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Performance Evaluation of the Wavestar Prototype

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Abstract— **Wave Star has produced and installed a test and demonstration Wave Energy Converter (WEC) by Roshage pier near Hanstholm at the west coast of Denmark. The test unit is a prototype test section of a complete commercial WEC. After an initial period of finalizing the installation and testing, the WEC was launched for production in January 2010 and in May 2010 automatic unmanned operation was initiated. The number of operational hours per month has increased significantly during the following months, but experience with the initial period of continuous automatic unmanned operation has shown difficulties in ensuring the ability to be in daily operation 24/7/365. During the period from January 2010 to April 2011 the control software has been updated three times, and significant increases in the measured power levels have been confirmed. The measurement points have verified the expected level of harvested power, although further development of the control system is expected to increase the level further.**

Keywords— **Wavestar, Wave Star, wave power, wave energy converter, wec, performance evaluation, performance assessment**

I. Introduction

In September 2009 Wave Star installed a large-scale test and demonstration Wave Energy Converter (WEC) by Roshage pier near Hanstholm at the Western coast of Denmark, see Fig. 1 and Fig. 2. The WEC is a prototype/test section of a complete commercial 600 kW WEC. As shown in Fig. 3 and Table 1 the prototype has 2 floats placed on one side whereas the full commercial converter will have 20 floats (10 floats on each side). The prototype was installed at a water depth of approximately 6 m while the commercial converter is expected to be installed at water depths of 10 to 20 m [1],[2].

The primary purposes of the test section are outlined below, and the results received so far concerning the last two bullets are given in the following chapters.

- Test the structure and components
- Prove the storm protection strategy
- Provide a test-platform for future new components
- Demonstrate the efficiency of the power take off
- Document the ability to be in daily operation 24/7/365
- Check that the measured power absorption is according to the expectations

Furthermore, the WEC is used as a demonstration plant for politicians, journalists, investors and other stakeholders. The WEC can be accessed at any time and in any weather condition due to its place by the Roshage pier and a 300 meter long access bridge.

Data concerning the performance of the platform together with the sea state is gathered continuously. It is valuable knowledge concerning the long term robustness of the platform which may indicate whether modifications on the future platforms should be considered.

A. *Wave Star Company*

Sailing enthusiasts Niels and Keld Hansen came up with the concept behind Wavestar in 2000. Per Resen Steenstrup purchased the rights to the machine in 2003 and the same year Wave Star Energy A/S was incorporated in Denmark (A/S is the Danish version of a Limited company, Ltd.). In February 2010 Wave Star Energy was reorganized and all intellectual property rights and assets related to the concept were consolidated in the company Wave Star A/S. The Clausen brothers, the family behind Danfoss, are now the sole shareholder, and Bent Kristensen is the Chief Executive Officer (CEO) of the company. The Hansen Brothers remain as consultants at Wave Star.

The further development and optimization of the concept is performed in cooperation with Aalborg University, with benefits for both the university and Wave Star.

B. *Wavestar Concept*

Today, the Wavestar concept is one of the world leading wave energy technologies. During the last ten years, the concept has developed through systematic public and private partnering. Wavestar now has the potential to become one of the first real commercial wave energy technologies.

The Wavestar device consists of two rows of round floats attached to a bridge structure, secured to the sea bed by the use of steel piles, which are cast into concrete foundations. All moving parts are therefore above normal seawater level. The device is installed with the structural bridge supporting the floats directed towards the dominant wave direction.

When the wave passes, the floats move up and down driven by the passing waves, thereby pumping hydraulic fluid into a common hydraulic manifold system which produces an even flow of high pressure oil into a hydraulic motor that directly drives an electric generator.

