WAVESTAR

Wavestar prototype at Roshage

Performance data for ForskVE project no 2009-1-10305 phase 1 & 2, January 2013

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1 Summary

A contract between Wave Star A/S 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 was to document that the Wavestar wave energy converter at Roshage was able to deliver the expected power according to the actual wave climate. The project is part of the so-called *ForskVE*-programme [1], and it is completed with Aalborg University as partner. Since 1 May 2010 Wave Star A/S has been measuring the waves at the location and the power produced by the Wavestar prototype. Every month a report and accompanying data file containing the raw measurements are submitted to EnergiNet.dk for approval [2].

Waves and power production are measured directly on-board the Wavestar prototype. An ultrasonic wave sensor is providing wave recordings at the exact location of the device. Figure 1 in the next page is showing the different power conversion stages. Two definitions are important in the report.

Hydraulic power, P_h [W]: The hydraulic power is measured at the hydraulic actuator, calculated by multiplying of the pressure across the cylinder and the flow in the cylinder. The hydraulic power of the prototype is the sum of the hydraulic power of both floats, $P_h = P_{h1} + P_{h2}$. The hydraulic energy, referred to as E_h, is the integration of the instantaneous hydraulic power over time.

Electrical power, P_e [W]: The electrical and consequently generated power is measured at the output of the generator, calculated by multiplying the voltage and the current. The electrical power of the prototype is the sum of the electric power of both floats, $P_e = P_{e1} + P_{e2}$. The electrical energy, referred to as E_e, is the integration of the instantaneous electrical power over time.

The project was split in two phases:

- **Phase 1**, May 2010 to September 2011: Focus was to demonstrate that the hydraulic power was higher than a specified target power performance curve. Phase 1 was finished in September 2011 where 14754 valid ten minute records with power production higher than the specifications, were recorded, documented and approved by EnergiNet.dk.
- **Phase 2**, October 2012 to December 2012 (three months): Emphasis was on the electrical energy. In phase 2 the capability of the machine to deliver at least 14.0[electrical MWh] in a three month period was documented. Phase 2 was completed after phase 1 was completed when the machine was ready for automatic continuous unmanned operation.

This document is the final report which presents the power measurements from both phase 1 and phase 2. Table 1 and 2 summarizes the measured results. The total electrical energy produced by the two generators was 52.9[MWh] in the period from May 2010 to December 2012. However, the largest amount of energy per month was produced during the three months in phase 2 where 15.6[MWh] was delivered by the generators. In phase 1 the absorbed hydraulic energy was high but the produced electricity and the operational time was low. However, in phase 2 the operational time and the PTO efficiency was high resulting in a high electrical energy production. Details on measurements of the power production during phase 1 are given in Section 3, and phase 2 results are given in Section 4.

Period	Hydraulic energy [MWh]	Electrical energy [MWh]	PTO efficiency [%]
May-10 to Sep-11 (phase 1)	51.6	6.9	13.3
Oct-11 to Sep-12	52.8	30.4	57.6
Oct-12 to Dec-12 (phase 2)	26.0	15.6	60.1
May-10 to Dec-12	130.4	52.9	-

Table 1: Summary of the measured energy production in the whole period covering phase 1 and phase 2.

Period	Operational time (%)	Production (%)
May-10 to Sep-11 (phase 1)	47.8	63.6
Oct-11 to Sep-12	66.7	64.3
Oct-12 to Dec-12 (phase 2)	99.4	82.3
May-10 to Dec-12	59.7	65.8

Table 2: Summary of the measured energy production in the whole period covering phase 1 and phase 2.

The target in phase 2 was to produce at least 14.0[electrical MWh] in the three month period. During the three month period from October 2012 to December 2012 the Wavestar demonstrator produced 15.6[MWh], which more than fulfills the expectations for the power performance. The target production was calculated using historic wave data measured by a wave rider in deep water offshore Hanstholm. However, as described in Appendix A, the actual measured waves in the shallow water at the Wavestar location are considerably smaller. Nevertheless, the goal was exceeded significantly. The reason was that the operational and production time was exceeding the expectations. The average operational time during phase 2 was 99.4[%] and the converter produced electricity to the grid in 82.3[%] of this time, see Table 2.

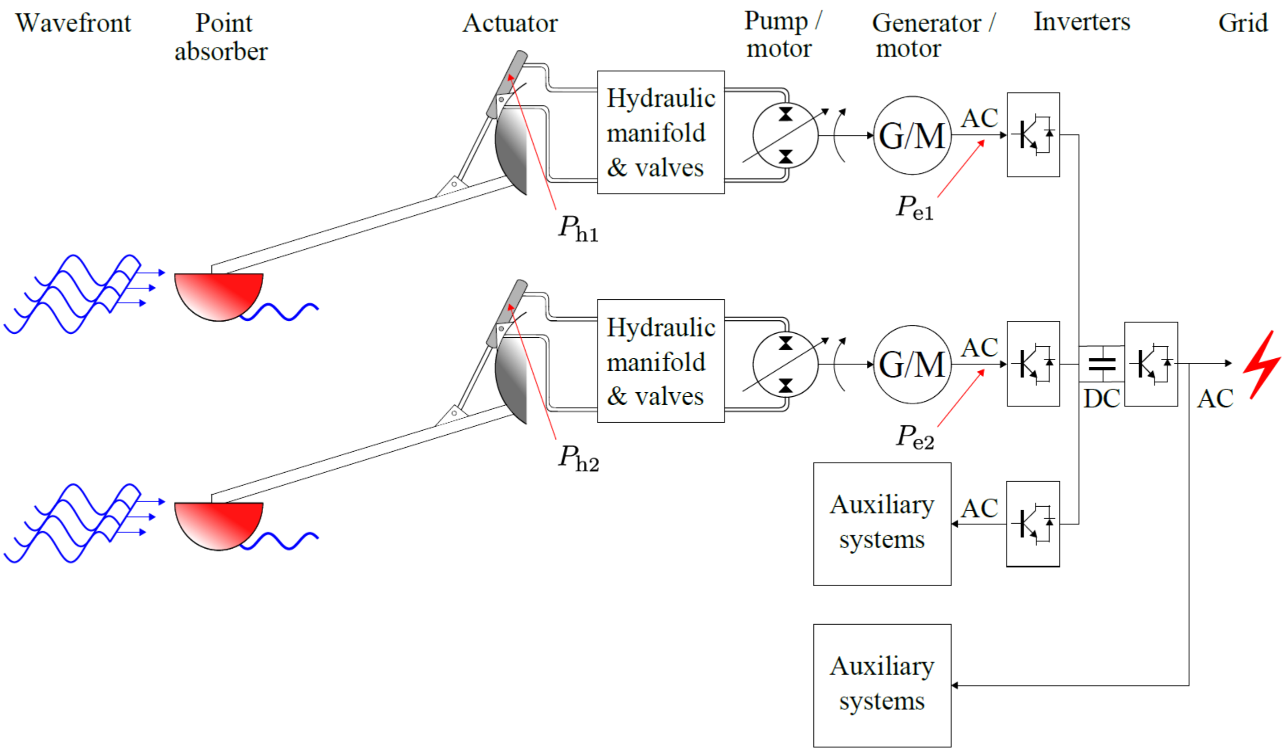

Figure 1: Overview of energy conversion stages of Wavestar's prototype in Hanstholm. The hydraulic power P_h[W] is measured at the hydraulic actuator (pressure across the cylinder multiplied by the flow in the cylinder). The electrical power P_e[W] is measured at the output of the generator (voltage multiplied by current).

A numerical model has been developed to make power and energy estimations of the Wavestar converter depending on physical configuration (e.g. number of floats) and wave climate at a specific location. The model results are described in detail in Appendix B and the wave climate at the site used for the calculations is described in Appendix A. The results show an expected production by the Roshage machine of 46[MWh/year] which corresponds to 46/4 = 11.5[MWh] in a three month period (taking three months as an average quarter of a year). Estimations for the Roshage WEC using the numerical model are provided in the right column of Table 3. It is seen that the measured electrical energy of 15.6[MWh] was somewhat higher than the model estimate. The maximum measured power was 32.4[kW] which was recorded when the significant wave height was 2.6[m]. The model estimate provided a maximum power of 38[kW], which is higher than the measured maximum. The measured power performance in high waves shows a large spread with a general trend lower than the model estimation. In Appendix A it is explained that due to the low water depth at the location the waves are steep and breaking when the significant wave height is higher than approximately 2.0[m]. Such waves are not ideal for the power performance and the deviation between the model estimate and the achieved measured power can be explained by the influence of steep and breaking waves.

