Advanced Wave Energy Converter II

AWEC II

Final report

PSO 2009

Project no. 2009-1-10232

Also final report for the related ForskEL project
MAWEC energy production
Project no. 2011-1-10815

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1 Resume of final report

1.1 Project start

The project started with a meeting with all involved partners participating. Theese were Aalborg University Wave Energy Research Group, Aalborg University Mechanical Engineering, DONG Energy and LEANCON Wave Energy. At that meeting it was agreed on the purpose of this project and what the outcome should be.

The purpose was:

- Measure energy production on the scale 1:10 model.
- Measure the loads on the scale 1:10.
- Establish an anchoring system with a power cable
- Full scale economics

The outcome of this project would be to test the structural design of the scale 1:10 WEC by equipping it with many strain gauges placed strategic over the WEC, and to test the energy production by measuring the air pressure and air flow. By making an anchoring system with a power cable it was secured that there always would be power for the onboard measuring equipment and that an anchoring system with a power cable that could make multiple turns was tested already in scale 1:10 and ready for the later scale 1:4 WEC.

1.2 Project economy and time schedule

The project was carried out within the PSO budget but the own financing has been much larger than in the budget. This is mainly due to the amount of tasks in the project turned out to be bigger than planned and the time schedule had to be extended more times. Details of project economy, time schedule etc. can be seen in the document "RegnskabsKommentarer.pdf".

1.3 Project outcome

The outcome of this project has been that the LEANCON scale 1:10 WEC was designed, build, launch in the sea and the offshore test were carried out which resulted in two reports from Aalborg University one describing energy production and the other describing structural loads on the scale 1:10 WEC. The results from these two reports are linked together in this final report from LEANCON Wave Energy.

The results show that the technology in this WEC is promissing even at the present stage and there is still room for improvements in the future.

It was expected that the final weight of the WEC would be 1.8 ton, but due to some conservative decisions the final weight inclusive control box and other equipment ended to be 3.0 ton.

The WEC was exposed to three big storms within a period of 4 weeks, which it withstood very well. Some days after the third storm the WEC was brought to land for winter storage and scheduled maintenance and update on equipment. Some loose bolt in the bolt connection had been detected, which has caused some stress related issues.

1.3.1 Energy production

The energy production was measured as air pressure [Pa] and air flow [m^3/s] which gives the power [W].

There should have been more test results regarding energy production, but there were some difficulties running in the measuring equipment for measuring the energy production. The purpose was to verify the energy measurements from the scale 1:40 tank test. The test period should have been longer to full fill this purpose. But there have been made improvements on the valves, the diameter of the tubes has been increased and other flow improvements, so the energy level in scale 1:10 would at least have been at the same level as in the scale 1:40 test.

As the WEC has proved its offshore capabilities, it is strongly recommended that a tank test for measuring energy production in all different sea states under controlled circumstances is performed. This should be made on only the right arm of the WEC as this is the one that is fully equipped with measuring equipment.

1.3.2 Load calculation and load measurements

The scale 1:10 was designed on load calculations and measurements from the scale 1:40 project. The loads for the structural design were calculated theoretically bassed on known theory. Theese loads were used to design the scale 1:10 main structure and the tubes. The theoretically loads were verified by load measurements on a section with 10 tubes in scale 1:40 and by measurements on one tube model in scale 1:40 that were fitted with force gauges.

The scale 1:10 WEC is equipped with 66 strain gauges placed on strategic places around the WEC. Some good load measurements have been achieved that shows, as expected, that the loads on the WEC is far from the design limit, and that future WEC's in bigger scale can be build with a relative smaller amount of material.

The mooring forces for the scale 1:10 was based on measured loads from the earlier scale 1:40 tank test, where the loads were measured in extreme wave states with the 6 meter wide model. The mooring force in scale 1:40 was measured to 82.54 N which in scale 1:10 is 5.28 kN (540 kg). The mooring force was measured in a 50 year extreme wave state during a 30 minutes test. In the scale 1:10 offshore test the wind load is also calculated in and it is estimated to be at the same level as the wave loads. When scaling up the wave loads is scaled up in the power of 3 but the wind loads only in the power of 2.

1.3.3 Structural design

The structural design for the scale 1:10 model was made by Aalborg University Mechanically Engineering in a previous project based on the load report from Aalborg University Wave Energy Research Group. The structural design were made on the basis on what was considered the worst case load scenario both regarding horizontal and vertical forces. The horizontal force was calculated to 15 kN/m and the vertical force were calculated to 5 kN/m. Theese forces were put into the finite element analysis program and the outcome were a result where each of the 16 m long main structure has a weight of 342 kg exclusive the tubes and gelcoat.

When actually produced, the arms had a weight of app 640 kg. The extra weight is mainly because of overlap of the glass fibre in the corners and that the gelcoat (the outside painting) was not included in the estimated weight.

The design load for the tubes was a local impact of 1.365 Mpa in an area of 0.00439 m^2 at the bottom of the tube. That is app. 600 kg in an area of 6.6 cm times 6.6 cm. The outcome was a laminate of 1.5 mm on each side of the PVC core. In the original design the tubes had an outside diameter of 438 mm. It was decided to increase the outer diameter from 438 mm to 500 mm, as this would increase the capture area and increase buoyancy.

Some structural load tests on the WEC were carried out in the workshop before the WEC was launched in the sea.

1.3.4 Production technology

The production technology for the scale 1:10 is based on the vacuum infusion technology. Today this is a well proven technology that gives a high quality and it is used for mass production of big glass fibre elements.

The 17 meter long vacuum tight mould for the main structure was set up in a rented workshop by Leancon. Four of these items (A-webs) were cast and two 17 meter long (I-webs) were cast.

The tubes were also cast with by the vacuum infusion technology.

The production technology of the two most important elements (main structure and tubes) in this WEC has been developed, tested and approved. Other elements such as vacuum valve case, and valve flaps has also been developed, tested and approved. They were also made by the vacuum infusion technology.

1.3.5 Conclusion

The WEC withstood three big storms (Freja, Gorm and Helga) within a period of 4 weeks and has thereby proved its survivability in extreme offshore conditions.

The strain gauge measurements on the main structure shows that the WEC is over dimensioned and that future bigger WEC’s can be build with relatively less material, whereby a cost reduction is achieved.

The amount of measurements on the energy production is not considered adequate, as it took much longer time to run in this test setup than expected. But anyway, there have been made improvements on the valves so the energy level in scale 1:10 would at least have been at the same level as in the scale 1:40 test.

The anchoring principle proved that it worked all though there was some running in issues with the primary anchoring line. Also the cable twisting device that allowed the WEC to make multiple 360 degrees turns with a power cable proved that it worked.

It is expected that already in scale 1:4 it can be proven in praxis how cost effective this WEC is. In full scale serial production it is considered realistic with an electricity price that can compete with off shore wind energy.

It is strongly recommended that a tank test for measuring energy production in all different sea states under controlled circumstances is performed. This could be made only on the right arm of the WEC, as this is the one that is fully equipped with measuring equipment. As the WEC has proven its offshore capabilities, this is the very last important thing to fully document.

