bring some economical considerations leading to an acceptable safety level.

Nevertheless, for the time being wave states with a 50 years return period is normally used for design. A phase 1 test will include visual observations of the device under design conditions.

Wave state	Hs	Tz	Tp	Return Period
	m	*sec*	*sec*	*years*
D10	8.0	9.4	13.1	10
D50	9.0	9.9	13.8	50
D100	10.0	10.4	14.5	100

Table 3: *Wave states describing design conditions in Danish seas.*

For tests in design conditions the minimum duration of the test in each wave state is 1000 waves, but often 2000 waves are used.

Fatigue will in many cases become the design case. Normally, fatigue is not considered in phase 1 and phase 2 testing.

Wave state	1	2	3	4	5	
Hs (m)	1	2	3	4	5	6-10
H (m)	0.7	1.4	2.1	2.8	3.5	4.2-7.1
N [$\cdot 10^4$]	450	170	71	25	7.5	2.0

Table 4: *Number of load cycles per year*

6 Requirements for accuracy of waves

The parameters describing the waves must be measured during tests. Measured values of Hs, Tz/Tp must be as specified ± 5%. For phase 2 tests also plots of the wave height distribution compared to a Rayleigh distribution is required.

7 Modeling the Power Take Off

A precise modeling of the power take off is important because of 2 reasons:

- The power production is responsible for all the income from the device
- The load from the power take feeds back to the hydraulic performance of the device.

Therefore, the load from the power take off on the system has to be controllable.

In a full scale wave energy device the power take off system will typically vary the reactive load on the system as the load on the device varies. However, at small scale the control on the power take off is often limited to a fixed level for a given wave state, disabling a "wave-to-wave" power take off control. Actually, it is impossible to implement a perfect control algorithm for the power take off system for tests performed in small scale. Furthermore, development of this control algorithm is often the goal of the whole mission, and a significant part of the challenge at phase 3 and 4.

Each of the wave states given in table 2 are equivaleted with a periodic wave with same energy content as the original wave state, and with a period equal to the peak period Tp of the irregular wave state.

At first attempts (phase 1 and sometimes also phase 2) the power take off is tuned to best performance with the given equivalent wave, using regular waves.

Wave State	Hs	Tz	Tp	H	T
	m	*sec*	*Sec*	*m*	*sec*
1	1.0	4.0	5.6	0.7	5.6
2	2.0	5.0	7.0	1.4	7.0
3	3.0	6.0	8.4	2.1	8.4
4	4.0	7.0	9.8	2.8	9.8
5	5.0	8.0	11.2	3.5	11.2

Table 5*: Equivalent periodic waves for tuning of power take off.*

When the power take off is tuned for each of the equivalent waves the system is ready for the measurement of the power production. Examples of results hereof are illustrated in figure 3.

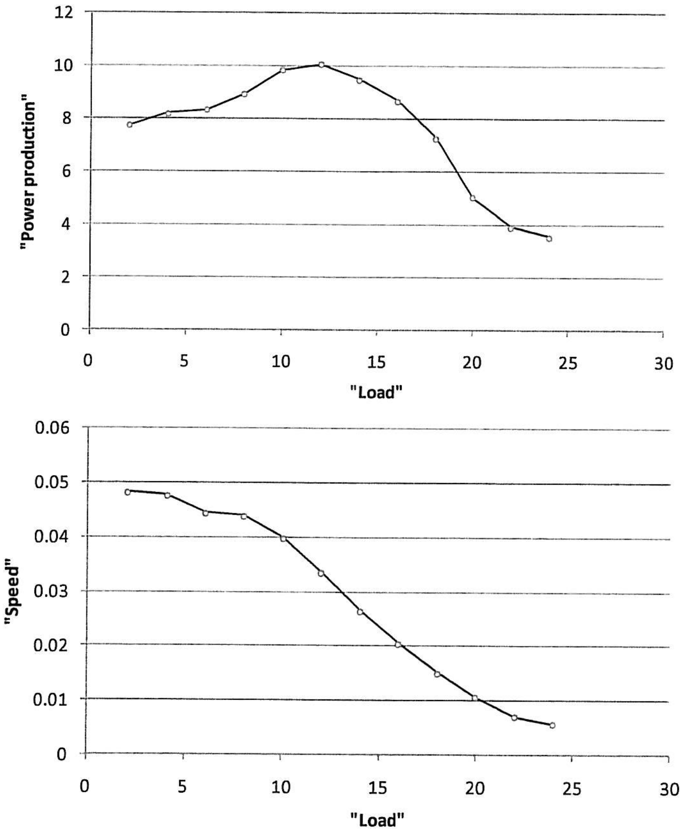

Figure 3: *Upper: Generic example of tuning of the power take off system in a single regular wave state, showing power production as a function of the load. Lower: The corresponding graph showing speed as a function of the load.*

Here, the "load" and "speed" should be interpreted broadly. Depending the device type "load" can be generator load, moment on axle, force on piston, pressure in flow, crest level, etc., and the "speed" can be e.g. generator speed, speed of displacement, flow velocity.