Parameter	**Measured at Roshage WEC**	**Estimated by WEC model**
Total electrical energy produced: E_e[MWh]	15.6	11.5
Max. generated electrical power: max. P_e[kW]	32.4	38

Table 3: Comparison of measured and estimated electrical energy and maximum power in phase 2.

2 History of events and performance

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 Figure 3 and Figure 4 on the following page. The WEC is a prototype/test section of a complete commercial 600 kW WEC. As shown in Figure 5 and Table 4 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 5[m] while the commercial converter is expected to be installed at water depths of 10 to 20[m]. Several publications about the prototype and the achieved results have been submitted to scientific conferences and journals, see e.g.[4,6-8]. 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. The primary purposes of the test section are outlined below, and the main results received so far concerning the last 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 meters long access bridge.

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. The control software has been updated several times with improvement in robustness and power performance efficiency. The combination of the extension in the operational time and improvement of power level has increased the kWh's produced each month. An outline of the events is shown in Figure 2.

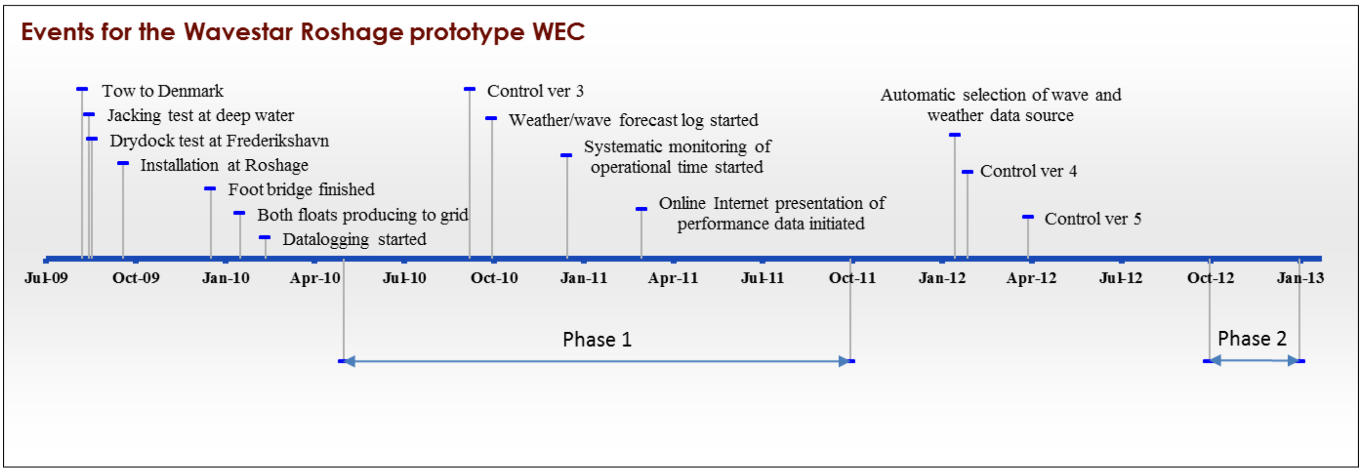

Figure 2: Timeline for events showing the two phases with reporting of performance to Energinet.dk.

Figure 3: 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.

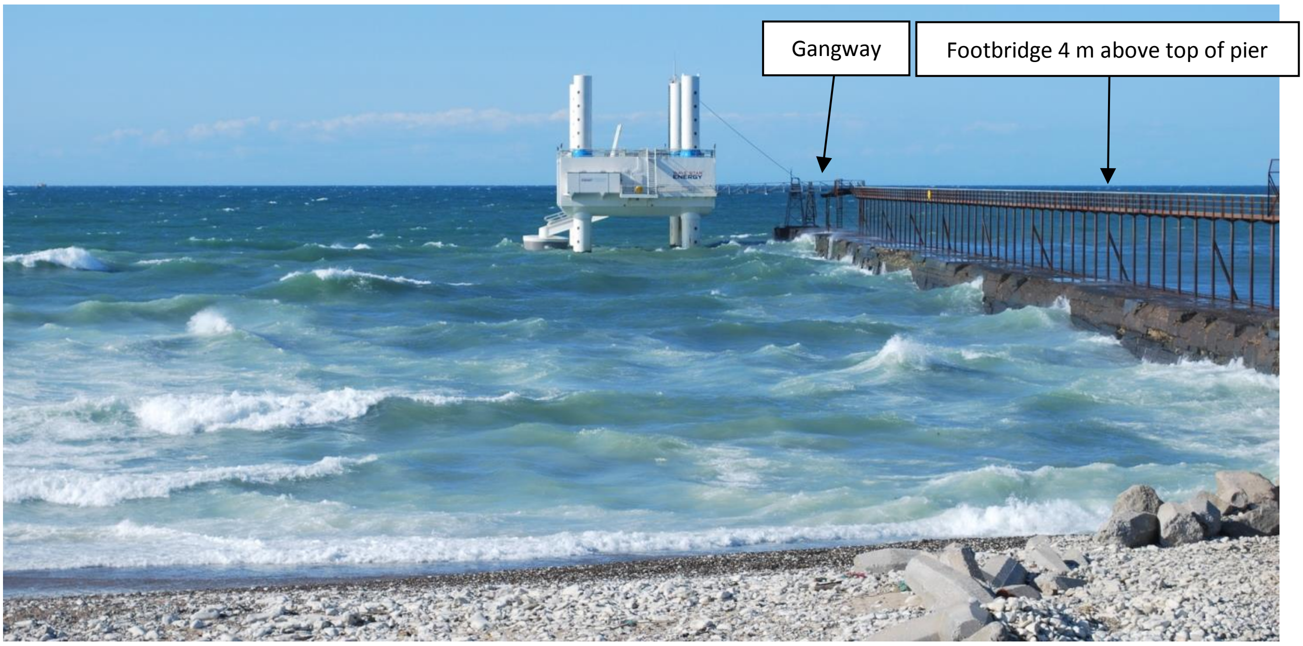

Figure 4: View of Wavestar prototype from the beach. The distance to the prototype from the beach is 300[m].

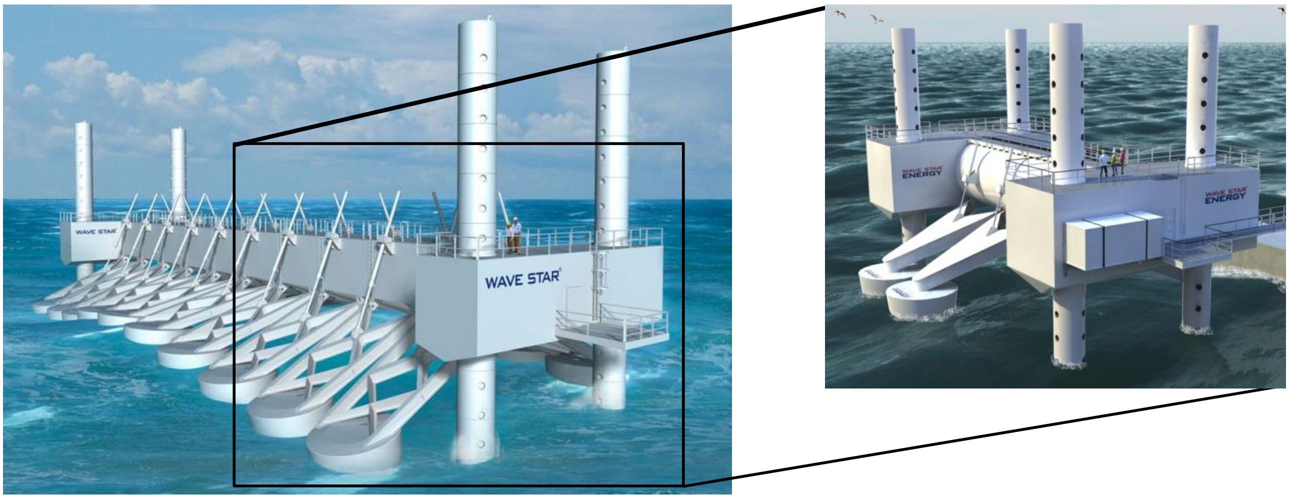

Figure 5: Commercial converter with 20 floats (left) and test-section at Hanstholm with two floats (right).