2 Final report

The content of this final report is a summary of the content from the reports that has been made in this project supplied with an interpretation of the results and potential future improvements.

2.1 Enclosed reports

All the tests, measurements and calculations in this project have result in two different reports describing energy production and structural loads.

2.1.1 Energy measurement report

The energy measurements, power curves under different conditions and anchoring forces are descreibed in the AAU report “Scale 1:10 Tests of the OWC WEC LEANCON at Nissum Bredning”.

2.1.2 Structural report

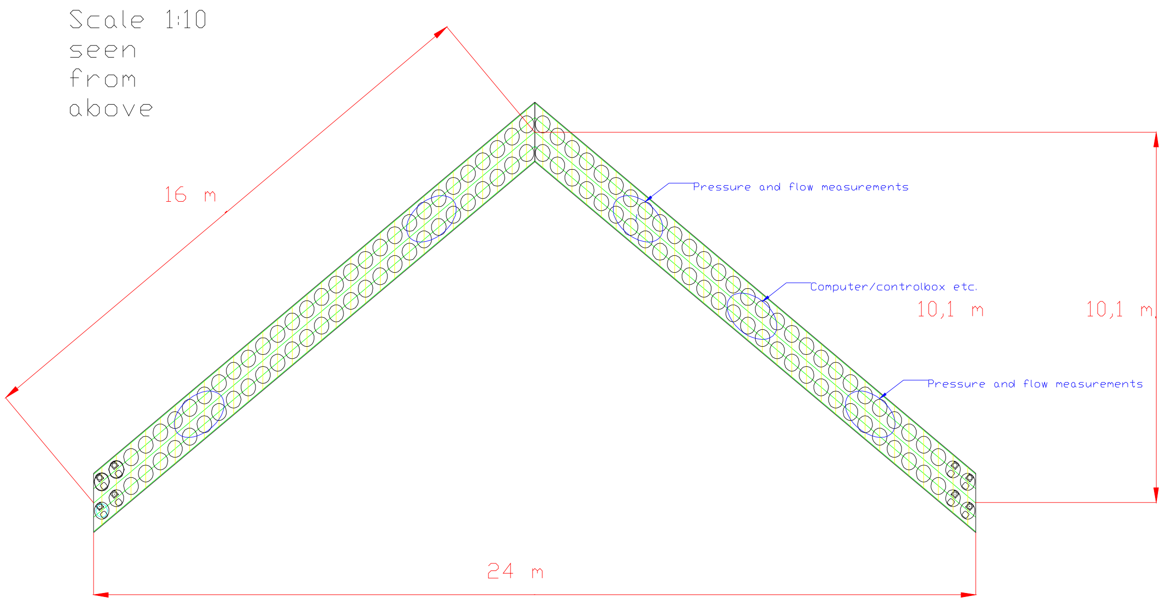
The analysis of the structural loads is described in the AAU report “Strain and strength measurements – Leancon 1:10 wave energy system”.

2.2 Energy production

From first stage it was desided to measure the energy production as air pressure [Pa] and air flow [m^3/s] which gives the power [W]. This is gives a much more precise measurement than using air turbines. As the right arm and left arm are identical, it was decided only to measure on the right arm.

2.2.1 Placement of airflow measuring units

To be able to measure the air flow and air pressure all the pressure flow was collected in two points on the right arm as seen on the figure below.



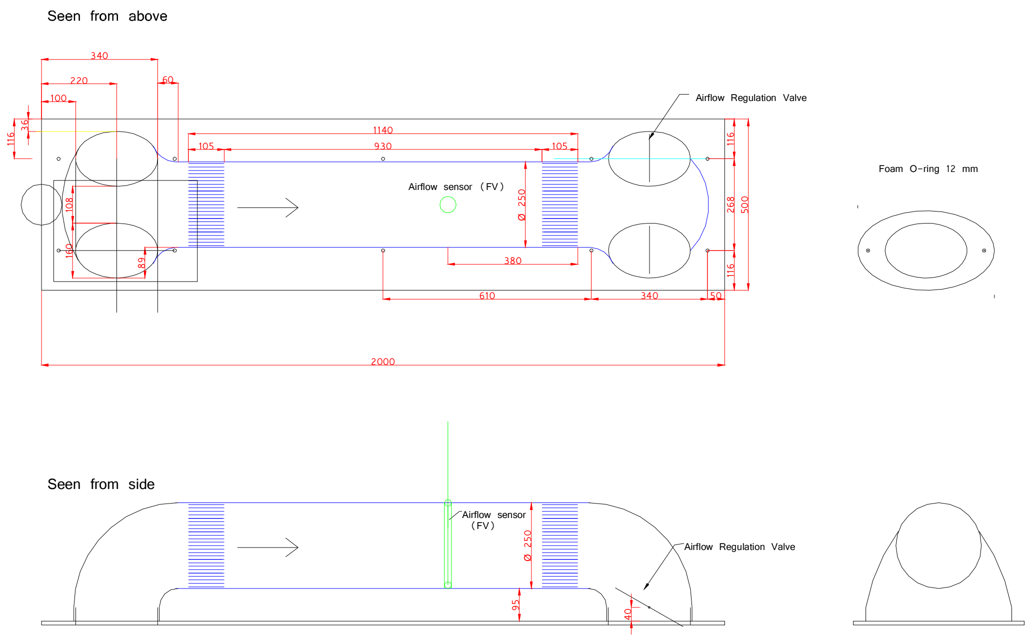
By placing the flow measuring units in this way the each covered app a half side of the right arm although they are not separated. If there has only been used on measuring equipment in the middle of the right arm the pressure losses would have been bigger.

The flow measuring units are placed on top of the WEC because in this way they are replaceable "Plug and Play" units. This is preferable if they should be taken in for special test or calibration or if they should be replaced with at turbine and generator unit.

On the picture below the flow measuring unit can be seen. The blue lines in the start and end of the Ø250 mm tube are small tubes that reduce air turbulences. The green sensor is a pitot sensor that measures the air flow speed. As seen on the side view picture it covers the whole diameter of the Ø 250 mm tube. This minimizes measuring failure due to different air flow speed in the middle and close to the side of the tube.

The airflow regulator valve is controlled by a fast reacting electrical motor control unit. This simulates the behaviour of an air turbine.

The plan was, after the comprehensive production tests in different sea states, to run a production test where the airflow regulator valve (air turbine simulator) was continuously adjusted during the production test. That's why a fast reacting electrical motor control unit was chosen. Due to lack of time this was not possible.



