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# Status and performance of the SSG Wave Energy Converter

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## The concept

The Seawave Slot-Cone Generator (SSG) is a wave energy converter of the overtopping type. It has a number of reservoirs one on the top of each other to optimize the storage of the potential energy of incoming waves. The use of multiple reservoirs will result in a higher overall efficiency, compared to a single reservoir structure (Kofoed, 2002; Kofoed, 2005; Kofoed and Osaland, 2005).

Part of the innovative SSG concept is the Multi Stage Turbine (MST): with its runners positioned in a common wheel it will contribute to minimize the number of starts/stops sequence and be able to work even if only one reservoir has an available head, resulting in a higher degree of utilization.

The design of the structure contributes positively to its robustness and reliability, with the turbines and the system to regulate the flow to them as the only moving parts of the device. This is an important characteristic for a wave energy converter for which structural loadings as well as environment conditions in case of extreme events can affect even more the moving parts and lead the structure to failure.

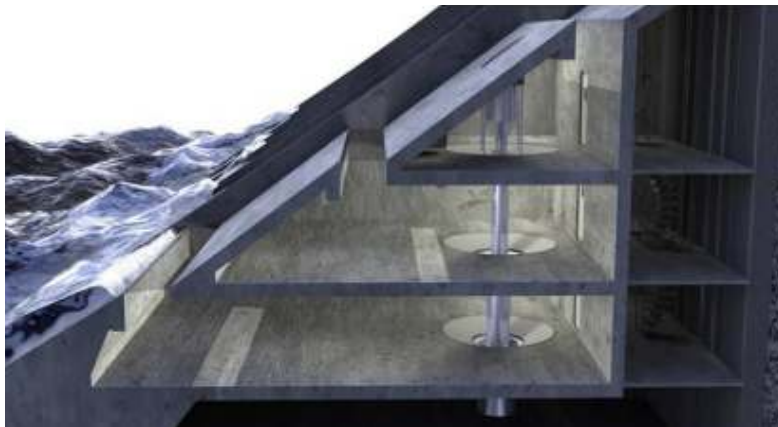


Figure 1. An artistic impression of the SSG wave energy converter.

## Status of the pilot project

The patent of the SSG was acquired in autumn 2003 and in spring 2004 the company WAVEenergy AS was found in Ålgård, near Stavanger, Norway, to develop the concept. The project has been partially funded by the European Commission FP6-2004-Energy and partners within EU have been selected to contribute to the realization of the pilot project that will regard a full scale module of the SSG on the west coast of the island of Kvitsøy, Norway (Figure 3).

The construction of the structure is foreseen for summer 2007 with the objective of demonstrating the operation of one 150 kW module of the SSG wave energy converter (3 levels reservoirs) at full-scale in a 19 kW/m wave climate, including turbine, generator, control system and connection to the public grid for electricity production.

Extensive physical model tests have been carried out on overtopping, wave loadings and turbine strategy during the three years preceding the installation of the device.