Parameter	**Commercial Wavestar C6-600 kW**	**Prototype at Hanstholm**
Number of floats	20	2
Float diameter	Ø6 m	Ø5 m
Maximum water depth (extreme)	20 m	8 m
Maximum wave height (operation)	8 m	6 m
Water depth	10 to 20 m	5 to 8 m
Arm length	12 m	10 m
Main structure dimensions	80m 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	6.5 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*)

Table 4: Technical Data for Wavestar C6-Converter and Prototype at Hanstholm. MWL is Mean Water Level. *) Deliberately over-rated to allow different tests.

When the significant wave height exceeds a certain limit the machine automatically enters storm protection mode. Storm protection involves un-ballasting the floats and retracting the hydraulic cylinders which thereby pull the floats out of the water. 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 five large storms with no damages and no service afterwards (Storms officially registered by the Danish Meteorological Institute on 18/11 2009, 7-8/2 2011, 27-28/11 2011, 8-9/12 2011, 3-4/1 2012 [9]). Only minor design faults with the float design and the jacking-system has been identified 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.

The operational time of the machine has increased over time, and the average operational time during phase 2 was 96[%], see upper graph in Figure 6. Further as seen on the lower graph in Figure 6 the generated electrical energy in Phase 2 was significantly higher than in Phase 1. The raw measurements are given in Table 4 and the relevant values are explained in more details in Section 3 and 4.

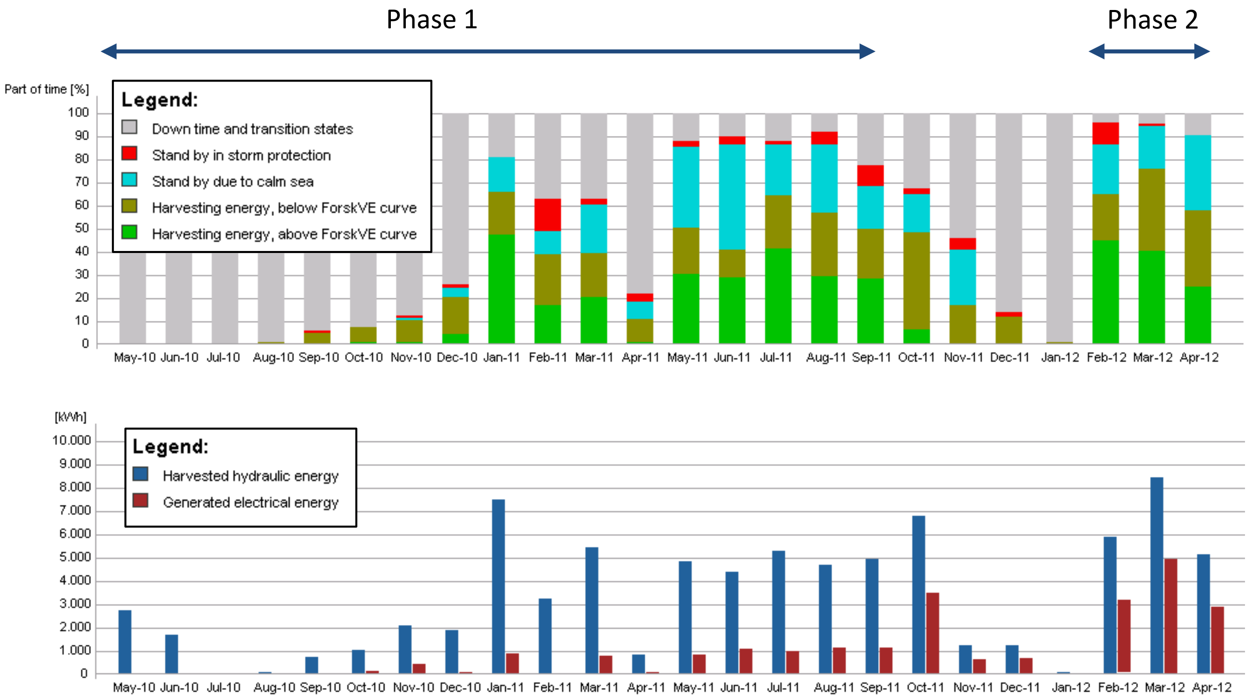

Figure 6: Operational time (upper figure) and produced energy (lower figure) in the period.

Float 1 & 2										
Month	Operational time (of total time) [%]	Production [%]	Storm (of operational time) [%]	Calm sea [%]	Transitions [%]	Harvested hydraulic energy [kWh]	Generated electrical energy [kWh]	PTO efficiency [%]	Max generated electrical power [kW]	
May-10	32	---	---	---	---	2,769	-175	-6.3	-	Phase 1
Jun-10	39	---	---	---	---	1,699	-446	-26.3	-	
Jul-10	0	---	---	---	---	0	0	-	-	
Aug-10	1	55	3	0	0	84	21	25.0	-	
Sep-10	10	54	10	0	36	739	-69	-9.4	23.6	
Oct-10	8	88	1	0	10	1,064	149	14.0	22.9	
Nov-11	14	74	6	7	13	2,101	460	21.9	24.7	
Dec-10	28	73	5	15	7	1,880	43	2.3	23.4	
Jan-11	82	81	0	18	1	7,521	918	12.2	23.1	
Feb-11	66	60	22	15	4	3,265	-104	-3.2	25.0	
Mar-11	64	62	4	32	2	5,469	790	14.4	23.4	
Apr-11	23	48	14	32	6	830	105	12.7	25.9	
May-11	91	56	2	39	3	4,859	827	17.0	25.8	
Jun-11	92	45	3	50	2	4,420	1,111	25.1	23.2	
Jul-11	90	72	1	25	3	5,278	992	18.8	21.5	
Aug-11	93	61	6	31	1	4,721	1,128	23.9	28.1	
Sep-11	79	63	11	24	2	4,941	1,127	22.8	25.3	
Oct-11	69	71	4	24	2	6,790	3,524	51.9	29.0	
Nov-11	46	36	12	50	2	1,256	666	53.0	15.9	
Dec-11	17	73	13	0	14	1,272	715	56.2	16.3	
Jan-12	1	77	0	0	23	62	24	39.4	4.5	
Feb-12	98	66	9	22	2	5,915	3,210	54.3	32.8	Phase 2
Mar-12	96	79	1	19	1	8,465	4,920	58.1	35.7	
Apr-12	93	62	0	35	2	5,131	2,901	56.5	30.0	

Table 5: Raw data of the operational time and produced energy in the period covering phase 1 & 2.

3 Production data in phase 1

Phase 1 covers the period from May 2010 to September 2011. Focus was to prove that the absorbed hydraulic power was higher than a specified target power performance curve [3]. Phase 1 was finished in September 2011 when 14754 ten minute records with power production higher than the specifications was recorded, documented and approved by EnergiNet.dk. Detailed documentation related to phase 1 is given in 17 reports, one report for each month in the period from May 2010 to September 2011 [2]. The results are summarized in the table and figure below.