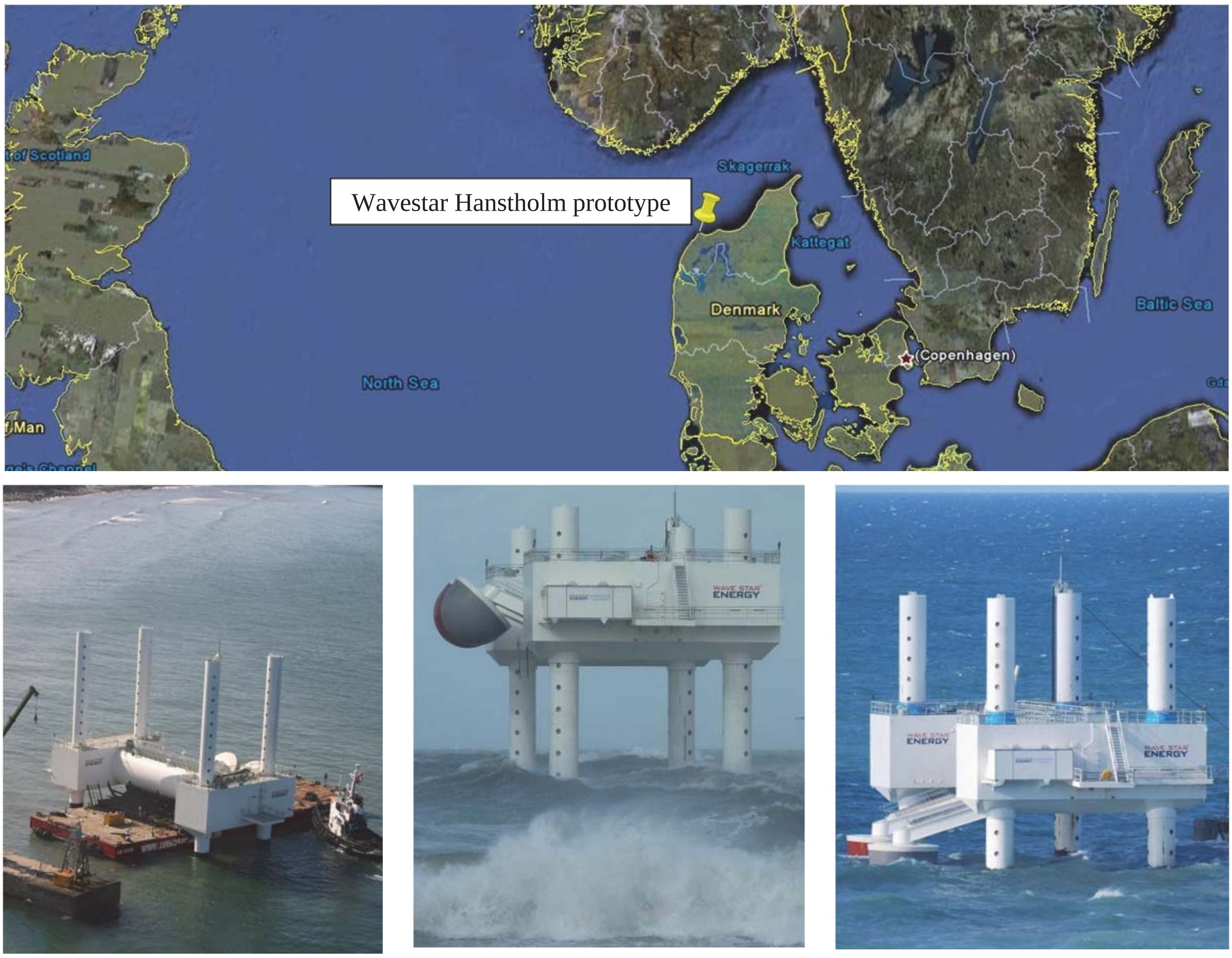

Fig. 1 Wavestar prototype. Top: Location of site (Google Earth). Bottom left: Photo of installation by barge. Bottom centre: Photo of storm protection. Bottom Right: Photo of normal operation

Fig. 2 View of Wavestar prototype from the beach. The distance to the prototype from the beach is 300 m

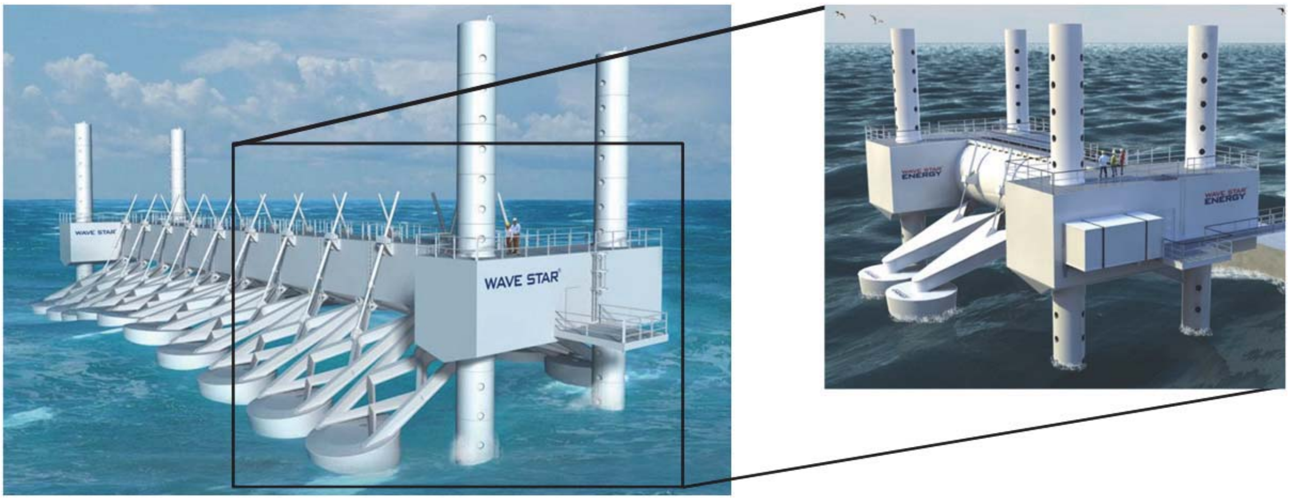

Fig. 3 Commercial converter with 20 floats (left) and test-section at Hanstholm with two floats (right)

