HIWAVE-3 PUBLIC REPORT – STAGE 3 GATE REVIEW

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REVISION SUMMARY TABLE

Revision	Date	Modifications	Edited by	Verified by	Approved by
-	2018-06-30	Creation	CPO team	J. Maillet	P. Möller
A	2018-08-22	Comments from review	J. Maillet		P. Möller

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1. INTRODUCTION

For Wave Energy Converters (WECs) projects to be successful, their performance need to be compared against other offshore renewable energy technology alternatives. Wave Energy Scotland (WES), Energimyndigheten and InnoEnergy have identified a number of target outcomes and associated metrics against which WECs should be compared to determine their performance and competitiveness.

The primary purpose of the HiWave project is to reach a reliable and proven WEC design that can produce energy at low cost and survive the conditions at any potential wave energy site. This deliverable presents the stage gate review after the completion of the Stage 3 HiWave project by comparing the HiWave project results to its objectives using target outcomes and metrics defined before starting the project.

The first section after this introduction gives background information about the HiWave project. Section 3 gives an overall conclusion on the Stage 3 program. Section 4 presents the Stage gate review and discuss HiWave main results and outcomes.

2. BACKGROUND INFORMATION - HIWAVE PROJECT

The primary purpose of the HiWave project is to reach a reliable and proven WEC design that can produce energy at low cost and survive the conditions at any potential wave energy site in European waters. The CorPower Ocean Power Take Off (PTO) is built into a point absorber hull and attached to the sea bed with a taut leg mooring. The WEC operates in resonance with the incoming wave using phase control technology and can thus extract a significantly larger amount of energy compared to a passive floating WEC device. The phase control function performed by the patented WaveSpring technology can be tuned so that the buoy becomes transparent to energetic storm waves by detuning the frequency response. This results in the WEC having minimized motion, loads and power absorption in large waves, causing less tension and stress in the mooring and WEC structure, providing survivability without the need of large dimensions of the system. The combination of such load shedding reducing peak loads with the strong amplification of power capture in regular waves results in a WEC with higher structural efficiency (output/mass, energy/force) compared with existing WEC designs. This lightweight design and its surface operated mooring connection allows the WEC to be swiftly installed and replaced using small workboats without any intervention needed from diver or work class ROV, reducing OPEX cost.

The HiWave program was performed by a consortium consisting of CorPower Ocean (CPO), Iberdrola Engineering & Construction (IEC), the European Marine Energy Centre (EMEC), WavEC Offshore Renewables and the University of Edinburgh (UEDIN). CorPower Ocean was the project lead responsible for device development and testing. EMEC was responsible for risk-assessment and best practice support on deployment and testing, Iberdrola Engineering & Construction for design basis and certification, and University of Edinburgh and WavEC for LCOE and numerical modelling. The Stage 3 activities were supported by Wave Energy Scotland, KIC InnoEnergy and the Swedish Energy Agency.

The market introduction of CPO’s WEC technology follows a structured five-stage verification process, established as best practices for ocean energy technology by the IEA-OES, ETIP Ocean and Wave Energy Scotland. It involves step-wise validation of survivability, performance, reliability and economics starting with small scale prototypes in Stage 1, continued by sub-system testing and then fully integrated WEC in increasing scales up to array demonstration in Stage 5. The purpose is to address risks in a managed way early in the product development process, where costs are still limited due to smaller device scale and team size. The current Stage 3 program with ocean deployment in Scotland follows the prior testing of multiple prototypes in smaller scales performed in Portugal, France and Sweden since 2012, and thousands of hours of numerical simulation work.