	No of 10 minute periods	No of hours	[%]
Valid data in phase 1	19365	3227.5	
Production above limit	14754	2459.0	76.2
Production below limit	4611	768.5	23.8

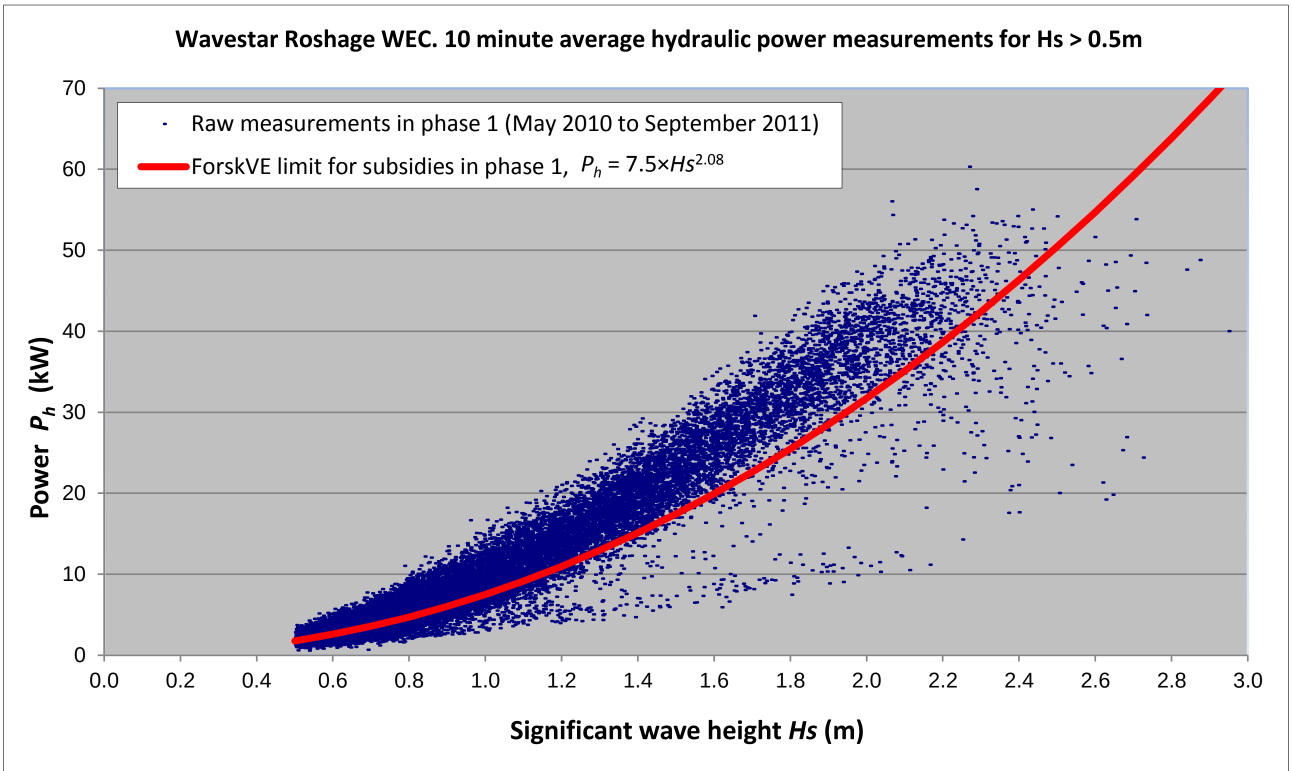

Figure 7: Power measurements in phase 1. All raw data in the period from May 2010 to September 2011 are shown. A total of 19365 data points are shown. The power is the sum of the power leaving the two hydraulic cylinders (pressure multiplied by flow).

All raw measurements are shown in the figure above, where the wave measurements are based on recordings from an ultrasonic wave sensor at the location. As described in Appendix A the wave measurements are only reliable up to about $Hs \approx 2.0$[m] as significant wave breaking and sea spray is affecting the measurements at higher sea states. Therefore only measurements for $Hs < 2.0$[m] should be used to evaluate the performance of the device.

4 Production data in phase 2

Phase 2 started in February 2012 and ended in April 2012. While the focus in phase 1 was on the hydraulic power and energy [7], the focus in phase 2 was on the electrical (generated) power and energy [4]. For that purpose the control algorithm was updated before phase 2 to maximize the electrical and not the hydraulic power (the strategy termed "Control ver 4" in Figure 2). Figure 8 presents all the recorded electrical power measurements of Wavestar's prototype during phase 1 (blue dots) and phase 2 (red dots). It is expected that the electrical power during phase 1 would have lower values than in phase 2 because the control strategy was not optimized for maximum electrical power (and energy) in phase 1. A significant portion of the raw measurements from phase 1 are negative. That is, electrical energy is being drawn from the grid. The results of numerical model simulations of the electrical power at the different wave heights are displayed by the black line (using a typical wave period and direction). It can be seen that up to $H_s \approx 2$[m] there is a reasonable degree of accuracy between the model and the measurements of phase 2. In Appendix A it is shown that due to the low water depth at the location the waves are steep and breaking when the significant wave height is higher than approximately 2.0[m]. Such waves are not ideal for the power performance and the deviation between the model estimate and the achieved measured maximum power may be explained by the influence of steep and breaking waves. Taking this into consideration, the model estimations are in good agreement with the measurements. Hence the model may be used to make approximate estimations of the annual generated energy production.

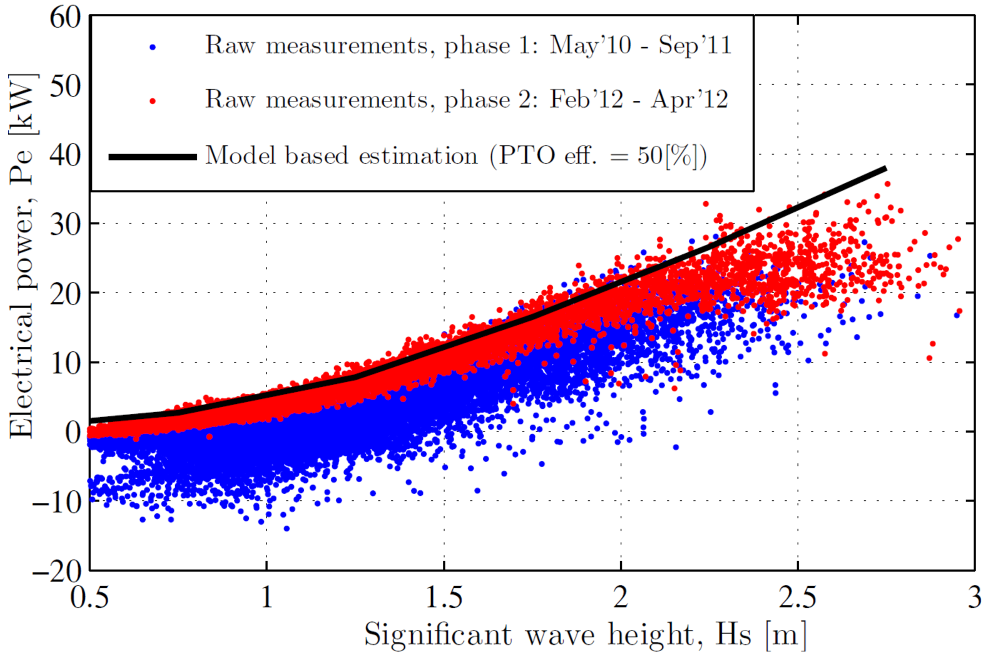

Figure 8: Raw data of electrical power measurements in phase 1 and phase 2. Approx. 18000 data points shown in phase 1 and approx. 8000 data points shown in phase 2. The black line shows the simulation result of the electrical generated power of the WEC with a PTO efficiency of 50[%]. The maximum electrical power measured is approx. 35[kW] at a significant wave height between 2.6[m] and 2.8[m].

The electrical energy production per month is summarized in Table 6. During phase 1 a total amount of electrical energy of approx. 7[MWh] was generated while in phase 2, which is a shorter period, the electrical energy was approx. 11[MWh]. In phase 2 the average effective production time was 66.3[%] and the average significant wave height during the time with production was 1.23[m].

