First Power Production Results from the Wave Star Roshage Wave Energy Converter

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The Wave Star machines

Test machine at Aalborg University
- Deployment: 2004-2005
- Scale: 1/40
- Float diameter: 0.25 m

Test machine at Nissum Bredning
- Deployment: 2006-2010
- Scale: 1/10
- Float diameter: 1.0 m

Test section at Roshage
- Deployment: 2009-
- Scale: 1/2
- Float diameter: 5.0 m
Wave Star make use of a unique concept

- 2 rows with 10 floats, 20 floats total
- The floats are mounted on a machine which is founded on the seabed
- All the moving parts are located above the waterline
- Hydraulic fluid is pumped from each float to a hydraulic motor, which drives a generator
- The Wave Star machine can lift the floats out of the water into safety position
Wave Star scale 1:40
Aalborg University, Denmark
Normal operation

Storm protection mode

Wave Star scale 1:10
Nissum Bredning, Denmark

More than 4 years in operation
and 15 storms without damage
The location for the test section (photo taken before deployment)

Roshage Pier, location for the Wave Star scale 1:2 test section
Hanstholm, Denmark
The machine was built in Gdansk and towed to Denmark in August 2009
The jacking system was tested in dry dock in Frederikshavn, Denmark
The machine was installed on 18 September 2009
The 19th of September 2009 the installation was finalized and the machine was placed in storm protection.
A bridge was built during the autumn 2009, and the first guests visited the plant during COP15. The machine has been supplying electricity to the grid since February 2010.
The Roshage test unit is a section of the complete machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Roshage test unit</th>
<th>Commercial Wave Star C5-600 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of floats</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Float diameter</td>
<td>Ø5 m</td>
<td>Ø5 m</td>
</tr>
<tr>
<td>Arm length</td>
<td>10 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Weight</td>
<td>1000 Tons</td>
<td>1600 Tons</td>
</tr>
<tr>
<td>Nominal electrical power</td>
<td>110 kW</td>
<td>600 kW</td>
</tr>
</tbody>
</table>
Power measurements from the Roshage test unit

Notes:
- Power is 10 minute average values of harvested power from one float (hydraulic power leaving one cylinder)
- The same data are shown in the figures, only the x-axis is different
- A typical wave period for the Roshage location is used for the simulated curve
Power measurements from the Roshage test unit

- Measured September 2010 (Control generation 3)
- Measured June 2010 (Control generation 2)
- Measured May 2010 (Control generation 1)
- Simulation, Control generation 3
- ForskVE Limit Curve

Notes:
- Power is 10 minute average values of harvested power from one float (hydraulic power leaving one cylinder)
- The same data are shown in the figures, only the x-axis is different
- A typical wave period for the Roshage location is used for the simulated curve
If the measured production is above the limit, subsidies are received from EnergiNet.

Example of measured data from the Roshage test unit (10 min average values):

<table>
<thead>
<tr>
<th>PLC_Datetime</th>
<th>AllDataValid</th>
<th>Hs</th>
<th>Tmean</th>
<th>P_TwoFloats</th>
<th>ForskVE_limit</th>
<th>AboveLimit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[%]</td>
<td>[m]</td>
<td>[s]</td>
<td>[kW]</td>
<td>[kW]</td>
<td>[True/False]</td>
</tr>
<tr>
<td>21/09/10 09:20</td>
<td>100</td>
<td>2.08</td>
<td>4.72</td>
<td>48.98</td>
<td>34.24</td>
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<tr>
<td>21/09/10 09:30</td>
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<td>1.91</td>
<td>4.31</td>
<td>37.50</td>
<td>28.71</td>
<td>True</td>
</tr>
<tr>
<td>21/09/10 09:40</td>
<td>100</td>
<td>1.94</td>
<td>4.10</td>
<td>38.02</td>
<td>29.80</td>
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</tr>
<tr>
<td>21/09/10 09:50</td>
<td>100</td>
<td>2.01</td>
<td>3.95</td>
<td>33.69</td>
<td>32.07</td>
<td>True</td>
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<tr>
<td>21/09/10 10:00</td>
<td>100</td>
<td>2.03</td>
<td>4.47</td>
<td>39.91</td>
<td>32.85</td>
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<tr>
<td>21/09/10 10:10</td>
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<td>2.17</td>
<td>4.23</td>
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<td>4.14</td>
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<td>32.02</td>
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<tr>
<td>21/09/10 10:40</td>
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<td>4.27</td>
<td>40.97</td>
<td>35.12</td>
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<tr>
<td>21/09/10 10:50</td>
<td>100</td>
<td>2.03</td>
<td>4.01</td>
<td>41.76</td>
<td>32.55</td>
<td>True</td>
</tr>
<tr>
<td>21/09/10 11:00</td>
<td>100</td>
<td>1.83</td>
<td>4.13</td>
<td>32.29</td>
<td>26.21</td>
<td>True</td>
</tr>
<tr>
<td>21/09/10 11:10</td>
<td>100</td>
<td>1.97</td>
<td>4.28</td>
<td>37.60</td>
<td>30.71</td>
<td>True</td>
</tr>
<tr>
<td>21/09/10 11:20</td>
<td>100</td>
<td>1.89</td>
<td>3.91</td>
<td>36.32</td>
<td>28.19</td>
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<tr>
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<tr>
<td>21/09/10 11:50</td>
<td>100</td>
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<td>4.34</td>
<td>38.75</td>
<td>30.35</td>
<td>True</td>
</tr>
</tbody>
</table>

Power numbers in kW are measured harvested power (hydraulic power leaving the two cylinders). Wave climate is calculated using wave measurements at the location.
Power measurements from the Roshage test unit

Notes:
• Power is 10 minute average values of harvested power from one float (hydraulic power leaving one cylinder)
• The same data are shown in the figures, only the y-axis is different
• A typical wave period for the Roshage location is used for the simulated curve
### Power matrix for a single Wave Star C5 600 kW machine with 20 floats

Values inside the table are average electrical power to grid in kW.