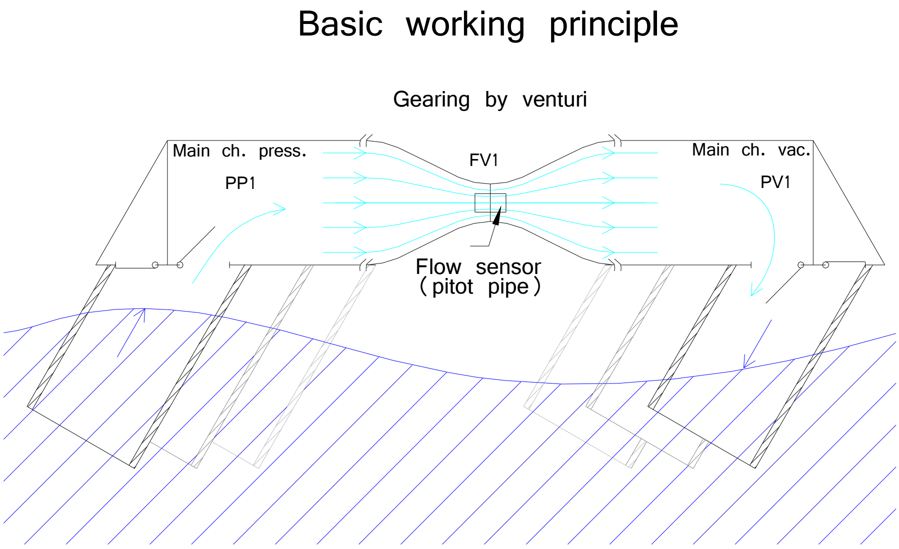
In scale 1:4 and bigger the turbine and generators will be inside the WEC.

2.2.2 **Basic working principle**

The basic working principle of this WEC is that above each tube there are two rectifier valves that rectify the airflow. All up going wave's presses air into a main pressure channel and all down going waves sucks air from a "vacuum" channel. Between the two main channels the air turbines and generators are placed. The WEC floats freely around a 360 degrees multi turn anchoring point.

The venturi principle is in fact the gearing that makes the slow moving waves into a high speed rotation by means of a standard air turbine. Due to the high speed rotation a standard asynchronous direct driven generator can be used without the need of a gearbox.

There will be 8 sets of turbines and generators on a big scale WEC. The WEC stretches over typically 2 wave lengths and works like a 100 cylinder air pump. This gives a very steady air flow, which makes it easier to fulfill the demands for grid compliance.



The drawing above is a principle sketch. The airflow regulation valve is placed at the same place as the flow sensor, as seen on the previous picture.

The energy production is measured as air pressure [Pa] times air flow [m^3/s] which gives the power [W].

When the airflow regulation valve is fully opened, there will be a huge air flow (FV1), but the pressure difference between the main pressure channel and the main vacuum channel (PP1 – PV1) is low. This gives a low energy production.

When the airflow regulation valve is fully closed, there will be no air flow (FV1), but the pressure difference between the main pressure channel and the main vacuum channel (PP1 – PV1) is high. This gives a low (zero) energy production.

Somewhere in between where there is a relatively high air flow and a relatively high pressure difference the most optimal energy production is.

The intention with this scale 1:10 offshore test was to test the energy production in all different kind of sea states and find the optimal valve settings in each sea state. Hereafter an active energy control system should be developed and tested. That's why the airflow regulator valve is controlled by a fast reacting electrical motor control unit. But due to the limited time for running test series, mainly due to the fact that doing offshore test is not easy as all equipment has to work at the same time and are not easily accessibly due to weather conditions, this was not achieved in the way that was wanted.

2.2.3 PTO advantages

The advantages of an OWC using this type of PTO is as follows:

Advantages

- No moving parts are beneath or in contact with the water
- No moving parts are exposed to big forces
- No mechanical or hydraulic gearing needed to get high speed rotation
- The venturi principle is the most reliable and maintenance free gearing principle
- High efficient standard air turbines are used instead of low efficient unidirectional wells turbines
- The valve flaps are light weight composite flaps that only are exposed to low pressure
- Uses standard inverter technology to feed the asynchronous generator to regulate and control the rotation speed of the air turbine

2.2.4 Test results

As seen in the AAU report "Scale 1:10 Tests of the OWC WEC LEANCON at Nissum Bredning" the amount of energy measurements is low. There should have been more time for that, but some different smaller technical issues turned up, which had to be taken care of, but they were all solved.

It took some time to get the wave gauge sensor to work properly as there was some signal noise on the line. It was some 50 Hz noise from the power cable, but it could be isolated. It also took some time to get the primary anchoring line adjusted in. It broke twice. The much stronger backup anchoring rope elongated more than expected. This caused a failure in the sea cable, which was substituted by an extra sea cable, until the ordinary sea cable could be repaired. In the beginning the data connection sometime was lost and could not always be re-established by the remote power control.

All these issues had to be solved in good weather conditions which in average occurred every second week. The anchoring issues had top priority which put the energy measurements a little in the background until they were solved.

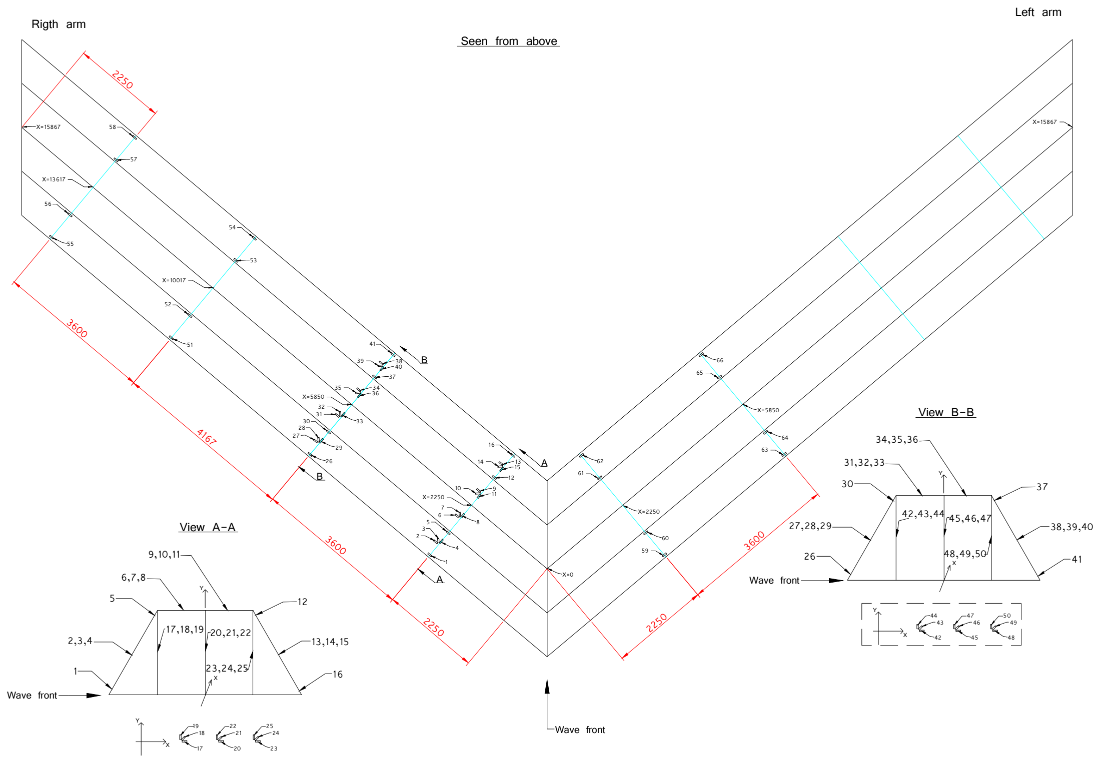
Some days before the Freja storm on the 7^{th} of November a plate that covered at hole in the control box apparently got damaged under the replacement of an antenna, this caused that sea water came into the control box during the Freja storm and caused damage to some of the equipment but this could be replaced by other equipment.