Month	Effective production time[%]	avg *Hs* [m]	E_h [kWh]	E_e [kWh]	Max. P_e[kW]
May'10 (*)	32	-	2769	-175	-
Jun'10 (*)	39	-	1699	-446	-
Jul'10 (*)	0	-	0	0	-
Aug'10 (*)	< 1	-	84	21	-
Sep'10	5	1.19	739	-69	23.6
Oct'10	7	1.35	1064	149	22.9
Nov'10	10	1.50	2101	460	24.7
Dec'10	20	1.12	1880	43	23.4
Jan'11	66	1.15	7521	918	23.1
Feb'11	40	1.13	3265	-104	25.0
Mar'11	40	1.27	5469	790	23.4
Apr'11	11	1.20	830	105	25.9
May'11	51	1.13	4859	827	25.8
Jun'11	41	1.16	4420	1111	23.2
Jul'11	65	1.04	5278	992	21.5
Aug'11	57	1.02	4721	1128	28.1
Sep'11	50	1.16	4941	1127	25.3
Total phase 1				6877	
Feb'12	65	1.21	5915	3210	32.8
Mar'12	76	1.30	8465	4920	35.7
Apr'12	58	1.18	5131	2901	30.0
Total phase 2				11031	

Table 6: Raw measurements of hydraulic and electrical energy per month. The average significant wave height *Hs* during the time with production is shown in the third column. The right column of the table shows the maximum electrical power in average over a 10 minute period. Before February 2012 the control strategy was not optimized for maximum generated energy. Note that *effective production time* is the result of multiplying the operational time with the production time. Taking June 11 as an example, since the operational time is 92[%] and the production time is 45[%], then the effective production time is 0.92x0.45x100 = 41[%]. That is, 41[%] of the time of a month the machine was in production mode.

In Appendix B the Case 1A model simulations for the Roshage WEC uses the actual PTO efficiency and the measured wave climate at the site. The simulations show an expected production by the Roshage WEC of 46[MWh/year] which corresponds to 46/4 = 11.5[MWh] in a three month period (taking three months as an average quarter of a year). It is seen that the estimated electrical energy by the model was only slightly higher than the actual measured energy during phase 2 of 11.0[MWh]. Taking the wave climate at the site into consideration the model estimations are in good agreement with the measurements.

Since the production time varies from month to month it is not possible to directly determine the performance of the control optimization on the electrical energy. In order to better compare the energy values, the entries in Table 6 are weighted as if the WEC had run an equal *effective production time* during each month. The average effective production time shown in the last three months is 66[%]. Taking June 2011 as an example, if the WEC was in production during 66[%] of the time, the *weighted* hydraulic and electrical energy would be E_h[kWh] = $\frac{66}{41} \cdot 4420 = 7115$ and E_e[kWh] = $\frac{66}{41} \cdot 1111 = 1788$. Figure 9 shows the result of weighting all the energy entries in Table 6 with a production time of 66[%].

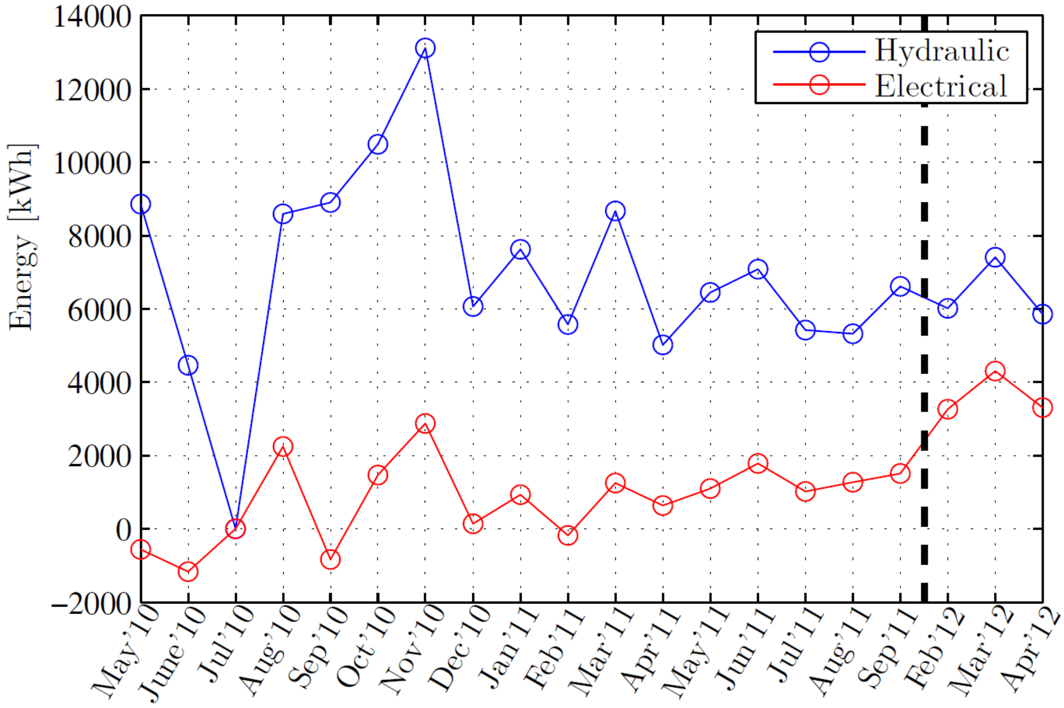

Figure 9: Weighted measurements of the monthly harvested and generated energy of the prototype (weighted with a production time of 66[%]).

It can be observed from Figure 9 that although the hydraulic energy after the control optimization is not higher than in the previous months, the electrical energy is approximately a factor of two higher, implying that without increasing the structural load, more energy is generated and a higher PTO efficiency is achieved as a consequence. In the months before the optimization, the highest PTO efficiency is recorded in June 2011 with an efficiency of 25[%] and after the optimization the highest PTO efficiency is recorded in March 2012 with an efficiency of 58[%]. PTO efficiency is here defined as the ratio between the electrical energy and the hydraulic energy (PTO efficiency = E_e/E_h x 100).

5 Future plans and activities

The Wavestar prototype at Hanstholm is an ideal test WEC for further development of Wavestar's 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. Important achievements have been made since the installation of the prototype, see the timeline for events in Figure 2, Section 2. Being the latest achievement the improved production time together with a substantial increase of electrical energy produced in phase 2 compared to phase 1. In order to ensure continuity in Wavestar towards a commercial WEC, a number of activities listed below have been discussed which could be carried out in the future.

- **Autonomous operation of WEC**
  Since the commercial WEC must be able to operate with a minimal human intervention, it would be relevant to further increase the degree of autonomy of Wavestar's prototype.
- **Upgrade to high efficient PTO**
  Once new high efficient PTOs that are under development have proved to work as intended, one or both PTOs in Wavestar's prototype could be upgraded with the new PTO generation. In addition of getting a higher WEC efficiency, the PTO could be tested and stressed in real operating conditions to gain more knowledge on how it behaves.
- **Mechanical optimization and improvement of operational reliability**
  The mechanical set-up of the moving arm and cylinder includes bearings, joints and suspensions which are subject to many motion cycles during the service life. The fatigue life, the operational reliability and the maintenance costs could be improved by a more thorough study on the mechanical set-up and further real life testing of new materials and components (especially the cylinder attachments, gyro suspension and bearings, seals and gaskets).
- **Installation of new arm and/or float made of concrete**
  There is an appealing economical reason of producing the arms and/or floats using concrete. Current studies are being made in order to assess the feasibility of concrete structures and whether the concrete properties are comparable or better to glass fiber (float) and steel (arm).
- **Equipping the WEC with additional sensors**
  By equipping the floats and arms with additional sensors, valuable knowledge on the forces and motions affecting the floats and arms can be acquired. It gives the possibility to design a more cost efficient structure and yet ensuring high performance at the desired operation range. Recently a load cell has been installed in the joint between the cylinder and the arm, and Wavestar is now in the process of selecting suitable pressure transducers to be equipped on the outer shell of the floats.
- **Further model development and experimental work**
  A small scale (float diameter of 0.25[m]) test rig has been designed and installed at Aalborg University with the purpose of investigating in greater details the complex interaction between the waves and the floats. The experimental results from the new test rig and the further development on non-linear numerical models are expected to enable predictions of the power performance of point absorbers operating in high seas [6]. Hereby more suitable control strategies can be applied permitting higher power output and/or smaller structural stresses. Medium scale tests (float diameter of 1.0[m]) are also planned for testing at a large indoor wave facility in Europe. The main focus in these tests will be the impact from slamming forces from steep and breaking waves on the float shell. These tests will enable a more suitable and economic design of the float shell structure.