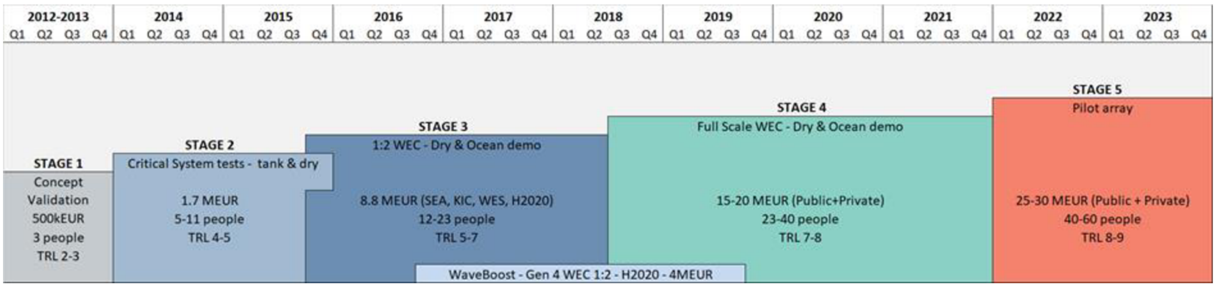


Figure 1 CPO's market introduction plan in 5 stages according to IEA-OES/EquiMar best practice

By June 30th 2018 CorPower concluded the Stage 3 testing by finalizing the ocean deployment and retrieving the C3 WEC from EMEC's Scapa flow site in Orkney, and is now reporting the outcomes while preparing for the next phase of full scale demonstration of the technology in collaboration with leading European partners across the value chain. The Stage 3 program has taken a large scale (1:2) Wave Energy Converter system through structured verification by dry testing in CorPower's machine hall facilities in Stockholm, followed by ocean deployment at the European Marine Energy in Orkney (Scotland).

Figure 2 Stage 3 WEC in CorPower dry Hardware-in-the-loop testing facility, Stockholm (Sweden)

During the test period EMEC was an integral part of the HIL rig testing and travelled to Stockholm on several occasions to work alongside the CPO team. HIL acceptance testing (with & without WEC attached) was completed with EMEC prior to commencing WEC performance testing; upon completion of performance testing, data and numerical model calibration materials were shared with EMEC in order to obtain a Performance Statement.

After verifying the specified functions, performance and availability through dry testing between March and November 2017 the WEC was transported to Orkney where it underwent pre-deployment checks and final preparations prior to deployment at the Scapa Flow test site in January 2018.

Deployment in the Ocean Environment

During the first 6 months of 2018, the C3 WEC has been tested in the ocean at the EMEC Scapa Flow site, Orkney. The purpose of the campaign was to verify the survivability, functionality and performance of the fully integrated WEC system in a relevant ocean environment. Having an extensive mapping of the device behavior and performance over a wide range of sea conditions from the dry testing, the key purpose of the wet testing was to verify the practical functionality of the device in the ocean environment, including auxiliary support functions such as station keeping, tidal range regulation, power export in microgrid configuration, communication to shore, remote control and associated operations and maintenance methods, while verifying motion and power production performance in a number of relevant sea states.

Following completion of dry testing, the prototype device was transported by road and sea to Orkney (Figure 3) where testing was planned at the EMEC Scapa test site, approximately 600 m offshore (Figure 4). The European Marine Energy Centre (EMEC) is a test centre, managing several test locations in Orkney. EMEC was established in 2003 to provide developers of wave and tidal energy converters with open sea testing facilities. The Scapa Flow site was selected for C3 ocean deployment due to its sheltered location which offered a wave resource suitable for the 1:2 scale device, and for access to nearby port facilities and local marine operators with previous experience of the sector.