TABLE I
TECHNICAL DATA FOR COMMERCIAL WAVE STAR C5-CONVERTER AND PROTOTYPE AT HANSTHOLM. MWL IS MEAN WATER LEVEL

Parameter	**Commercial Wave Star C5-600 kW**	**Prototype at Hanstholm**
Number of floats	20	2
Float diameter	Ø5 m	Ø5 m
Maximum water depth (extreme)	20 m	8 m
Maximum wave height (operation)	6 m	6 m
Water depth	10 to 20 m	5 to 8 m
Arm length	10 m	10 m
Main structure dimensions	70m x 17m x 6.5m (LxWxH)	32m x 17m x 6.5m
Length of legs	Site depended, ~ 15-25 m above MWL	~ 18 m above MWL
Operation height	5.5 m above MWL	5.5 m above MWL
Storm secure height	Site depended, ~ 6-15 m above MWL	~ 8 m above MWL
Weight	1600 Tons	1000 Tons
Materials	Main structure: Steel. Floats: Fibreglass	Main structure: Steel Floats: Fibreglass
Foundation	Four skirted spud cans, or two mono piles or gravity based foundations	Four gravity based foundations
Design service life	Minimum 20 years	Minimum 20 years
Maintenance interval	1 service period per year	-
Nominal electrical power	600 kW	110 kW

When the significant wave height exceeds a certain limit the machine automatically enters storm protection mode, see Fig. 4 and 5. Storm protection involves un-ballasting the floats and retracting the hydraulic cylinders which thereby pull the floats out of the water. Each single float will be pulled out one at the time and all floats are out within approximately 30 min. Jacking into safety position takes less than 1 hour.

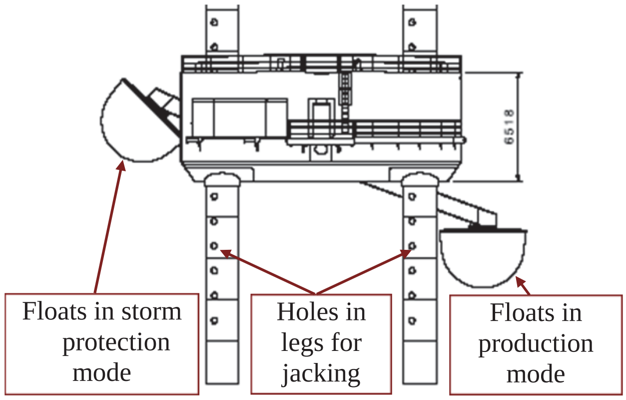

Fig. 4 Wave Star storm protection concept

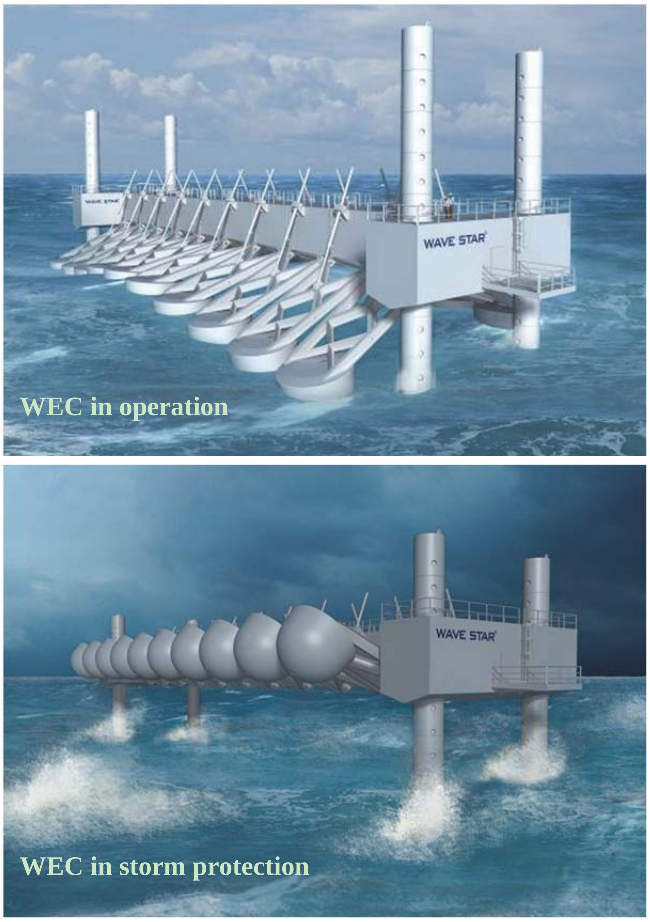

Fig. 5 Artist impression of a commercial Wave Star WEC

Further information about the Wavestar concept and test machines are given in [3]-[9].