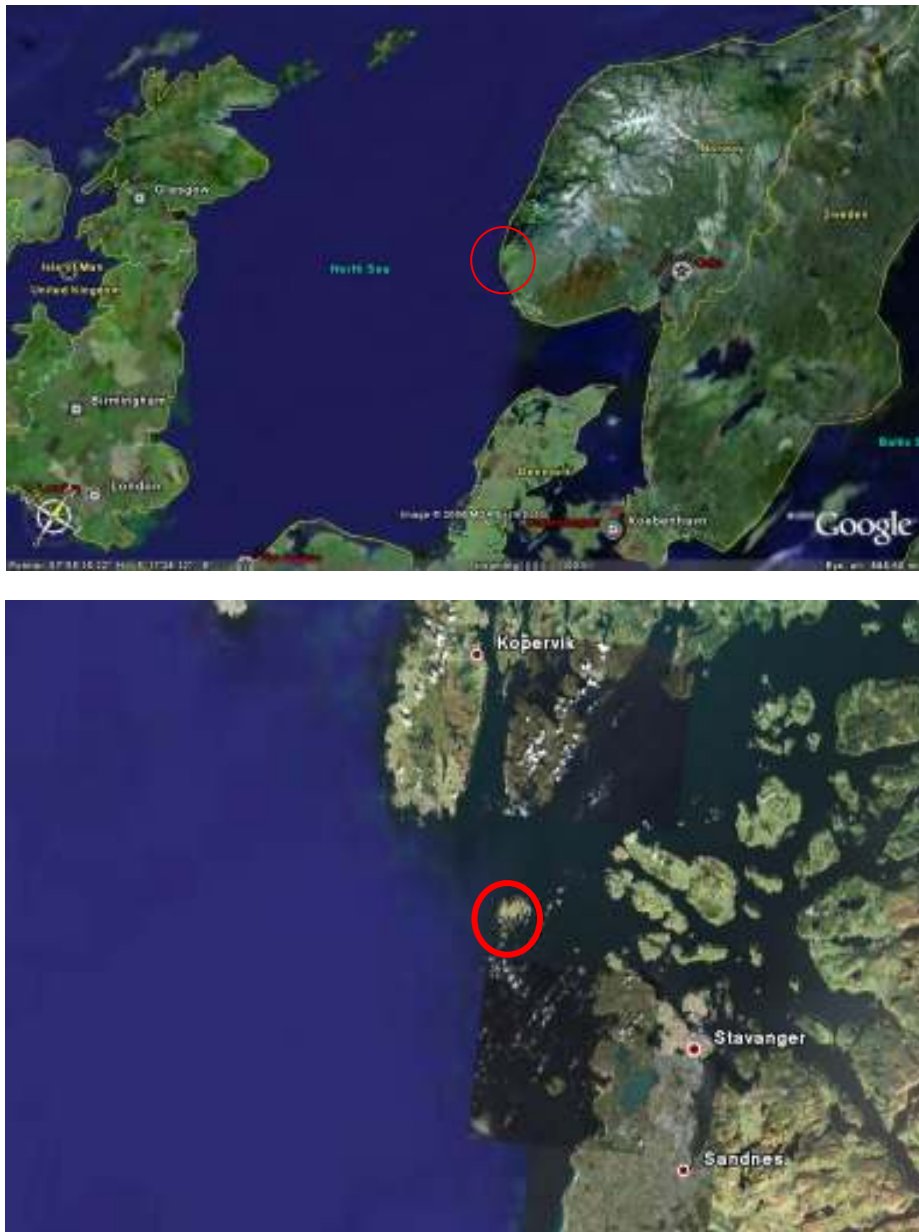
The partners more involved in this stage were Aalborg University, DK, for the hydraulic performances and the Technical University of Munich and the Norwegian University for Science and Technology, for the strategy of the turbines as well as WAVEenergy AS as coordinator of the project. At the present state, the geometry of the structure has been defined and the extreme loads calculated. The strategy of the turbines will regard 4 Klapan turbines (2 in the first reservoir, 1 in the second and 1 in the third reservoir, see definition sketch, Figure 7). Further in time, a two-stage MST will be installed on the pilot module of the SSG in order to test the performance of this innovative turbine under development at the Norwegian University for Science and Technology.



**Figure 2. Multistage turbine for 3 reservoirs.**

### **Wave conditions at the island of Kvitsøy: the pilot project location.**

In order to provide a realistic description of wave conditions at the selected pilot location (Figure 3), transformation of waves from offshore to shore has been done by using the computer model MildSim developed at AAU. The study has been realized using three different offshore wave data sets: measurements at Utsira during the period 1961-1990 and from a bouy explicitly installed during the period 4/11/2004-11/3/2005; hindcast data from DNMI (Norwegian Meteorological Institute) during the period 1955-2005.