2.3 Structural loads and measurements

The loads that the waves expose to this WEC was calculated theoretically and afterwards verified on smaller models when the structural design of the WEC was made. The loads was measured in scale 1:40 on a section of the WEC with 10 tubes and also on a one tube system fittet with force sensors that could measure forces in different directions. In practice when the WEC was build, it was build much stronger due overlay of glass fibres in the corners, which is necessary in real production when laying up the glass fibre.

The WEC is equipped with 66 strain gauges placed on well chosen points on the WEC. As both arms are equal it was chosen to make a full equipment of the right arm and only place 8 strain gauges on the left arm, so it was possible to see if there were any differences in the behaviour of the two arms.

In the picture below it can be seen where the strain gauges are placed. The details can only be seen on a screen when using the zoom option.



2.3.1 Measured loads

The measured results can be seen in the AAU report “Strain and strength measurements – Leancon 1:10 wave energy system”.

2.4 Structural design of main structure

The main structures were designed in a previous project on the basis on the input from the load calculations on what was considered the worst load scenario. A finite element model was made and the structure was tested regarding deformation, buckling, max stress and max strain. The FEM analysis was made to a level of detail that was relevant according to the knowledge of how waves attack the WEC. The structural design is made on what is considered the worst case load scenario regarding horizontally and vertically forces. These forces are in the finite element analysis put to an attack point on the middle of the tubes. This attack point that is below the main structure also gives torque forces to the main structure. This scale 1:10 WEC is designed up against what is considered the worst load case scenario. This is where half of the 24 m wide WEC is hit on the whole front with a force of 15 kN/m and an almost equal force on the back of the other half of the WEC. In practice this does not happen as the WEC floats on top of the waves. It was highly expected, and it turned also out so, that a real sea test of the 1:10 scale WEC would show that it was exposed to significantly lower loads than it is designed to.

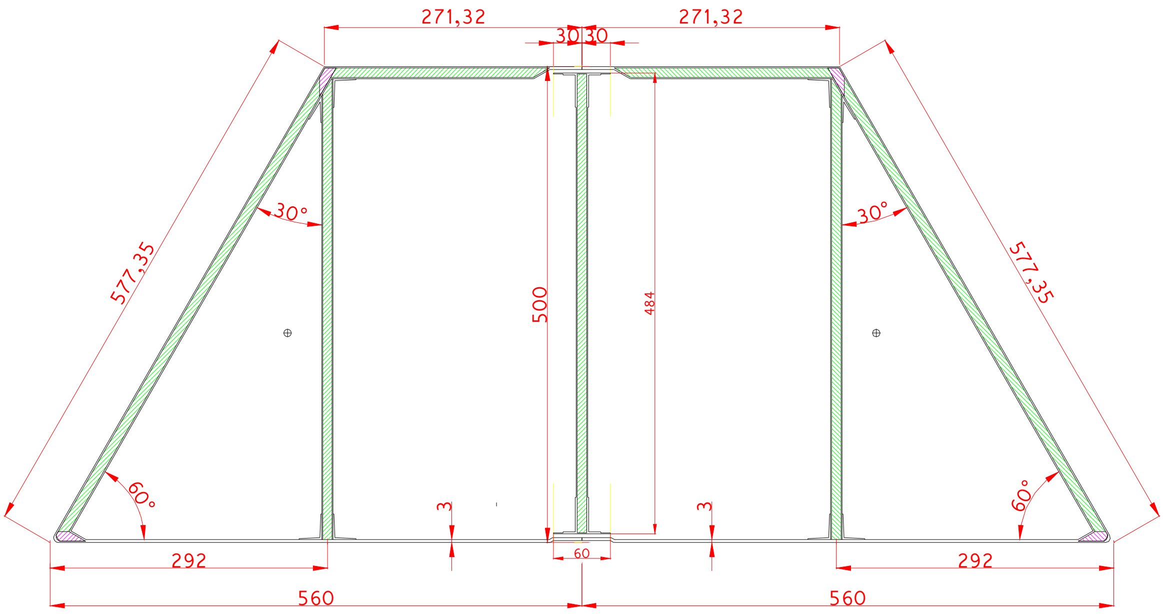
The result of the finite element analyse was a main structure with the following specifications:

A PVC core of 10 mm thickness
2 mm of laminate on each side of the front and rear wall
2 mm of laminate on each side of the top and bottom surface
1 mm of laminate on each side of the webs

This gives each 16 meter arm of the main structure a theoretical weight of 342 kg (excl. weight of tubes). In practice when build the main structure had a weight of in average app 640 kg (647 kg for the right arm and 630 kg for the left arm). The 30 kg of the extra weight per arm is the gelcoat that is not included in the theoretical weight. Another 30 kg is the weight of the bolt connection flange. The rest 240 kg is split equally between extra glass fibre in the corners due to glass fibre overlay and the fact that the PVC foam core did such more polyester than expected.

2.4.1 **Production technology main structure**

The main structure consists of 7 walls. To minimize the amount of glue connections the main structure was cast in three pieces, two identically front and back sections and one web in the middle. These three sections was glued and laminated together in two glue joints. All sections were made with the vacuum infusion technology.



2.4.2 **Future improvements**

In the future when more knowledge has been gained on how the wave impact and the forces in the WEC interact with each other a much more detailed finite element analysis can be made with a material reduction as result. Material can be moved to the edges where it gives most strength. The use of pultruded elements with a high strength will also result in lower material usage. Making the WEC wider by adding an extra row of tubes or increasing the diameter of the tubes will also increase the relatively strength of the WEC.

2.5 Structural design of tubes

The outcome of the theoretical design of tubes in a previous project was a laminate of 1.5 mm on each side of the PVC core. The thickness of the PVC core were chosen forehand to 16 mm to give the wanted buoyancy to the WEC. In the last calculations before production start the thickness of the PVC core were changed to 20 mm to increase buoyancy.

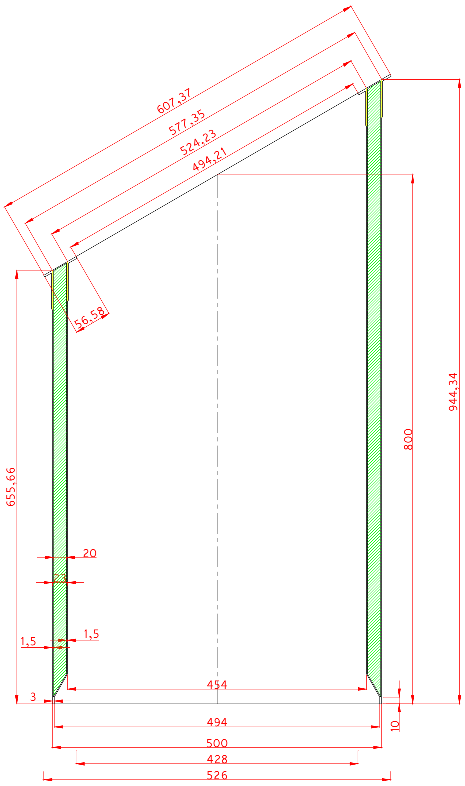
When produced the average weight of the tubes was 11.7 kg with gelcoat included.