C. *Wavestar Test Machines*

The Wavestar prototype at Hanstholm is the main result of several years of development in Denmark, see Fig. 6. Starting in 2004 a small 6 m long scale 1:40 converter with 40 floats was tested in an indoor wave basin at Aalborg University. In 2006 a 30 m long scale 1:10 converter with 40 floats was installed in the open sea at Nissum Bredning (a sheltered bay in the Western part of the Limfjord). The converter has been in daily operation in Nissum Bredning since, and has been connected to the public grid. The WEC has been able to produce energy persistently during 4 years. During the test period the WEC has demonstrated high reliability. Only very limited maintenance has been necessary. At present (Spring 2011) the scale 1:10 converter is about to be removed as focus is now on the large scale prototype at Hanstholm.

Based on positive results from the small-scale experiments Wave Star started designing the large-scale prototype in 2007 and in 2008-2009 it was built at a shipyard. It was installed in September 2009 by Hanstholm at the Western coast of Denmark. After an initial period of finalizing the installation and testing, the WEC was launched for production in January 2010 and from May 2010 power performance measurements have been approved by Energinet.dk (explained in Section III).

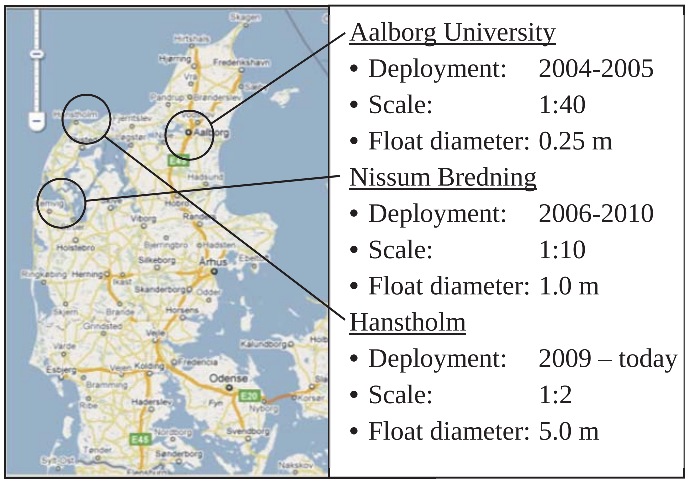

Fig. 6 Map of Denmark with locations of Wavestar WEC's

II. TIMELINE FOR EVENTS AND MAINTENANCE

A timeline and table showing the major events and repairs on the Hanstholm prototype is shown in Fig. 7 and Table 2. The timeline starts in August 2009 when the prototype was towed to Denmark and ends by April 2011, i.e. a period of almost two years. In Fig. 7 it should be noted that events are shown above the blue timeline, and damages/repairs are shown below the line.

A. *Events*

About the events it is noted that the prototype was installed in September 2009 and the converter was considered appropriately operational after software updates in September 2010, i.e. it took approximately one year to get the prototype to run according to the specifications, which was somewhat longer than expected initially.