6 References

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Appendix A Wave climate at the location

Wavestar is located on the western side of the Roshage pier at a water depth of approximately 5[m], see Figure 10. Historic wave measurements from the area were available prior to the installation from a wave rider located in front of the Hanstholm Harbour at a water depth of approximately 17[m]. As the Wavestar WEC is located close to the shore by the pier at a low water depth the wave power at this location is smaller than what is available further offshore. Figure 11 shows a map of the average wave power in the region. The wave power decreases significantly as the waves are approaching the shore, decreasing from 9 [kW/m] at 30[m] depth to 6[kW/m] at 17[m] depth to about 3[kW/m] at 5[m] depth. In other words the available wave power at the Wavestar location is about the half of what is found at the location of the wave rider. Since the installation of Wavestar wave recordings at the exact location of the WEC have been recorded by an ultrasonic wave sensor, see the upper right picture in Figure 11.

Figure 10: Position of Wavestar by Roshage pier and the wave rider in front of the Hanstholm Harbour.

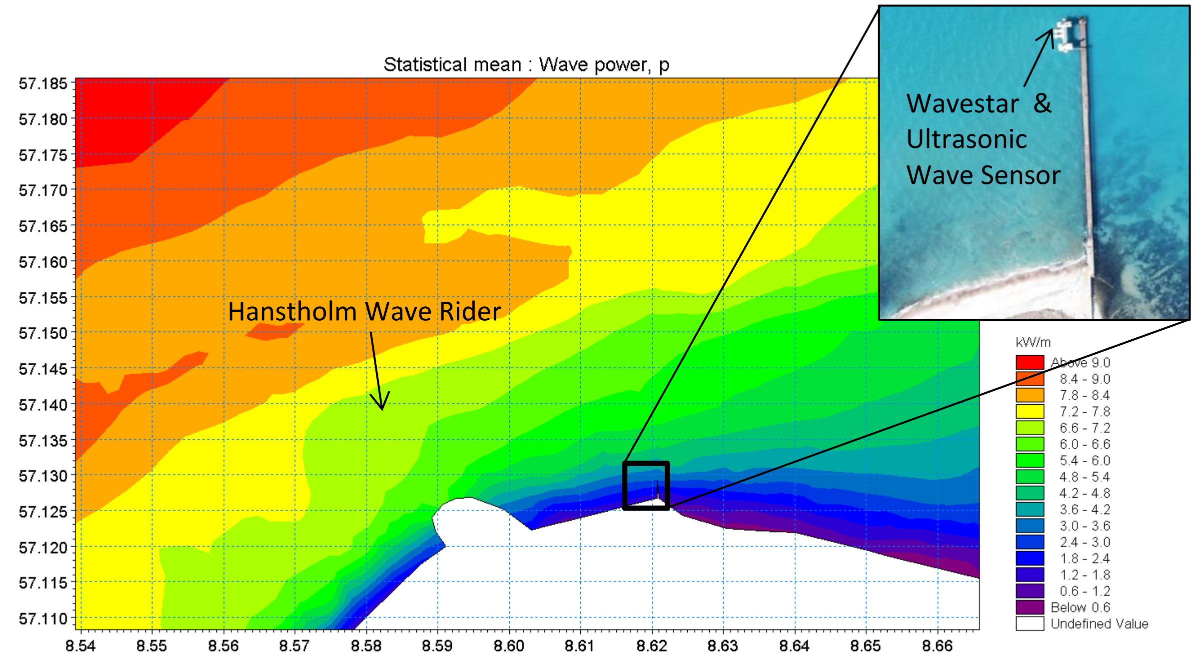


Figure 11: Map showing average wave power (30 year average, figure is from [10]). The upper right picture shows the location of Wavestar by the seaward end of the Roshage pier and the location of the ultrasonic wave sensor.

The measurements of the waves at the two locations have been analyzed to provide the average annual wave climate. The wave climate by the Hanstholm Wave Rider is given in Table 7, and the wave climate by Wavestar is given in Table 8. The frequency table with wave climate at the Wavestar WEC is based on a complete one year of measurements covering the period for phase 1 and 2 (1 May 2011 to 1 May 2012). The software package Wavelab developed at Aalborg University has been used to analyze the measurements from the ultrasonic sensor [11].

		Wave period $T_{0,2}$ (s)										
H_{m0} (m)	H_{m0} (m)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	All
		0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	
0.0 - 0.5	0.25			2.65	8.18	1.84	0.38	0.14	0.03	0.01		13.23
0.5 - 1.0	0.75			1.22	19.21	11.44	2.21	0.18	0.06	0.02		34.35
1.0 - 1.5	1.25				6.84	13.07	2.96	0.30	0.04			23.21
1.5 - 2.0	1.75				0.33	9.58	3.05	0.29	0.04			13.30
2.0 - 2.5	2.25				0.02	3.34	4.60	0.20	0.04			8.20
2.5 - 3.0	2.75				0.01	0.22	3.89	0.21	0.01	0.01		4.35
3.0 - 3.5	3.25						1.38	0.51	0.01	0.01		1.92
3.5 - 4.0	3.75						0.17	0.57	0.02	0.01		0.78
4.0 - 4.5	4.25							0.24	0.07			0.32
4.5 -	4.75							0.07	0.21	0.05	0.01	0.34
All				3.87	34.60	39.50	18.64	2.72	0.52	0.12	0.04	100.00

Table 7: Frequency table with annual wave climate by the Hanstholm Wave Rider (based on 7 years of 30 minute historic data). Values inside the table are in [%] of the time.

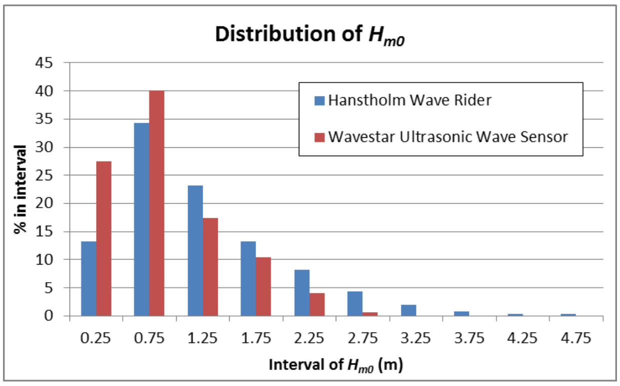
		Wave period $T_{0,2}$ (s)										
H_{m0} (m)	H_{m0} (m)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	All
		0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	
0.0 - 0.5	0.25			7.88	13.07	5.42	0.93	0.14	0.02			27.45
0.5 - 1.0	0.75			2.59	23.38	11.56	2.39	0.15				40.06
1.0 - 1.5	1.25				8.61	8.48	0.38					17.48
1.5 - 2.0	1.75				0.97	9.12	0.31					10.40
2.0 - 2.5	2.25				0.02	3.87	0.13					4.03
2.5 - 3.0	2.75					0.57	0.01					0.58
3.0 - 3.5	3.25											0.00
3.5 - 4.0	3.75											0.00
4.0 - 4.5	4.25											0.00
4.5 -	4.75											0.00
All		0.00	0.00	10.46	46.05	39.02	4.15	0.29	0.02	0.00	0.00	100.00

Table 8: Frequency table with annual wave climate by Wavestar (based on 1 year of 30 minute data from an ultrasonic sensor, 1 May 2011 – 1 May 2012). Values inside the table are in [%] of the time.

The yearly average wave climate at the two locations and the part of time with waves suitable for production is shown in Table 8 and Figure 12 shows the occurrence probability of the waves at the two locations. It is seen that the waves are small in height and short by the Wavestar location in a higher percentage of the time and that there is a lower percentage of large and long waves at the Wavestar location. In the following two sections the reasons for these effects are explained further.

Location	**Wave climate**		**Part of time with different wave climate [%]**		
	Significant wave height	**Wave period**	**Calm sea**	**Storm**	**Production**
	H_{m0} [m]	**$T_{0,2}$ [s]**	**(H_{m0}<0.5m)**	**(H_{m0}>3.0m)**	**(0.5m<H_{m0}<3.0m)**
Hanstholm Wave Rider	1.24	4.34	13.2	3.4	83.4
Wavestar location	0.88	3.88	27.5	0.0	72.5

Table 9: Overview of annual wave climate by Wavestar and by the Hanstholm Wave Rider.