**Figure 3. Location of the pilot project, island of Kvitsøy, Norway.**

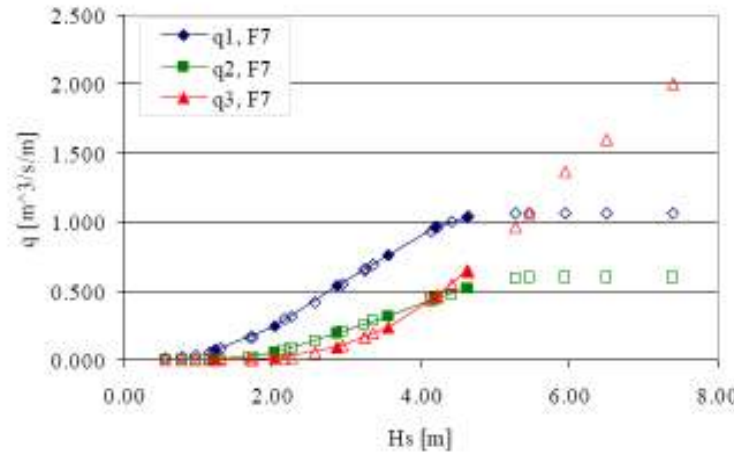
On Table 1 are summarized the wave conditions at the selected location (Kofoed & Guinot, 2005). From the table it can be seen that the near shore overall average power is estimated to be 19.6 kW/m (when neglecting wave conditions with Hs less than 1 m and more than 8 m, with a probability of occurrence respectively of 12.9% and 0.1%).

Hs [m]	1-2	2-3	3-4	4-5	5-6	6-7	7-8	Sum
<b>Tp [s]</b>	<b>6.1</b>	<b>7.9</b>	<b>9.3</b>	<b>10.6</b>	<b>11.7</b>	<b>12.7</b>	<b>13.7</b>	
Hs [m] NW-315	1.2	1.7	2.2	2.6	3.2	4.4	6	
Dir [deg.]	315	313	310	308	305	303	300	
Prob	9.9%	8.7%	5.4%	2.7%	1.1%	0.5%	0.2%	<b>28.5%</b>
Pwave [kW/m]	3.8	10.0	18.7	29.8	52.7	106.1	210.8	
Pwave*Prob	0.382	0.873	1.007	0.811	0.604	0.522	0.346	<b>4.5</b>
Hs [m] W-270	1.3	2.3	3.4	4.6	5.9	7.4	8.9	
Dir [deg.]	270	273	275	278	280	283	285	
Prob	4.8%	4.2%	2.6%	1.3%	0.6%	0.2%	0.1%	<b>13.8%</b>
Pwave [kW/m]	4.4	17.1	44.9	97.3	176.5	298.1	458.7	
Pwave*Prob	0.213	0.716	1.164	1.277	0.976	0.707	0.363	<b>5.4</b>
Hs [m] SW-225	0.8	1.7	2.9	4.1	5.3	6.5	7.7	
Dir [deg.]	225	230	235	240	245	250	255	
Prob	7.5%	6.5%	4.0%	2.0%	0.9%	0.4%	0.1%	<b>21.5%</b>
Pwave [kW/m]	1.6	9.8	34.4	77.7	139.4	229.4	349.5	
Pwave*Prob	0.119	0.638	1.390	1.590	1.204	0.849	0.431	<b>6.2</b>
Hs [m] S-180	0.6	1.0	1.2	3.2	4.2	5.5	7.1	
Dir [deg.]	225	228	230	233	235	238	240	
Prob	8.1%	7.1%	4.4%	2.2%	0.9%	0.4%	0.1%	<b>23.3%</b>
Pwave [kW/m]	0.8	3.2	5.3	47.6	89.7	161.8	291.1	
Pwave*Prob	0.065	0.227	0.233	1.056	0.839	0.649	0.389	<b>3.5</b>
<b>Sum</b>								
Prob	<b>30.3%</b>	<b>26.5%</b>	<b>16.4%</b>	<b>8.3%</b>	<b>3.5%</b>	<b>1.5%</b>	<b>0.5%</b>	<b>87.0%</b>
Pwave*Prob	<b>0.8</b>	<b>2.5</b>	<b>3.8</b>	<b>4.7</b>	<b>3.6</b>	<b>2.7</b>	<b>1.5</b>	<b>19.6</b>

**Table 1. Near shore wave conditions in terms of significant wave height, peak period, direction and probability of occurrence. An indication of the wave power in the individual wave condition is also given.**

The bathymetry of the area has been scanned and used for 3D tests on overtopping and wave loadings on the structure (scale model 1:60 to prototype).