2.5.1 Design loads

The design loads for the tubes in the previous project were a local impact of 1.365 MPa in an area of 0.00439 m^2. That is app. 600 kg in an area of 6.6 cm times 6.6 cm. The slamming effects were here chosen as design parameter.

2.5.2 Production technology tubes

The tubes were cast with the vacuum infusion technology. They were cast as a double tube that was cut over in the middle in a 30 degree cut, which gave two identically tubes.



2.5.3 Future improvements

The loads for the design of the tubes seem conservative and the real sea test should show if this assumption is correct. Looking at the scale 1:40 model the slamming doesn't seem to be very violently. The round shapes of the tubes that are tilted 30 degrees make that the waves to a certain degree slides of the WEC.

In the real sea test the structural design of the tubes was verified and it withstood all the storms. To be able to determine the correct loads for designing the tubes, more measuring equipment must be installed in some of the tubes.

2.6 Anchoring

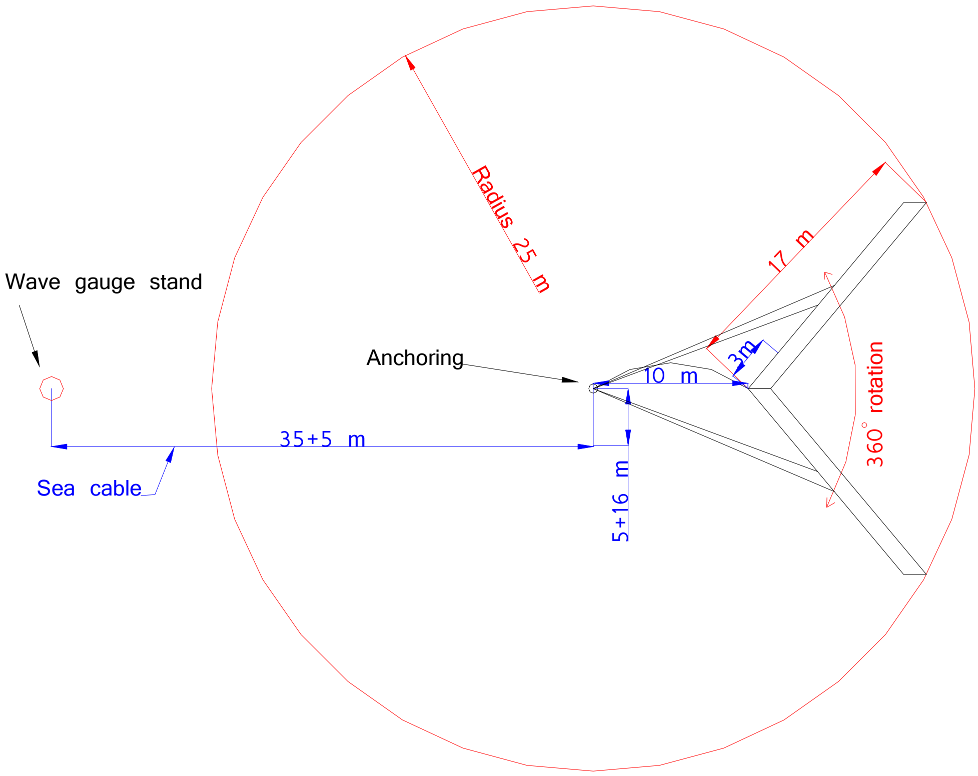
The anchoring force was in the design phase measured on the 6 m wide scale 1:40 WEC in a 50 year wave state in a previous project. The measurement was made with an anchoring with an appropriate stiffness. The anchoring force was measured to 82.54 N which in scale 1:10 is 5.28 kN (540 kg). The displacement of the 1:40 scale WEC was 1.4 m which in scale 1:10 was rounded up to 5.7 meters. The load from the wind was calculated to be app. 5 kN in scale 1:10.

In the scale 1:40 test the WEC was anchored in the tip end. In the scale 1:10 it was chosen that the anchoring points of the WEC should be in the middle of the two arms divided out on two points on each arm. This decreases the loads in each anchoring point and the load on the area of the WEC where the anchoring point is.

The WEC is very good to smooth out the forces internally whereby the anchoring forces are kept small.

2.6.1 Anchoring overview

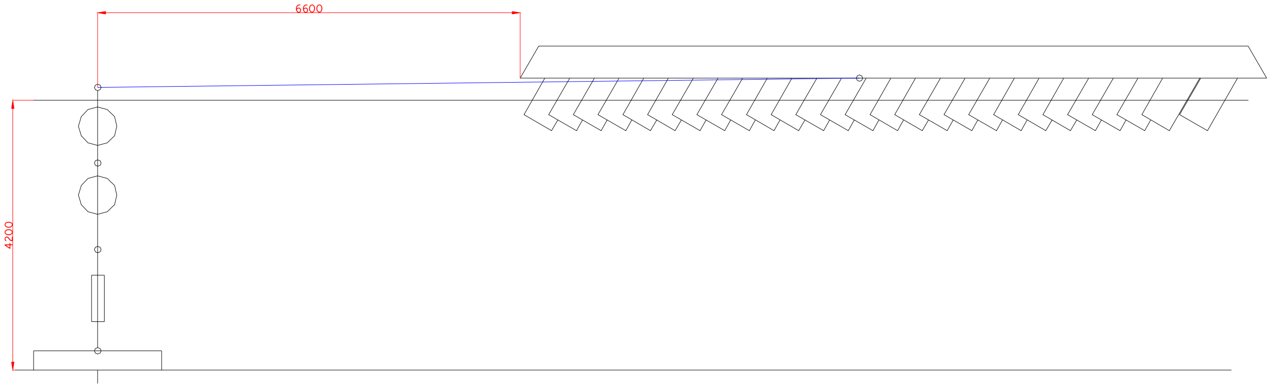
On the picture below an overview of the anchoring system can be seen. The WEC can make multiple turns around the anchoring point. The blue lines show the sea cable. The blue numbers show the cable length and not the actual physical distance.