Now time series of power production can be measured (or calculated via the measured parameters) for each of the irregular wave states.

The average power $\overline{P}$ for the given wave state is found by integrating the time series:

$$\overline{P} = \frac{1}{T_t} \int_0^{T_t} P(t)dt \qquad (1)$$

with T_t being duration of test.

Remember that very high values of P(t) typically must be cut off due to limited installed power.

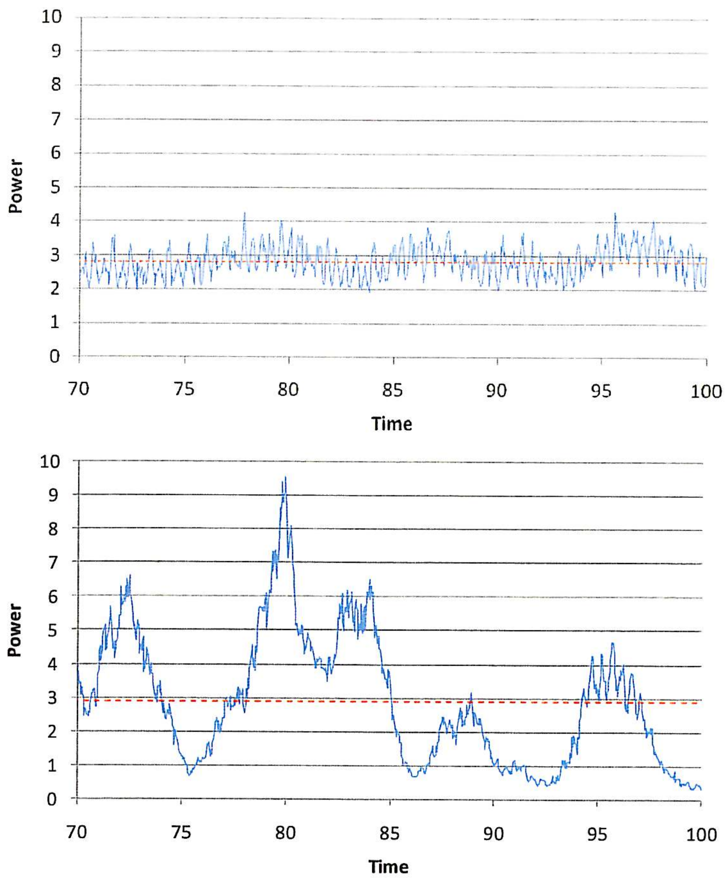

Figure 4: *Example of measured time series of power. Mean power over the showed time series indicated by dotted line. Upper: Regular waves. Lower: Irregular waves.*

The reason for using the equivalent waves in the tuning process of the power take off is that experience has shown that tuning the power take off with irregular waves is a very time consuming process, and almost no difference is seen in the final results.

The yearly production is calculated using the probabilities of occurrence for the 5 different wave states listed in table 2.

$$E_y = \sum_{i=1}^{N} \overline{P}_i \cdot S_i * 24 * 365 \qquad (2)$$

with E_y being the yearly power production, N the number of wave states and S the corresponding probability of occurrence.

When evaluating the power production it is important to note where in the power chain the power has been measured. Typically, at small scale testing, the power is measured as early as possible in the power chain to avoid including losses, which normally is heavily exaggerated at small scale. However, this also means that realistic losses should be estimated and accounted for in the scaling up of the measured power production numbers.

Wave State	Pwave [kW]	Prob [%]	Prob*Pwave [kW]	Eff. [-]	Energy prod. [kW]	Pgen [kW]
1	120	0.468	56	0.195	11	23
2	598	0.226	135	0.284	38	170
3	1616	0.108	175	0.152	27	246
4	3351	0.051	171	0.098	17	330
5	5985	0.024	144	0.084	12	505
Yearly average [kW]			680		105	
Overall eff. [-]					0.154	
Yearly prod. [MWh/y]					919	
Max. Pgen [MW]						0.505
Load factor [-]						0.21

Table 6*: Example of power production results based on the testing in the 5 standardized wave states.*

The results of the testing in the 5 standardized wave states can then be presented as given in table 6.

From here it can be seen that the performance in the individual wave states have been presented as efficiencies, here meaning the ratio between the power produced and the wave power reaching the width of the device. The overall efficiency is then the ratio between the total amount of power produced over all the wave states distributed, with the given probabilities, and the corresponding power in the waves reaching the width of the device. Another important value in the table is the load factor, i.e. the ratio between the yearly average power production and the installed generator power, here assumed to be equal to the produced power in the largest wave state. It is worth mentioning that typically the installed power needs to be significantly larger than the average power production in the largest wave states in order to make full use of all the available energy (depending on the available buffer in the system before the power is delivered to the generator).