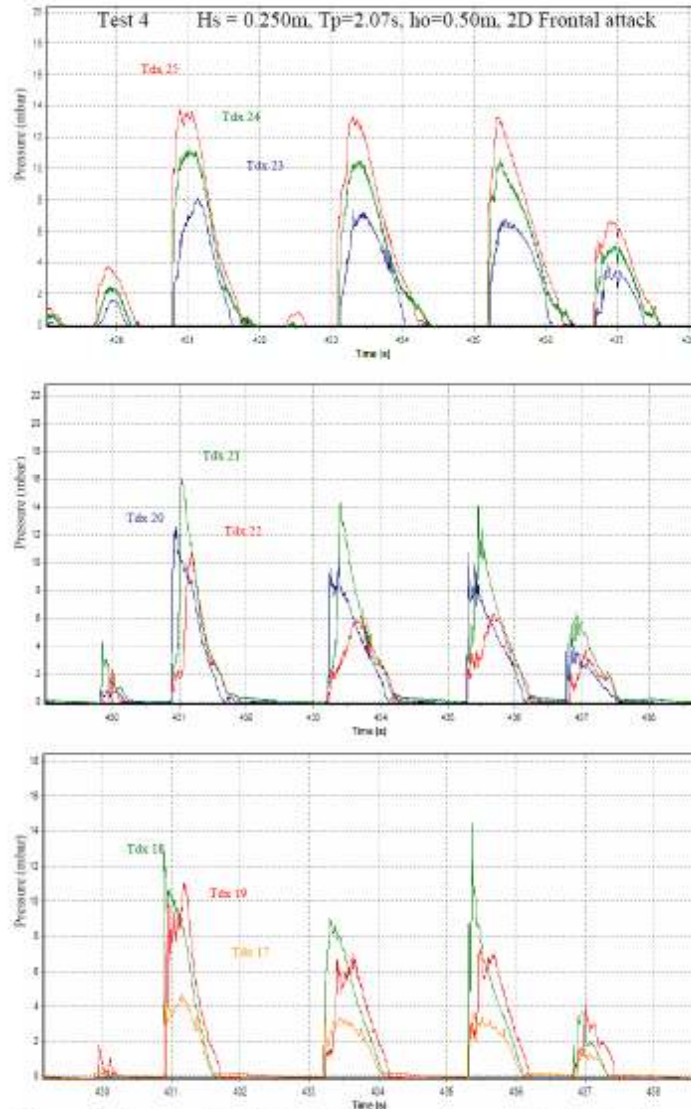
For overtopping, the first stage of testing has been carried out in 2D conditions. 17 different geometries have been tested with 3-6 irregular wave conditions each. Average overtopping discharges into individual reservoirs have been measured (Kofoed, 2005). The performance of the tests allowed the choice of the optimal geometry and orientation of the structure and an estimation of the Hydraulic efficiency (see paragraph on “Performance”). In Figure 4, the overtopping rates for the three reservoirs for one of the seven geometries tested (F7) are plotted.



**Figure 4. Model test results for the optimum geometry (full markers) and inter and extrapolated data (open markers). Effect of orientation of the structure is not considered.**

Later 3D overtopping tests have been carried out taking into account a 3D structure in 3D conditions: directionality, spreading and bathymetry. The Hydraulic efficiency in 2D conditions resulted to be around 50 %. This result must be lowered of a factor to take into account the effect of boundary effects for 3D waves (a part of the overtopping water is bunting on the side walls and not entering in any reservoir, referred to one single module of SSG wave energy converter in a 2D structure).

For head-on waves (from West-270°), the 100 year event at the plateau can be given by the two following parameters:  $H_s = 12.5$  m and  $T_p = 15.2$  s, based on the study by Nygaard & Kenneth (2002). The pressure has been measured in 25 different positions under extreme waves (32 wave conditions taking into account also direction and high water due to storm conditions), leading to rearrangement of the design concerning vertical walls, where impact loadings are unacceptable (Vicinanza et. al, 2006). In Figure 5 the pressure time history of the front plates for each reservoir has been presented from physical model tests results.