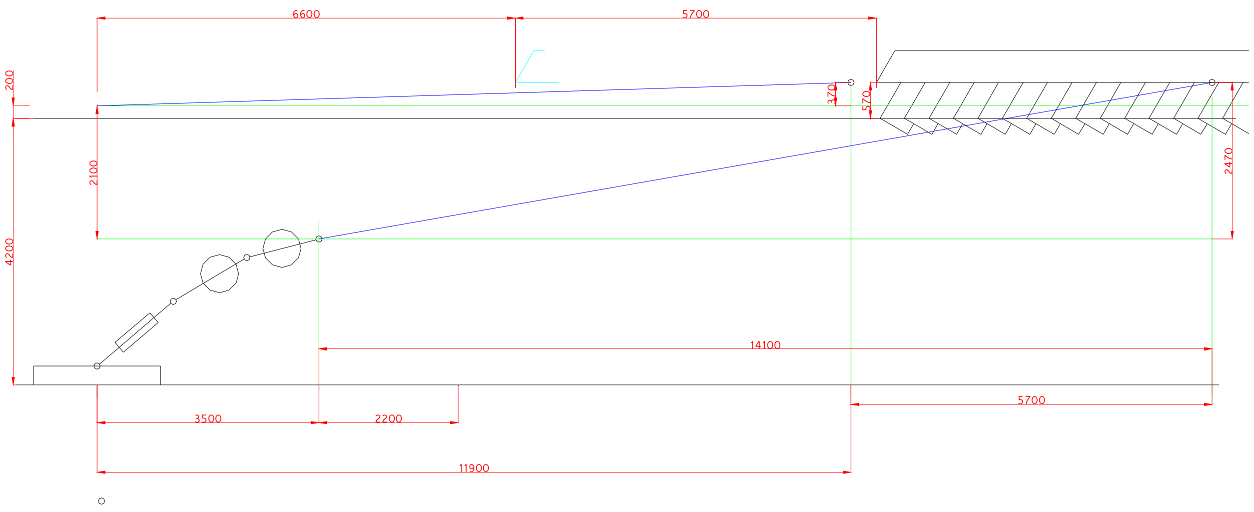


2.6.2 Anchoring principle

The anchoring principle is a 3 ton (above water) heavy concrete plate with two buoys each with a buoyancy of 110 kg. The WEC is connected to the anchoring point with an elastic line.

In the worst case scenario the WEC has a linear movement of 5.7 meters, with the 3.5 meters coming from the buoy system and the rest 2.2 meters from the elastic lines.

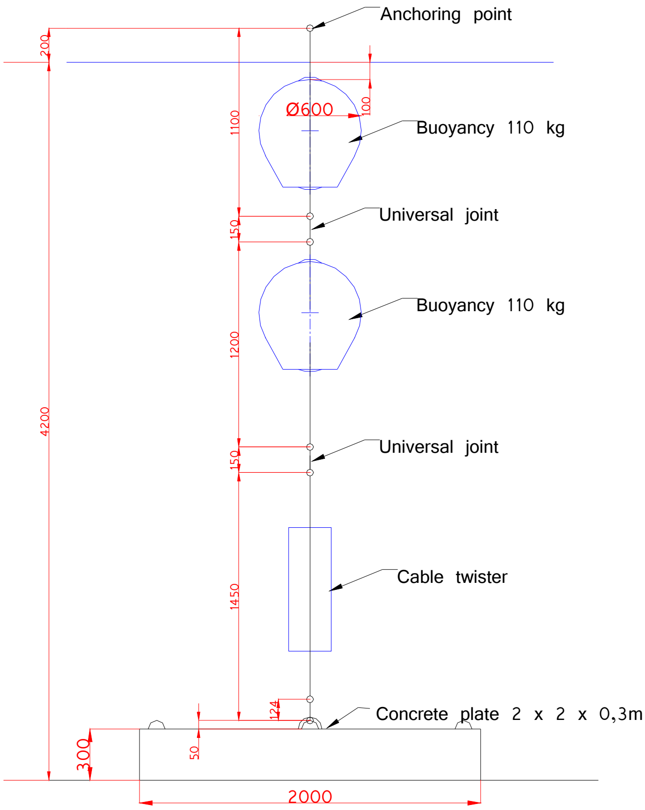




2.6.3 Anchoring buoy system

The picture below shows a detailed view of the buoyancy anchoring system. All the steel parts (rods, bolts, universal joints etc.) are made in AISI 316 stainless steel.

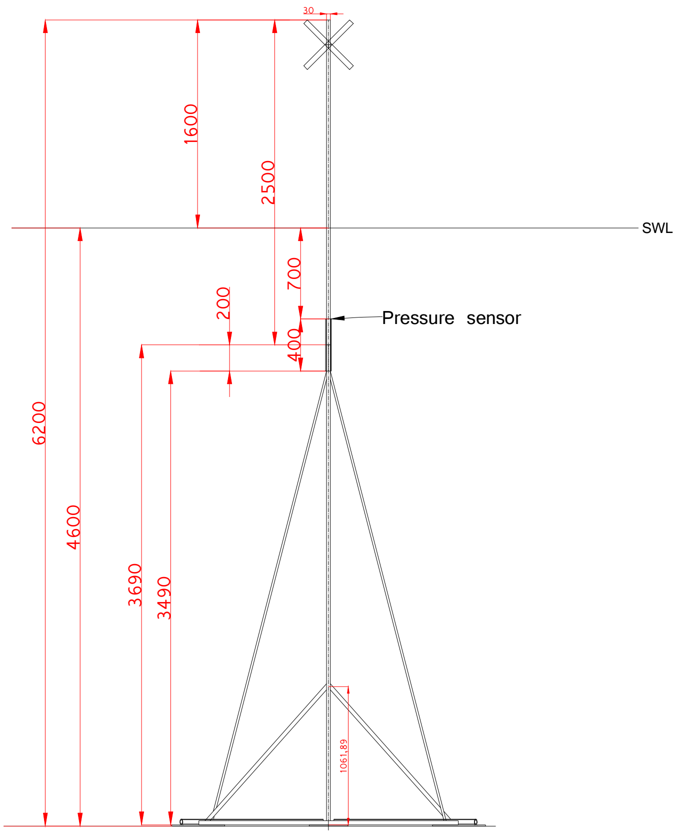
The cable twister allows the sea cable to turn +/- 10 turns from zero position. This system worked very well.



2.6.4 **Wave gauge stand**

The wave gauge stand is placed 35 meter in front of the WEC. This stand also withstood three storms without any problems. The wave gauge sensor is a 0-50,000 Pa pressure sensor and is placed 0.7 meter below sea level.

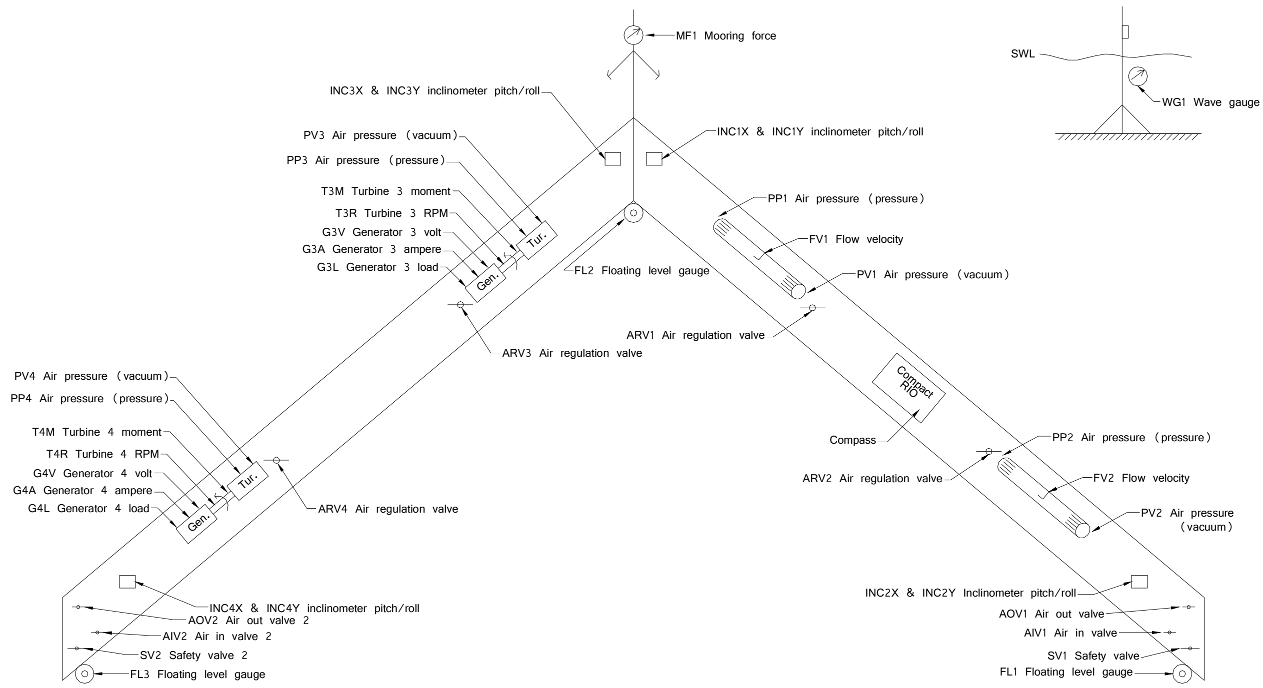
The 500 meter long sea cable from land is connected with the sea cable from the WEC at the top of wave gauge stand.