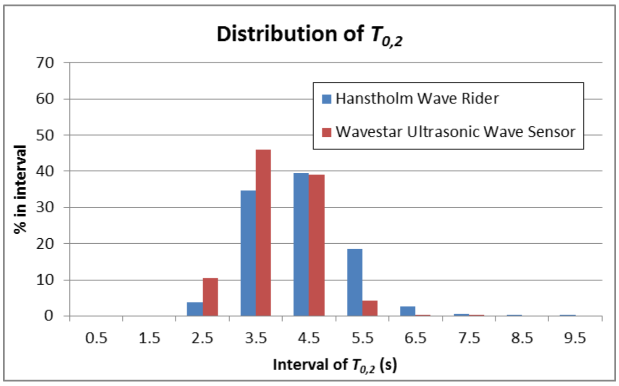


Figure 12: Annual distribution of waves by Wavestar and by the Hanstholm Wave Rider.

A.1. Reflections from the pier and no production in calm sea

The WEC is placed by the side of the Roshage Pier and waves coming from Eastern directions will therefore not reach the converter, see Figure 13. As the WEC is often in shelter of the pier there will be a relatively large percentage of the time with calm sea at the location of the WEC. When *Hs* is below 0.5[m] the WEC is out of operation due to calm sea, and as seen in the recorded data the WEC was out of operation in about 25[%] during phase 2:

February 2012	22.3[%]
March 2012	19.1[%]
April 2012	35.0[%]

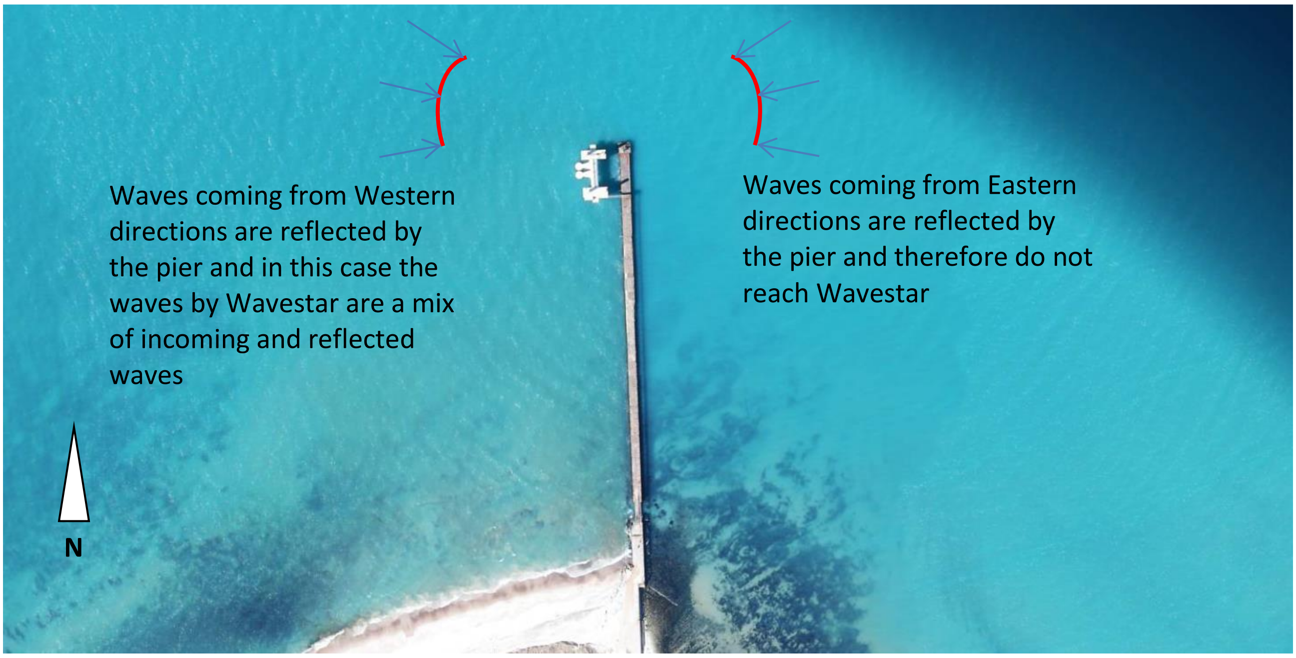


Figure 13: Position of Wavestar by Roshage with sketch of waves from Eastern and Western directions.

In case of waves coming from Western directions the reflections from the pier gives a more chaotic wave field between the floats and the pier, see Figure 14. This is preventing an accurate control of the floats, and thereby a loss in power absorption efficiency.

Figure 14: Picture showing the chaotic wave field between the floats and the pier in case of waves from West.

A.2. No consistent high waves

The bathymetry in the area and the low water depth at the location is causing substantial wave breaking when the significant wave height is exceeding approximately 2.0[m]. A few measurements are available in the highest recorded sea states with significant wave heights slightly higher than 2.5[m], in which almost all the individual waves are breaking before or at the structure. It is obvious to visually notice that the wave breaking with steep wave crests with foam at the top is not ideal for the operation of the WEC and for the energy production by the WEC, see Figure 15.

Figure 15: Picture showing wave breaking in front of the WEC. The significant wave height is 2.2[m].

Appendix B Production estimates by the WEC model

In Section 4 it was demonstrated that there is a reasonable agreement between the measurements and the model of the WEC. Based on the same model six relevant cases are considered in order to have an estimate on how a Wavestar machine may perform under different configurations and wave conditions. Three machine configurations are considered in Case 1, 2 and 3, and different wave climates are considered in Case A and B. Details of the estimations are given in the following pages and the results are summarized in Table 10.

	Location	No. of floats	Float diameter [m]	PTO eff [%]	Production [MWh/year]
Case 1A	Roshage	2	5	50	46
Case 1B	Hanstholm Wave Rider	2	5	50	73
Case 2A	Roshage	20	5	70	589
Case 2B	Horns Rev II	20	5	70	873
Case 3A	Roshage	20	6	70	804
Case 3B	Horns Rev II	20	6	70	1383

Table 10: Summary of the estimated annual production of energy in six different cases.

The main difference between Case 1 and the other cases is that Case 1 deals with a prototype, with two floats and a PTO efficiency of approx. 50[%], and not with a commercial WEC. Wave Star is currently working on a new PTO where conservative estimates indicate that an efficiency of 70[%] from the floats to the grid should be possible with the potential of an efficiency above 80[%], see [5].

When going into sites with larger water depth than what is present at Roshage Wave Star has done COE calculations which show better economy for larger machines. This is the reason for configuration Case 3 with larger floats of Ø6[m].

Looking at the production results in Table 10 the following main conclusions are drawn.

<u>Comparing Case 1A with Case 1B:</u>
It is known that the location of the prototype in Roshage is not ideal, see Appendix A, seen from a performance point of view. By placing the same machine in deeper waters by the Hanstholm Wave Rider, a significant improvement on the annual production is anticipated. The estimated yearly production is increased from 46[MWh/year] to 76[MWh/year], corresponding to an increase of (76-46)/46*100 = 65 %.

<u>Comparing Case 2A with Case 2B:</u>
A commercial Wavestar WEC with 20 floats of Ø5[m] placed by Roshage will according to the calculations produce 589[MWh/year], but if the same machine is placed at Horns Rev II it is expected to produce 873[MWh/year], corresponding to an increase of (873-589)/589*100 = 48 %.

<u>Comparing Case 3A with Case 3B:</u>
A commercial Wavestar WEC with 20 floats of Ø6[m] placed by Roshage will according to the calculations produce 804[MWh/year], but if the same machine is placed at Horns Rev II it is expected to produce 1383[MWh/year], corresponding to an increase of (1383-804)/804*100 = 72 %.

<u>Comparing Case 2B with Case 3B:</u>
A commercial Wavestar WEC with 20 floats placed at Horns Rev II will according to the calculations produce 873[MWh/year] if the floats are Ø5[m], but if the same machine is scaled up to use Ø6[m] floats it is expected to produce 1383[MWh/year], corresponding to an increase of (1383-873)/873*100 = 58 %.