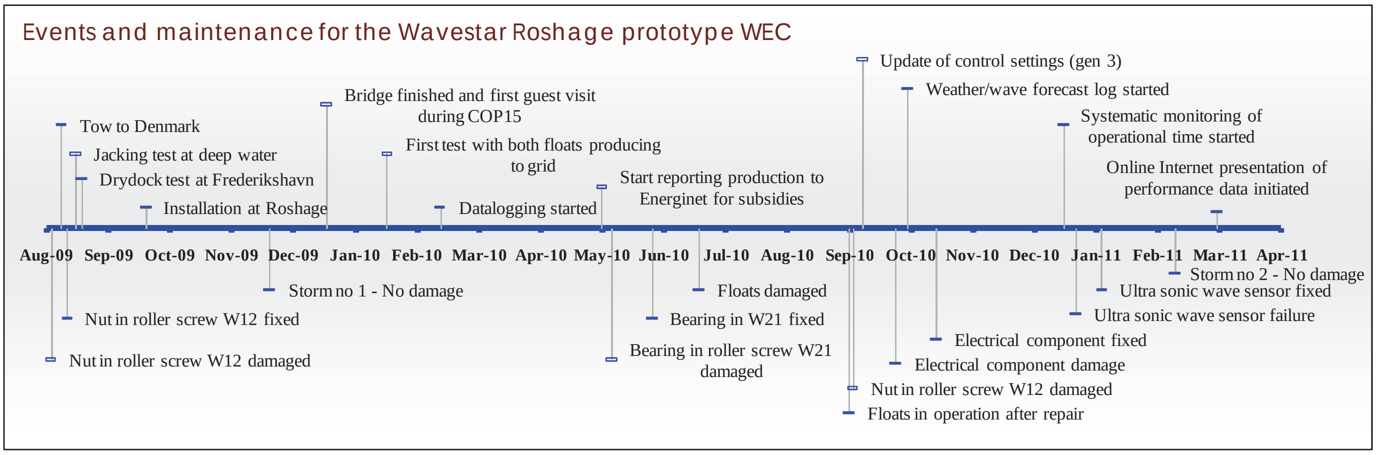

Fig. 7 Timeline for events (above blue timeline) and maintenance (below blue timeline) for the Wavestar prototype

TABLE II
DATES OF EVENTS AND REPAIRS ON THE WAVESTAR PROTOTYPE

Date	Event or maintenance
02/08/2009	Nut in roller screw W12 damaged
07/08/2009	Tow to Denmark
10/08/2009	Nut in roller screw W12 fixed
14/08/2009	Jacking test at deep water
17/08/2009	Drydock test at Frederikshavn
18/09/2009	Installation at Roshage
18/11/2009	Storm no 1 - No damage
16/12/2009	Bridge finished and first guest visit during COP15
15/01/2010	First test with both floats producing to grid
10/02/2010	Datalogging started
01/05/2010	Start reporting production to Energinet.dk for subsidies
06/05/2010	Bearing in roller screw W21 damaged
26/05/2010	Bearing in W21 fixed
18/06/2010	Floats damaged
31/08/2010	Floats in operation after repair
02/09/2010	Nut in roller screw W12 damaged
07/09/2010	Update of control settings (gen 3)
23/09/2010	Electrical component damage
29/09/2010	Weather/wave forecast log started
13/10/2010	Electrical component fixed
15/12/2010	Systematic monitoring of operational time started
21/12/2010	Ultra sonic wave sensor failure
03/01/2011	Ultra sonic wave sensor fixed
08/02/2011	Storm no 2 - No damage
01/03/2011	Online Internet presentation of performance data initiated

Another interesting event is the automatic weather and wave forecast system that was started in September 2010. Two times a day the company StormGeo is providing a digital weather forecast of temperature, wind speeds, and most importantly significant wave heights, wave periods and wave directions (StormGeo is a weather services provider in Scandinavia and the North Sea region with worldwide operations in the renewables and offshore industries). The weather forecast is automatically read and stored by the machine. The weather forecast reach several days into the future, and it will be used primarily for:

- Estimate the future production from the converter
- Storm protection strategy
- Planning periods for maintenance and suitable test-periods

The main active use of the forecast so far has been for planning maintenance and test-periods. In this respect the forecast has been used in addition and as supplement to public forecasts available from the Internet. Further, the data are being used in studies on wave power prediction, integration of wave power in the grid, and integration of wave power in renewable energy parks together with wind and solar. This work is ongoing in corporation with Aalborg University and Energinet.dk (Energinet.dk is a non-profit enterprise owned by the Danish Climate and Energy Ministry) [10].

In the period after September 2010 difficulties turned up in ensuring a stable and continuous operation, and the operational time in September to November 2010 was rather low (less than 10 %). To examine the reason for this in a systematic manner on a daily basis a system for online monitoring was integrated in the software. Hereby it was possible to follow the course of the downtime regularly and evaluate whether the course needed action or not. Results are explained further in Section IV.

B. *Maintenance*

In general there has been no major problem with the design of the prototype. All structural and mechanical components in the WEC have proven functionality as intended. The WEC has survived two large storms with no damages and no service afterwards. Only minor design faults with the float design and the jacking-system has been indentified and corrected.

The WEC is running in automatic unmanned operation and the control system automatically extracts the floats from the water lifting them to the upper latched position when needed. However, the jacking procedure to storm protection level is still operated manually, as some roller screws and bearings in the jacking system still needs adjustment.

In June 2010 the upper part of the outer float shell showed damages in the fibreglass. The problem was caused mainly by too weak support structures inside the floats. The problem was fixed by strengthening the inside of the floats with reinforcements, and the floats were back in operation by the end of August 2010.