2.7 Control system

The control system consists of a CompacRIO system from National instruments. This is a standalone data acquisition system approved for marine environment. This system is also intended to be used in the scheduled scale 1:4 test.

On the picture below it can be seen where the sensors are placed. The right arm is equipped with the two flows and pressure measuring units (PP1, PV1, FV1, ARV1) and (PP2, PV2, FV2, ARV2). The control box is placed in the middle of the right arm close to the strain gauges. Strain gauges are not shown on this picture. There are 4 inclinometers (INC X, INC Y) to measure the tilt and motion of the WEC. The left arm is equipped with a "Dummy turbine" that is regulated in the same way as on the right arm, but it is prepared for installing actual turbines.



The CompacRIO system is equipped with 13 measuring modules which in total give:

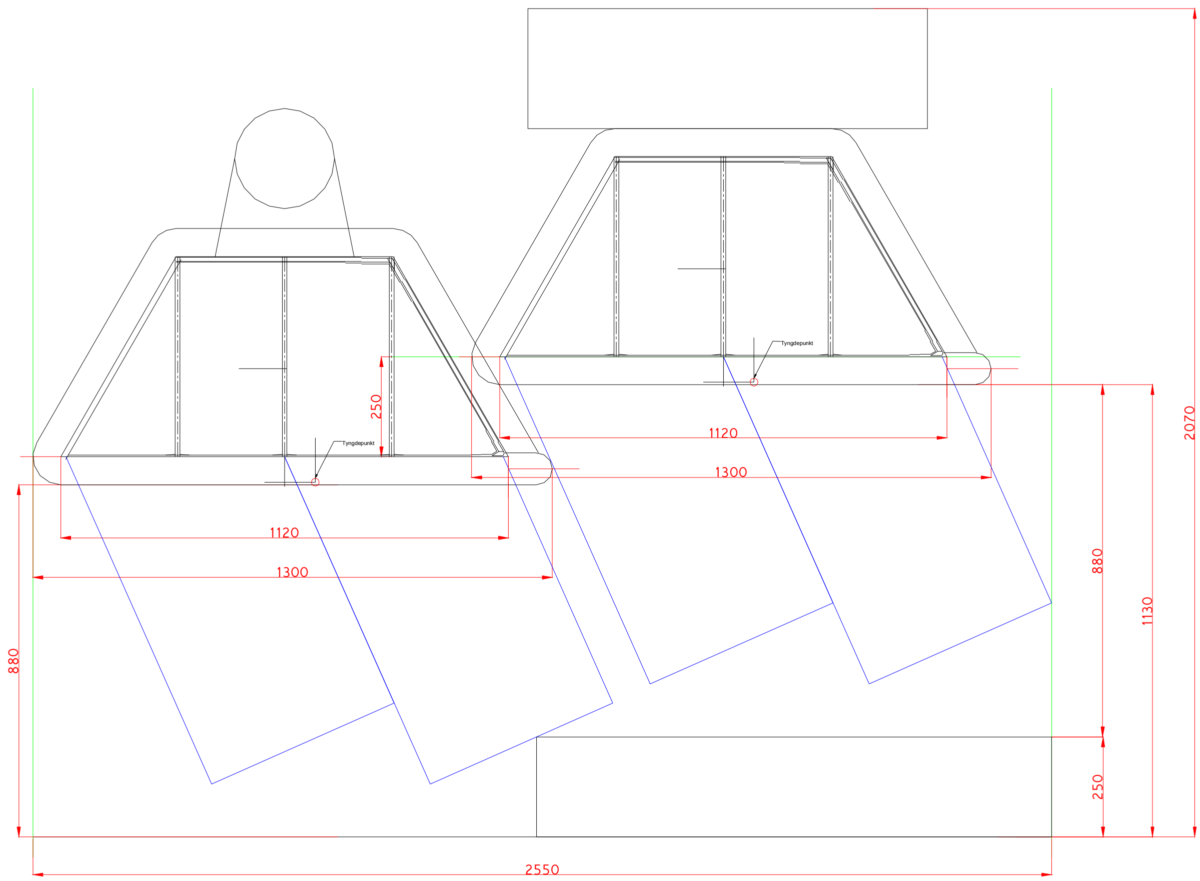
- 48 quarter bridge strain gauge amplifiers
- 8 full bridge strain gauge amplifiers
- 32 analogue input channels
- 4 analogue output channels
- 8   4-20 mA input channels
- 8 digital output channels
- 8 digital input channels

2.8 Transportation

The picture below show how the WEC was transported on the truck to the test site. By placing the WEC in this way, the width was within the max limit of 2550 mm for normal transports.

2.8.1 Road transportation

The future scale 1:4 can still be transported on the road, but only with one arm at the time. This is important because it makes it possible to manufacture it anywhere in land, far from harbours. Near full scale WEC's must be produced in connection to a harbour.



2.8.2 Launching in the sea

The concrete anchoring plate with the buoy system and the wave gauge stand was installed on July 3th 2015. The WEC was installed on July 23th 2015.

Due to some problems it turned out that the wave gauge stand was placed 5 meter too far from the wave gauge stand and had to be moved before the sea cable from the WEC could be connected.

2.9 Future improvements and tests

There has been gained a lot of experience in this project about things that worked very well and about things that can be improved and how the WEC behaviours in real off shore conditions.

The anchoring system actually worked well but it took some time to adjust the primary anchoring line in so that worked in corporation with the much stronger backup rope. This primary anchoring line (high elastic) and backup rope (very strong) has to be invested more carefully. The used anchoring system with the extractable bar can also be used in the planned scale 1:4 test but in near full scale another system is intended.