B.1. Case 1: *Wavestar prototype (2 floats Ø5[m])*

Case 1A (Roshage)

Machine specifications	
Production to grid [MWh/year]	46
Float diameter [m]	5
Length of arm [m]	10
Site depth [m]	5
Max control torque e6[Nm]	1
Array interaction [%]	85
Number of floats	2
Main parameters	
Site	ROSHAGE (may'11-'12)
Number of floats	2
Machine geometry	default
Float diameter [m]	5
Length of arm [m]	Scalable (ref = 10[m])
PTO efficiency [%]	50
Storm protection [m]	3
Secondary parameters	
Min. PTO power [kW]	0
Max. PTO power [kW]	110
Background consumption [kW]	0
Part of time in production [%]	95

Case 1B (Hanstholm Wave Rider)

Machine specifications	
Production to grid [MWh/year]	73
Float diameter [m]	5
Length of arm [m]	10
Site depth [m]	5
Max control torque e6[Nm]	1
Array interaction [%]	85
Number of floats	2
Main parameters	
Site	Hanstholm Wave Rider
Number of floats	2
Machine geometry	default
Float diameter [m]	5
Length of arm [m]	Scalable (ref = 10[m])
PTO efficiency [%]	50
Storm protection [m]	3
Secondary parameters	
Min. PTO power [kW]	0
Max. PTO power [kW]	110
Background consumption [kW]	0
Part of time in production [%]	95

Table 11: Estimated generated energy per year and model parameters for Case 1A (left) & Case 1B (right).

	Machine: Electrical power [kW]		100% operation, array interaction, power limit and storm protection limit														
	Hm0 [m]		Wave period *T0,2* [s]. Range and center value on second row.														
PTO efficiency [%]	Range	Center	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15
50			0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
Arm length [m]	0.0 - 0.5	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.5 - 1.0	0.75	0	0	1	2	3	3	3	3	3	3	3	2	2	2	2
Float diameter [m]	1.0 - 1.5	1.25	0	0	3	7	9	9	9	8	8	7	6	6	6	5	5
5	1.5 - 2.0	1.75	0	1	6	13	17	17	16	14	13	12	11	10	10	9	8
Number of floats	2.0 - 2.5	2.25	0	1	10	22	27	26	24	21	19	18	16	15	14	13	12
2	2.5 - 3.0	2.75	0	2	15	33	38	36	32	29	26	24	22	20	18	17	16
Storm protection [m]	3.0 - 3.5	3.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.00	3.5 - 4.0	3.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nominal power [kW]	4.0 - 4.5	4.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
110	4.5 -	4.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 12: Power matrix of generated electrical power for Case 1. Values inside the table are in [kW].

B.2. Case 2: Wavestar commercial machine (20 floats Ø5[m])

Case 2A (Roshage)

Machine specifications	
Production to grid [MWh/year]	589
Float diameter [m]	5
Length of arm [m]	10
Site depth [m]	5
Max control torque e6[Nm]	1
Array interaction [%]	85
Number of floats	20
Main parameters	
Site	ROSHAGE (may'11-'12)
Number of floats	20
Machine geometry	default
Float diameter [m]	5
Length of arm [m]	Scalable (ref = 10[m])
PTO efficiency [%]	70
Storm protection [m]	3
Secondary parameters	
Min. PTO power [kW]	20
Max. PTO power [kW]	320
Background consumption [kW]	10
Part of time in production [%]	95

Case 2B (Horns Rev II)

Machine specifications	
Production to grid [MWh/year]	873
Float diameter [m]	5
Length of arm [m]	10
Site depth [m]	approx. 15
Max control torque e6[Nm]	1
Array interaction [%]	85
Number of floats	20
Main parameters	
Site	HORNS REV 2
Number of floats	20
Machine geometry	default
Float diameter [m]	5
Length of arm [m]	Scalable (ref = 10[m])
PTO efficiency [%]	70
Storm protection [m]	3
Secondary parameters	
Min. PTO power [kW]	20
Max. PTO power [kW]	320
Background consumption [kW]	10
Part of time in production [%]	95

Table 13: Estimated generated energy per year and model parameters for Case 2A (left) & Case 2B (right).

	Machine: Electrical power [kW]		100% operation, array interaction, power limit and storm protection limit														
	Hm0 [m]		Wave period *T0,2* [s]. Range and center value on second row.														
PTO efficiency [%]	Range	Center	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15
70			0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
Arm length [m]	0.0 - 0.5	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.5 - 1.0	0.75	0	0	0	38	54	60	61	58	54	51	47	44	42	39	37
Float diameter [m]	1.0 - 1.5	1.25	0	0	44	106	147	155	148	136	125	115	107	99	92	86	81
5	1.5 - 2.0	1.75	0	0	87	207	273	270	251	228	206	188	173	160	149	139	131
Number of floats	2.0 - 2.5	2.25	0	0	144	320	320	320	320	320	294	268	245	225	210	195	183
20	2.5 - 3.0	2.75	0	25	214	320	320	320	320	320	320	320	320	294	273	254	238
Storm protection [m]	3.0 - 3.5	3.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.00	3.5 - 4.0	3.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nominal power [kW]	4.0 - 4.5	4.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
320	4.5 -	4.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 14: Power matrix of generated electrical power for Case 2. Values inside the table are in [kW].

B.3. Case 3: Wavestar commercial machine (20 floats Ø6[m])

Case 3A (Roshage)

Machine specifications	
Production to grid [MWh/year]	804
Float diameter [m]	6
Length of arm [m]	12
Site depth [m]	5
Max control torque e6[Nm]	2.1
Array interaction [%]	85
Number of floats	20

Main parameters	
Site	ROSHAGE (may'11-'12)
Number of floats	20
Machine geometry	default
Float diameter [m]	6
Length of arm [m]	Scalable (ref = 10[m])
PTO efficiency [%]	70
Storm protection [m]	4

Secondary parameters	
Min. PTO power [kW]	40
Max. PTO power [kW]	600
Background consumption [kW]	10
Part of time in production [%]	95

Case 3B (Horns Rev II)

Machine specifications	
Production to grid [MWh/year]	1383
Float diameter [m]	6
Length of arm [m]	12
Site depth [m]	approx. 15
Max control torque e6[Nm]	2.1
Array interaction [%]	85
Number of floats	20

Main parameters	
Site	HORNS REV 2
Number of floats	20
Machine geometry	default
Float diameter [m]	6
Length of arm [m]	Scalable (ref = 10[m])
PTO efficiency [%]	70
Storm protection [m]	4

Secondary parameters	
Min. PTO power [kW]	40
Max. PTO power [kW]	600
Background consumption [kW]	10
Part of time in production [%]	95

Table 15: Estimated generated energy per year and model parameters for Case 3A (left) & Case 3B (right).

	Machine: Electrical power [kW]		100% operation, array interaction, power limit and storm protection limit														
	Hm0 [m]		Wave period *T0,2* [s]. Range and center value on second row.														
PTO efficiency [%]	Range	Center	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15
70			0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
Arm length [m]	0.0 - 0.5	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.5 - 1.0	0.75	0	0	0	46	71	85	89	88	84	79	74	69	66	62	59
Float diameter [m]	1.0 - 1.5	1.25	0	0	50	121	182	212	215	206	192	178	166	155	145	136	128
6	1.5 - 2.0	1.75	0	0	95	231	339	381	374	350	322	296	274	254	237	222	208
Number of floats	2.0 - 2.5	2.25	0	0	154	375	535	579	554	511	466	426	391	361	336	314	295
20	2.5 - 3.0	2.75	0	0	228	552	600	600	600	600	600	563	516	475	441	412	386
Storm protection [m]	3.0 - 3.5	3.25	0	40	319	600	600	600	600	600	600	600	600	593	550	513	480
4.00	3.5 - 4.0	3.75	0	53	425	600	600	600	600	600	600	600	600	600	600	600	577
Nominal power [kW]	4.0 - 4.5	4.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
600	4.5 -	4.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 16: Power matrix of generated electrical power for Case 3. Values inside the table are in [kW].