III. Approved by Energinet.dk

A contract between Wave Star and Energinet.dk was established in July 2010 with the project title "Energy production on Roshage test systems (WSE-02)", project no. 2009-1-10305. The aim of the project is to document that the prototype is able to deliver the expected power according to the actual wave climate and the expectations for the full commercial converter. The project is part of the so-called ForskVE-programme [11], and it is completed with Aalborg University as partner. The documentation is performed in practice using monthly reporting of measurements and results. Since 1 May 2010 Wave Star A/S has been measuring the power produced by the Wavestar prototype and recorded all the data with intervals of 10 minutes. Every month a report and accompanying data file containing the raw measurements are submitted to Energinet.dk for approval.

The idea with the test section was not to make a commercial production unit. From the beginning it was clear that the amount of produced kWh would be low, and that the price per kWh would be high. In other words subsidies based on a specified price per kWh (i.e. a system such as typically used for energy from wind turbines) would not be appropriate for the Wavestar prototype. Instead a system was chosen such that if the measured production in a period was higher than a limit it would release an amount of money. In this way the subsidies are in fact not given due to an actual production in kWh, but instead on whether the power performance is satisfactory or not. The limit was simply given as a target power performance curve (green curve in Fig. 8).

In order to establish the target power performance curve historic measurements of the wave climate at the location and correspondingly simulated power performance was studied. The wave climate at the location was established using 7 years of measurements acquired using a wave rider located near Hanstholm Harbour. Wave data was provided by the Danish Coastal Authority (KDI). From the simulations an expected power curve for the test section at Hanstholm was established.

The original curve used to settle the subsidies is in fact given as production in kWh in a period of 10 minutes. As this corresponds to a given average power in kW, this representation is used here. If the measured production in a ten minute period is above the limit, subsidies are received from Energinet.dk. An example with 2 hours of production is shown in Table 3. In the shown period all the measurements were above the limit, and subsidies were received. This has not always been the case as explained in the following.

Each line in Table 3 represents one 10 minute period corresponding to one data-point in Fig. 8. The limit for the subsidies is given as the green curve and measurements are given as dots. It is seen that the measurements from May 2010