**Figure 5. Pressure time history of the transducers at the front plates.**

The results of physical model tests on overtopping has been used as input, a long parameters as wave states, reservoir sized, turbine characteristics and control strategy of the turbines, for the the development (in close cooperation with another project partner, Technical University, Munich) of a power simulation software tool (Meinert et al., 2006), which has been used for evaluation the optimal plant geometry, turbine and generator capacity and yearly power production. The outputs of the program are: flow in each reservoir, flow in each turbine, spilled volume of water when the reservoirs are full, produced energy, average power; efficiency of the overtopping, of the turbines and overall. In Figure 6 it is shown one of the windows of the program, from where it is possible to input the desired data (sea state, turbine strategy, geometry.)







$\eta_{crest} = \frac{P_{crest}}{P_{wave}}$ , indicates the efficiency of the overtopping (hydraulic efficiency); the power in the waves is given by the expression:

$$P_{wave} = \frac{\rho g^2}{64\pi} H_S^2 T_E$$

related to the squared significant wave height and period,

while the power on the crest is related to the crest freeboard  $R_{c,j}$  agreeing with the following expression:

$$P_{crest} = \sum_{j=1}^3 q_{ov,j} R_{C,j} \rho g$$

The term  $q_{ov,j}$  (= overtopping flow for each reservoir) is not directly measurable on the prototype and has been measured only in laboratory (Kofoed, 2002); to give an estimation of it, an expression that takes into account different flow rate contributions, as flow in reservoir, flow through turbine and spilling, is considered (L. Margheritini, J. Peter Kofoed, 2006).

$\eta_{res} = \frac{P_{res}}{P_{wave}}$ , indicates the efficiency of the conversion of the wave power into potential power obtained in the water in the reservoirs: the amount of potential power in the overtopping water minus the loss of energy due to not full reservoirs; the power in the reservoirs is given by:

$$P_{res,j} = \rho g H_j q_j$$

$\eta_{tur} = \frac{P_{tur}}{P_{wave}}$ , indicates the efficiency of the conversion of the wave power into mechanical power on the shaft of the turbines;

$\eta_{net} = \frac{P_{net}}{P_{wave}}$ , indicates the efficiency of the conversion of the wave power into electrical power delivered to the grid.

The overall hydraulic efficiency across all sea states weighed with probability is evaluated to be in the order of 50 %. In total the overall efficiency is expected to be approx. 22 %.

The power matrix on Table 2 gives the power (kW) in different sea states for a structure of 10 m width and crest free board level equal to 1.5 m, 3 m and 5 m (respectively:  $R_{c1}$ ,  $R_{c2}$ ,  $R_{c3}$ ). When

we multiply the power matrix given in table 2 with the probability of occurrence (number of hours with a given sea state) we reach the conclusion that the test structure will be able to produce 320 MWh/y.

TP Hs	5.0 s	6.1 s	7.9 s	9.3 s	10.6 s	11.7 s	12.7 s	Prob. %	Production MWh/y
5.9 m	150	150	150	150	149	148	147	2.7	35
4.7 m	150	150	150	148	146	144	143	3.5	44.8
3.6 m	144	140	134	130	127	124	122	8.4	94.5
2.4 m	67	65	62	60	59	57	56	16.4	89.1
1.7 m	21	21	21	20	20	20	20	26.5	48.7
1.0 m	3	3	3	3	3	3	3	30.3	8
0.5 m	0	0	0	0	0	0	0	12.3	0

**Table 2. Power matrix and expected production in regard to the single sea states.**

## Conclusions

All the preliminary studies for the realization of the SSG pilot project have been completed.

With regard with the expected production of the device:

- The wave data at the pilot location have been exhaustively collected offshore in front the selected area. These data have been then elaborated and close to shore conditions have been derived, obtaining relevant parameters like: significant wave heights, periods, probability of occurrence and direction. A study on tidal fluctuation has also been done.
- Extensive tests on hydraulic optimization of the structure have been concluded leading, among others, to a 3 reservoir device with crest free boards at 1.5 m, 3 m and 5 m and inclinations of the front plates of 35°. Extreme forces on the structure are also known.
- The strategy of the turbines has being decided and will regard 150 kW installed capacity. The design will allow the late installation of a 2 stage MST turbine.
- The work on hydraulic optimization and turbine strategy has been concentrated on the realization of the SSG simulation program that allowed the calculation of the power production of the SSG for different sea states that have not been tested in the laboratory.
- The power production of one module of the SSG wave energy converter (10 m width) is around 320 MWh/y.

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