Thus, trying to maximize the overall efficiency means lowering the load factor, will typically lead to less cost-effective devices.

8 Requirements to accuracy of the energy production

No precise requirements to accuracy of the measurements leading to estimates of the yearly energy production exist. Some of the measured values can be difficult to measure with high accuracy. Nevertheless, it is believed that the estimates of the yearly energy production can be given with uncertainty less than 20 % in phase 1 tests. In phase 2 tests the uncertainty is typically believed to be lowered to approximately 5 %.

9 Real sea testing

When arriving at phase 3 (1:3-10), and later also at phase 4 (1:1-2), the development has to be taken to real sea conditions. At this stage the power take off system is tested in its real layout, enabling detailed testing of control algorithms etc. In the real sea conditions there is no control on the waves arriving at the device. Therefore it is important to measure the wave conditions at the site, and then refer the performance of the device to the measure wave states. Based on this and the full scale wave conditions, with corresponding probabilities of occurrence, the full scale power production can again be estimated.

In figure 5 pictures of the Wave Dragon (1:4.5) and Wave Star (1:10) prototypes tested at Nissum Bredning are shown as examples of phase 3 projects.

Figure 5: *Examples of two phase 3 prototypes – Wave Dragon (left ©EarthVision) and Wave Star (right), both undergoing real sea testing at the main test site at Nissum Bredning.*

9 Standardization efforts

A common reference is important and necessary when comparing devices.

The 'best practice' presented in the paper has focused on phase 1 and 2 tests, and briefly showed examples of phase 3 projects. As the wave energy sector develops the need for such (and further developed) protocols is growing.

Some work aiming at this has already been carried out, e.g. by IEA, EMEC and DNV, further efforts are currently ongoing:

The EquiMar (Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact) project is funded by the European Commission as part of its 7th Framework programme under the Energy topic. It is a collaborative research and development project involving a consortium of 23 partners and will run for three years from the 15th of April 2008.

The aim of EquiMar is to deliver a suite of protocols for the equitable evaluation of marine energy converters (based on either tidal or wave energy). These protocols will harmonize testing and evaluation procedures across the wide variety of devices presently available with the aim of accelerating adoption though technology matching and improved understanding of the environmental and economic impacts associated with the deployment of arrays of devices. A series of protocols will be developed through a robust, auditable process and disseminated to the wider community. Results from the EquiMar project will establish a sound base for future marine energy standards.

The work has been divided into 10 work packages (WP's):

1. Knowledge base for marine energy systems
2. Physical environment specification
3. Concept appraisal and tank testing practices for 1st stage prototype devices
4. Sea trial testing procedures for ocean energy extraction devices
5. Deployment assessment - performance of multimegawatt device arrays
6. Environmental impact assessment
7. Economic assessment of large-scale wave energy deployment
8. Protocols synthesis
9. Dissemination and public engagement
10. Project coordination and management

The involvement of AAU in this work is focused on WP 3 and 4.

Another major effort is the IEC/TC114, a technical committee working under the scope of IEC (International Electrotechnical Commission - the world's leading organization that prepares and publishes International Standards for all electrical, electronic and related technologies) creating standards for the ocean energy sector

The title of the work is Marine energy – Wave, tidal and other water current converters, and the scope is to prepare international standards for marine energy conversion systems. The primary focus will be on conversion of wave, tidal and other water current energy into electrical energy, although other conversion methods, systems and products are included. Tidal barrage and dam installations, as covered by TC 4, are excluded.

The standards produced by TC 114 will address:

1. system definition
2. performance measurement of wave, tidal and water current energy converters
3. resource assessment requirements, design and survivability
4. safety requirements
5. power quality
6. manufacturing and factory testing
7. evaluation and mitigation of environmental impacts.

In Denmark a corresponding national subcommittee S-614, lead by AAU, has been established under Dansk Standard. The Danish focus has so far been on item 2.

10 Conclusions

The paper has presented the Danish case of development of wave energy devices, and outlined the established best practice. A brief overview of international standardization efforts have been given, and the Danish involvement in this described.

The Danish best practice which is being carried over to the work on the international standardization involves a phase divided development. The main idea is that each of the phases should provide valuable information for the developers and investors, before the project is taken to the next phase. Thus, the risk of using unnecessary resources on a device before reliable estimates of the concepts potential is known, is hereby minimized. Furthermore, it eases the comparison of various projects at the same phases of development.

It is advocated that through all the phases the same template for concept evaluation should be applied. For each increase in development phases the level of details are raised and correspondingly the uncertainties are lowered.

Through the evaluation and classification of the concepts, the uncertainty on the individual elements has to visible – a large uncertainty level should be punished, and a small uncertainty level should be rewarded. The level of reward or punishment should be weighed with importance of the element. Thus, the project development is focused towards dealing with the most important items with the largest uncertainties first.

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