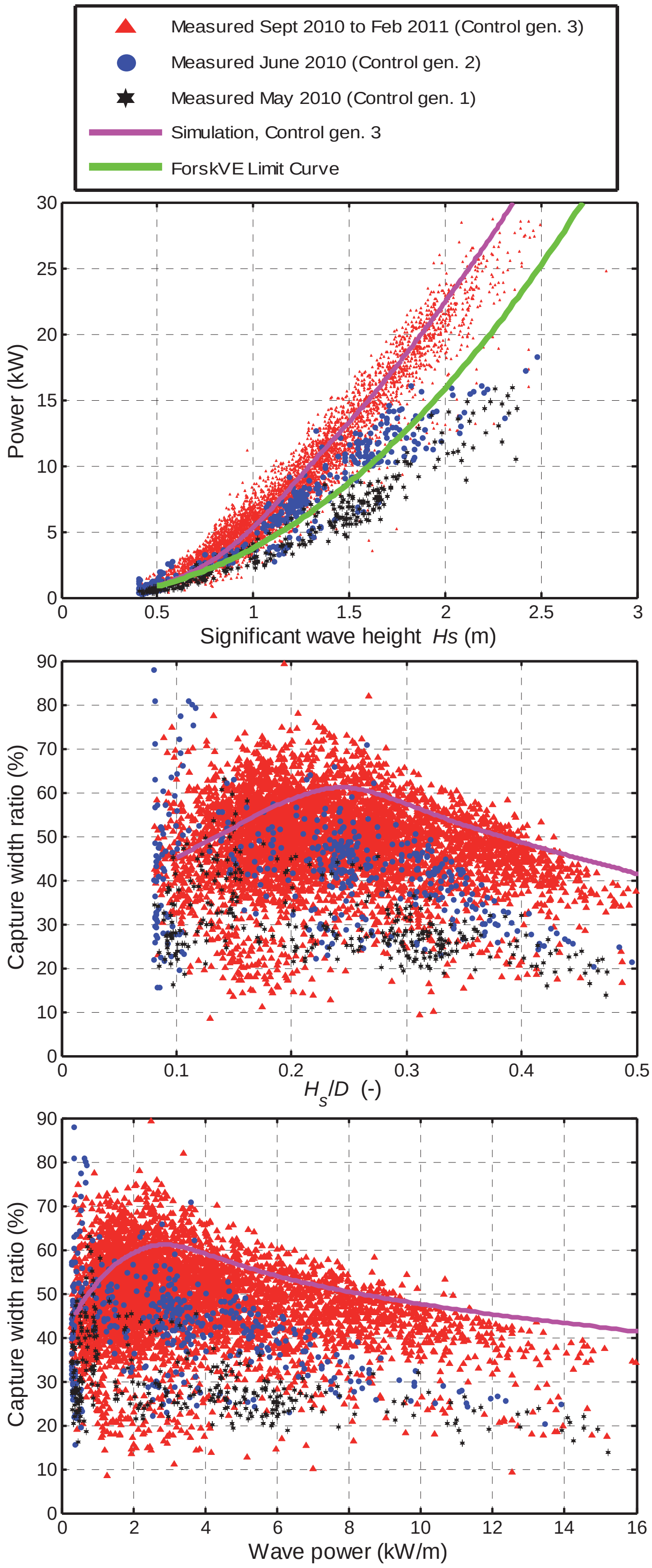

Fig. 8 Wavestar Hanstholm prototype power measurements. The same data are shown in the three plots. D = 5 m is the float diameter. Capture Width Ratio (CWR) is given by:

$$CWR\ [\%] = \frac{Power\ [\mathrm{kW}]/Wave\ power\ [\mathrm{kW/m}]}{Float\ diameter\ [\mathrm{m}]} \cdot 100$$

was below the ForskVE curve (i.e. no subsidies was received from May 2010), but due to optimization of the control software the majority of the measurements are now above the curve (i.e. subsidies are now received for most of the time when in operation). The following should be noted when looking at Fig. 8:

- Power is 10 minute average values of harvested power from one float (hydraulic power leaving the cylinder connected to the first float)
- Simultaneous measurements of the wave climate and the power production are performed at the location.
- All raw measurements are shown. No filtering has been performed and no invalid data have been discarded.
- A typical wave climate (typical wave direction, peak wave period, and spectral shape) for the Hanstholm location is used for the simulated curves

In order to limit the forces from the Power Take Off (PTO) a very "gentle" control parameter setting was initially applied using a linear damping control strategy (control generation 1 and 2). On the 7th of September 2010 the control software was updated with new parameter settings using reactive force control (control generation 3), which increased the power performance. The most recent measurements using control generation 3, i.e. the measurements marked with red dots in Fig. 8, confirms that the machine is now able to harvest power according to the expectations. In high waves (Hs ~2m) the power production using the new control generation has increased by more than 50 % compared to the former control generations. For information on modelling and control on the Wavestar reference is given to [12] ,[13]. New control strategies are under investigation as calculations shows a potential for further increases in production.

On the middle graph in Fig. 8 it is seen that the capture width ratio is about 40 to 60 %, with the peak efficiency achieved at $Hs/D \cong 0.25$. As the float diameter D = 5 m the maximum efficiency is corresponding to a wave climate with Hs = 1.25 m which is equivalent to a wave climate with wave power ≅ 3 kW/m. The figure shows remarkably scatter in the data. A more detailed post analysis has been performed on the data, but this analysis was not completely finished by the deadline. However, this investigation shows that the scatter is caused mainly because no filtering has been performed on the wave data and no invalid data have been discarded. Another reason is the influence of other parameters such as wave period, spectral shape and wave direction.

IV. Operational Time

The prototype can be set in different modes; stop, manual mode, or automatic mode. Production measurements and operational time is only considered valid when in automatic mode producing to grid. The prototype is rather often in manual mode, for example when special testing is performed. The time with production in automatic mode is shown in Fig. 9. The operational time in June 2010 was relatively high but the measured power level was relatively low. The following two months the float repairs caused the prototype to be out of operation. After the software update in September 2010 the power performance was satisfactory (i.e. the majority of the measurements were above the ForskVE curve as shown in Fig. 8), and the following months small steps have been taken to increase the operational time.

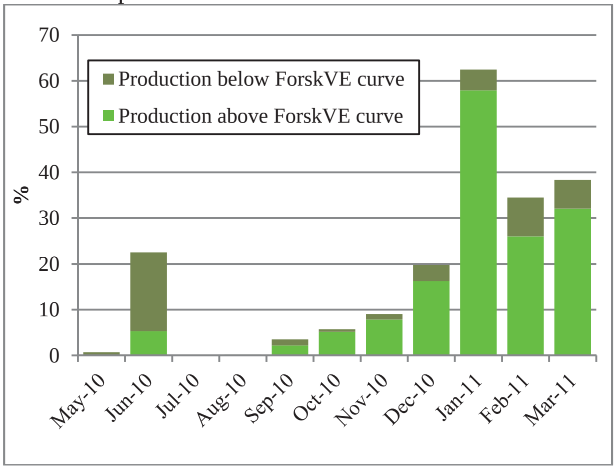

Fig. 9 Time in % of month with production

The period from September 2010 up to present is shown in greater detail in Fig. 10. Here it is seen that some part of the remaining time the prototype has been stoped due to:

- Down time and transition states: Machine has been manually stoped or special testing is being performed
- Storm protection: Entered when the significant wave height rises above a certain limit. The limit has been adjusted up and down, but was typically set to 2.5 m or even lower in the shown period in order to minimize the risk of damage.
- Calm sea: The machine is stoped when the significant wave height is below a certain limit, which typically has been set to 0.5 m.