For the manufacturing of this scale 1:10 WEC there has been used the same production technology that are used by the wind turbine industri for mass production of wind turbine blades. As the main structure and the tubes has a more simpel structure than a wind turbine blade the production proces for this WEC can be automated to a higher degree than the production proces for wind turbine blades is today.

The valve system over the tubes worked very well, and as expected it still look like new as it is completely made in glass fibre and plastic that has no problems with the harsh salt sea water. Actually no improvements are intended here.

The bolt connection system that bolts the two arms together will be improved in bigger models, where another principle can be used as more space is available. On December 8th a failure in the bolt connecting system due to lose bolts was detected, and the WEC was brought on land for winter storage. A finite element analysis and an accelerated lifetime test should be performed on this system when designing a scale 1:4 WEC

There are some good strain gauge measurements from the Freja storm that will be used to make a finite element analysis to design an improved scale 1:4 WEC with relatively less material.

An optimized control strategy for the optimal energy production should be tested and developed in a tank test on the right arm of the scale 1:10 WEC and later tested on a scale 1:4 in an offshore test.

3 Cost calculations

Cost calculations still shows that this concept has the capability to be able to compete with offshore wind energy in the future, but there is still some know improvements and load conditions that have to be tested before this can be proven with certainty.

3.1 Inputs for cost calculations

The three major inputs to the cost calculation are the energy production, the cost of the device and maintenance cost. The cost calculations are based on the assumption that the known improvements are implemented when full scale serial production is reached. As the energy production measurements made in this project is not considered valid able enough, as explained earlier in chapter 1.3.1 Energy production, the energy measurements from the tank test of the scale 1:40 has been used. According to the measured and calculated results the following improvements are worked in:

The energy production is increased with 50 %. This is achieved by improvements of the aerodynamic function of the valves, the shape of the pipes and a little increasing of the diameter of the tubes. The loads are considered to be very conservative and are reduced by a factor 2. The structural design are improved by moving material to the edges where by more strength is obtained with the same amount of material. A factor 2 improvement is assumed.
By using pultruded fibre glass elements with a high glass content a factor 2 improvement is assumed.

The above mentioned improvements have to be verified in a FEM analysis of the structural design. Most of the improvements can be integrated and proven within 1-3 years. The rest will be within 5-10 years when the WEC has been in serial production for a couple of years in full scale or near full scale.

The total result of all these improvements is that the strength/load proportion is reduced by a factor 8 and the energy production is increased by a factor 1.5. When scaling up the WEC the material usage is assumed to rise in the power of four.

The actual weight of the scale 1:10 WEC is 3.0 ton. Some of this weight will not be scaled up in the power of 4. The weight of gelcoat and polyester sucked into the PVC foam will only scaled up in the power of 2. The extra weight due to overlay of glass fibre will be scaled up in the power of app 2. Other technical items like the control box, cables, motor valves etc. will be scaled up in the power of app. 1.5. All this gives a technical calculation weight of app 1,800 kg.

When scaling up the 1,800 kg scale 1:10 WEC up to full scale (10 times) the weight will be
1.8 [ton] * 1/8 * 10^4 = 2,250 ton.

Glass fibre raw material cost is set to 20,000 kr. /ton. This is the price that big glass fibre companies pay.

It is assumed that there will be build 20 WEC per year for a period of 5 years in total 100 devices.

Labour cost is set to 30,000 kr. per labour per month. It is assumed that it will take 100 labours a month to build a WEC, in total this gives 3 mio. kr. per WEC.

Production equipment cost is set to 200 mio. kr. which gives 2 mio. kr. per WEC. As the production is relatively easily to automate, this cost is set high.

Rent and other IPO's is set to 40 mio. kr./year which gives 2 mio. kr. per WEC.

The profit is set to 3 mio kr. per WEC.

The installed power of the WEC is set to 1.44 MW [*1] times 1.5 in total 2.16 MW.

The yearly production is set to 3.43 GWh/year [*1] times 1.5 in total 5.15 GWh/year.

Installation cost of the WEC at the site is set to 1 mio. kr.

Controlling and regulations technique cost is set to 1 mio. kr.

Maintenance cost is set to 0.5 mio kr. per WEC per year for 20 years in total 10 mio. kr.

Note: [*1]. Are results from the scale 1:40 tank test.

3.2 Full scale WEC costs

Based on the cost calculation inputs this gives the following simple kWh cost:

Basis for calculations		
Cost of installed power	2,500	kr./kW
Glass fibre raw material	20,000	kr./ton
Weight of WEC	2,250	ton
Labor cost	30,000	kr./labor*month
Labor per device	100	labor*month
Installed power	2.16	MW
Yearly production	5.15	GWh/year

Cost of WEC		
Glass fibre raw material	45,000,000	kr.
Labor cost	3,000,000	kr.
Production equipment	2,000,000	kr.
Installed power cost	5,400,000	kr.
Controlling and regulation	1,000,000	kr.
Rent and other IPO	2,000,000	kr.
Installation cost at site	1,000,000	kr.
Maintenance (20 years)	10,000,000	kr.
Profit	3,000,000	kr.
Total cost of WEC (20 years)	**72,400,000**	**kr.**

Simple kWh cost		
Cost of WEC (20 years)	72,400,000	kr.
Energy production (20 years)	103,000,000	kWh
Cost per kWh	**0.70**	**kr./kWh**

The simple kWh cost is without financial cost and cost of bringing the electricity ashore. Depending on the linearity of the future feed in tarifs, the kWh cost with financial cost would be around 0.9 kr./kWh.

In the future there might be other improvements than the known one that has been stated here, that could bring the kWh cost price further down.

Although this cost calculation is based on known and stated improvements there is always an uncertainty in the result. It could turn out to be 0.60 kr./kWh or 1.40 kr./ kWh. But after the planned structural design of the scale 1:4 and the suggested energy measurement tank test of the right arm the uncertainty in the COE will probably be reduced to +/- 0.20 kr./kWh. And when this future scale 1:4 WEC is build and tested offshore the uncertainty will be reduced further.

The in Denmark used standard spreadsheet for calculating the COE of WEC's gives a price of 1.29 kr./kWh. In this price is an internal interest of 5% calculated in. This spreadsheet is enclosed to this report as "COE_spreadsheet.xlsx"

4 Conclusion

This project has been carried through as descreibed in the proposal, but with delays and without the structural designs of a scale 1:4 WEC.

Production technology was developed; the WEC was build, launched in the sea, tested for 4½ month, survived 3 big storms and has now been brought ashore. Some good load measurements were collected during the Freja storm that shall be used to design a scale 1:4 WEC. The anchoring system has proved its capabilities, but with known possibilities for improvements.

More energy measurements should have been carried out, but this was not possible due to lack of time. It is strongly recommended that a tank test for measuring energy production in all different sea states under controlled circumstances is performed in a future project.

The cost calculation shows that a simple kWh price (without interest) at 0.70 kr./kWh is reachable with improvements that has been stated out. Other improvements in the future might decrease kWh cost further. The standard spreadsheet for calculating the COE of WEC's gives a price of 1.29 kr./kWh with the internal interest of 5 %.

The major parts of the production technology has been developed, tested and used in practice. This has performed a solid background for taking the decision of building a scale 1:4 in a later project and to determine what the cost will be.

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