<table>
<thead>
<tr>
<th>Wave height $H_m0$ (m)</th>
<th>Wave period $T_{0,2}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 - 3</td>
</tr>
<tr>
<td>0.0 - 0.5</td>
<td>0</td>
</tr>
<tr>
<td>0.5 - 1.0</td>
<td>0</td>
</tr>
<tr>
<td>1.0 - 1.5</td>
<td>54</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>106</td>
</tr>
<tr>
<td>2.0 - 2.5</td>
<td>175</td>
</tr>
<tr>
<td>2.5 - 3.0</td>
<td>262</td>
</tr>
<tr>
<td>3.0 -</td>
<td>Storm protection</td>
</tr>
</tbody>
</table>
Perspectives: Wave Star C5 performance at different sites in Europe

<table>
<thead>
<tr>
<th>Site</th>
<th>Belmullet, IR</th>
<th>EMEC, UK</th>
<th>Horns Rev 2, DK</th>
<th>SEM-REV, F</th>
<th>BIMEP, ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power</td>
<td>1200 kW</td>
<td>1200 kW</td>
<td>600 kW</td>
<td>1200 kW</td>
<td>1200 kW</td>
</tr>
<tr>
<td>Storm protection</td>
<td>Hs &gt; 5 m</td>
<td>Hs &gt; 5 m</td>
<td>Hs &gt; 3 m</td>
<td>Hs &gt; 5 m</td>
<td>Hs &gt; 5 m</td>
</tr>
<tr>
<td>Annual production</td>
<td>4.29 GWh</td>
<td>2.88 GWh</td>
<td>1.41 GWh</td>
<td>2.37 GWh</td>
<td>2.21 GWh</td>
</tr>
</tbody>
</table>

Site Belmullet, IR:
- Nominal Power: 1200 kW
- Storm protection: Hs > 5 m
- Annual production: 4.29 GWh

Site EMEC, UK:
- Nominal Power: 1200 kW
- Storm protection: Hs > 5 m
- Annual production: 2.88 GWh

Site Horns Rev 2, DK:
- Nominal Power: 600 kW
- Storm protection: Hs > 3 m
- Annual production: 1.41 GWh

Site SEM-REV, F:
- Nominal Power: 1200 kW
- Storm protection: Hs > 5 m
- Annual production: 2.37 GWh

Site BIMEP, ES:
- Nominal Power: 1200 kW
- Storm protection: Hs > 5 m
- Annual production: 2.21 GWh
C5 Wave Star and C10 Wave Star

• C5
  - 70 m long
  - 20 floats of Ø 5 m
  - ~10-15 m of water depth
  - 500 kW @ 2.5m Hs

• C10
  - 140 m long
  - 20 floats of Ø10 m
  - ~20-30 m of water depth
  - 6 MW @ 5.0m Hs

Double size = 11 times more power
Road Map for Cost of Energy for Wave Star WEC
Based on average wave energy potential at European sites
(WEC lifetime: 20 years, Interest of investment: 9%)

Development factors
Energy production: 1.0
Total investment: 1.0
Maintenance: 1.0

Development factors
Energy production: 1.1
Total investment: 0.5
Maintenance: 0.8

Development factors
Energy production: 1.5
Total investment: 0.1
Maintenance: 0.5

Year:

€/kWh:
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Activities in Wave Star at present

- The Roshage test section will actively be used as test platform for Power Take-Off optimization, test of other component/parts, and for getting maintenance data.

- Improvement of the structural design of the C5-machine, and optimization and reduction of systems for future machines

- Focus on reducing production and development cost for the next projects: Expertise from similar industries

- Focus on increasing the Power Take-Off efficiency: In collaboration with innovative companies and universities

- Agreement with utility company

- Find subsidiaries
Wave Star cracks the nuts!

<table>
<thead>
<tr>
<th>To stay in the sea</th>
<th>Take energy out of waves</th>
<th>Cost decreasing</th>
<th>More efficient PTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>The storm protection strategy effectively protects the Wave Star machines.</td>
<td>The Roshage WEC is connected to the grid, and it has produced energy since January 2010.</td>
<td>The energy costs for the first full WEC will not be competitive to other conventional sources of energy.</td>
<td>The first test results have shown challenges in ensuring a high efficiency of the complete power transmission to the electrical grid.</td>
</tr>
<tr>
<td>The Roshage WEC has survived several storms with no severe damages and no service afterwards.</td>
<td>The measurements fits the expected power curve.</td>
<td>The calculated costs has already been decreased by 30 %, but further cost reduction is needed.</td>
<td>Projects on improvements are on-going with universities.</td>
</tr>
</tbody>
</table>
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