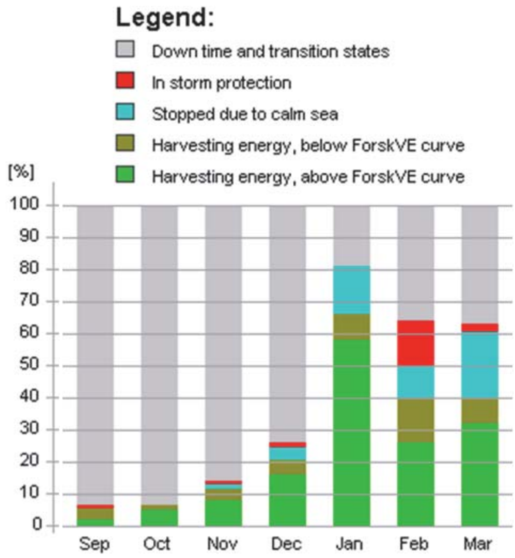

Fig. 10 Details on operational time from September 2010 to March 2011. Screen dump from HMI (Human–Machine Interface) on prototype

V. CONCLUSIONS

The Wavestar prototype at Hanstholm was installed in September 2009. Starting from May 2010 measurements of wave climate and production are verified and approved by Energinet.dk. Since September 2011 the measurements of the power production are in agreement with the expectations. New and improved control strategy is under investigation, as these have proved mathematically to increase the power production even further.

In general there have been no major problems with the design of the prototype. All structural and mechanical components in the WEC have proven functionality as intended. The WEC has survived two large storms with no damages and no service afterwards. Only minor design faults with the float design, the jacking-system, and some electrical problems have been indentified and corrected.

Small steps have been taken to increase the operational time, but so far the operational time during a whole month has just reached about 40 % to 60 %. Further steps are needed in order to prove the reliability and document the ability to be in daily operation 24/7/365. A longer period (of several months) with continuous operation without stops is still to be documented.

The Wavestar prototype at Hanstholm is an ideal test WEC for the further development of the Wavestar concept. So far the prototype has proved valuable in design validation, and based on the experiences with the prototype several modifications to the original design are now being incorporated in the design of future commercial WEC's. Building, installing and operating the prototype has provided a unique chance to correct design errors, which for the prototype was of minor consequence, but which for a full converter could have been a show-stopper for the concept.

The first test results have shown challenges in ensuring a high efficiency of the complete power transmission to the electrical grid. A focus point for the future work with Wavestar is optimization and efficiency improvements of the hydraulic and electrical systems [14]. New components are planned to be tested on the test-unit before inclusion in the commercial WEC.

ACKNOWLEDGMENT

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TABLE III

EXAMPLE OF MEASUREMENTS FROM THE WAVESTAR HANSTHOLM PROTOTYPE. *HS* AND *TMEAN* IS MEASURED SIGNIFICANT WAVE HEIGHT AND AVERAGE WAVE PERIOD, RESPECTIVELY. *P_TWOFLOATS* IS THE SUM OF MEASURED ABSORBED POWER FROM BOTH FLOATS, AND *FORSKVE_LIMIT* IS THE LIMIT FOR SUBSIDIES FROM ENERGINET.DK.

PLC_Datetime	**AllDataValid**	**Hs**	**Tmean**	**P_TwoFloats**	**ForskVE_limit**	**AboveLimit**
	[%]	[m]	[s]	[kW]	[kW]	[True/False]
21/09/10 09:20	100	2.08	4.72	48.98	34.24	True
21/09/10 09:30	100	1.91	4.31	37.50	28.71	True
21/09/10 09:40	100	1.94	4.10	38.02	29.80	True
21/09/10 09:50	100	2.01	3.95	33.69	32.07	True
21/09/10 10:00	100	2.03	4.47	39.91	32.85	True
21/09/10 10:10	100	2.17	4.23	42.91	37.42	True
21/09/10 10:20	100	2.01	4.39	38.94	32.04	True
21/09/10 10:30	100	2.01	4.14	39.84	32.02	True
21/09/10 10:40	100	2.10	4.27	40.97	35.12	True
21/09/10 10:50	100	2.03	4.01	41.76	32.55	True
21/09/10 11:00	100	1.83	4.13	32.29	26.21	True
21/09/10 11:10	100	1.97	4.28	37.60	30.71	True