Figure 3. C3 arriving on trailer in Orkney (Scotland)

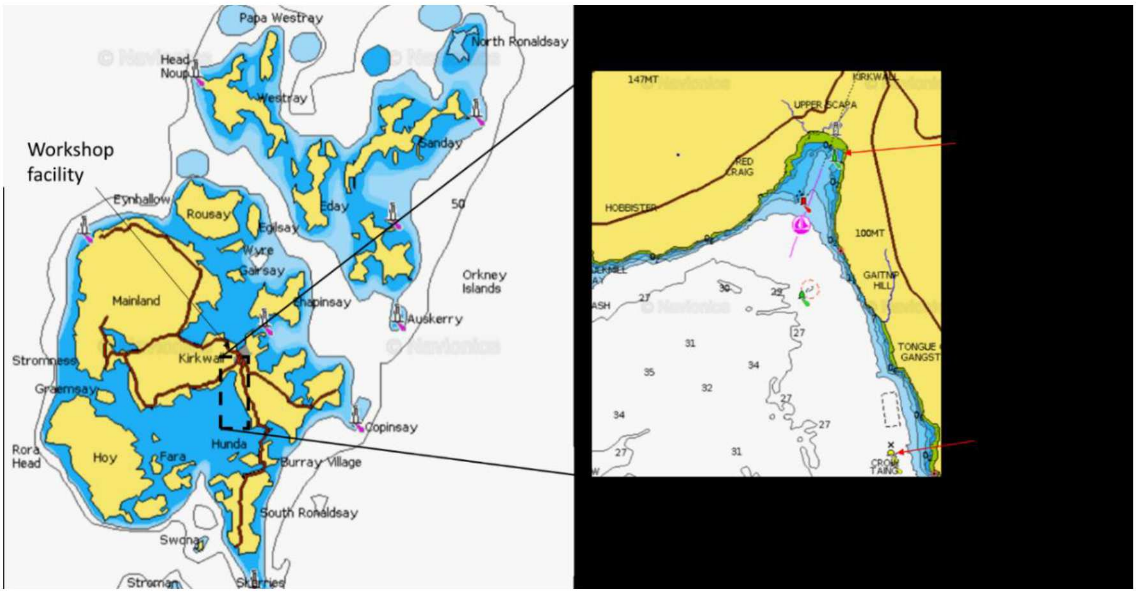


Figure 4. CPO test location, Orkney (Navionics website)

A gravity base anchor consisting of 8 concrete blocks arranged on a steel base plate was already on the EMEC test site. CPO commissioned the design and fabrication of a cross frame and winch to install over the concrete blocks, enabling anchoring of the WEC and tidal regulation of the device to maintain its position in the water as the tide changes, see Figure 5.

Figure 5. Anchor bracket with sub-sea winch and dynema tether.

As part of the test programme, EMEC and CorPower commissioned and installed a test support buoy (TSB), i.e. a micro-grid to support off-grid testing which is housed within a 10 foot container and installed on a 3-point moored pontoon (Figure 6).

Figure 6. Microgrid contained installation and 300m cable lay between WEC and Microgrid.

The micro-grid delivers power to and absorbs power from the WEC, which it is connected to via an electrical umbilical, using SMA Sunny Island inverters and TesVolt batteries. It also powers the winch system which is controlled by a hydraulic power unit (HPU) on the TSB, connected by approximately 200 m of hydraulic cables and an encoder cable. This solution (anchoring and tidal regulation) is not intended for subsequent iterations of the device, i.e. its sole purpose was to enable C3 device testing. The experience developed with the floating microgrid operation is relevant for future off-grid installations, such as aquaculture or oil & gas applications where remote installations may be powered by CPO WECs while floating microgrid units house energy storage.

The WEC was periodically brought to shore during the test period, demonstrating the CPO strategy for the rapid replacement of entire units rather than costly offshore maintenance.

During the ocean testing period, CPO had access to an onshore workshop located in Kirkwall (Figure 7) where the device could be housed and prepared prior to deployment, and periodic maintenance conducted during the test period. Detailed method statements were developed in close collaboration with Orkney marine operators, lifting contractors and EMEC, supported by lessons learned and best practice from the sector. CPO's operations team also has significant field experience from previous marine energy projects.

Figure 7. Onshore workshop in Kirkwall, Orkney used in the Stage 3 program.

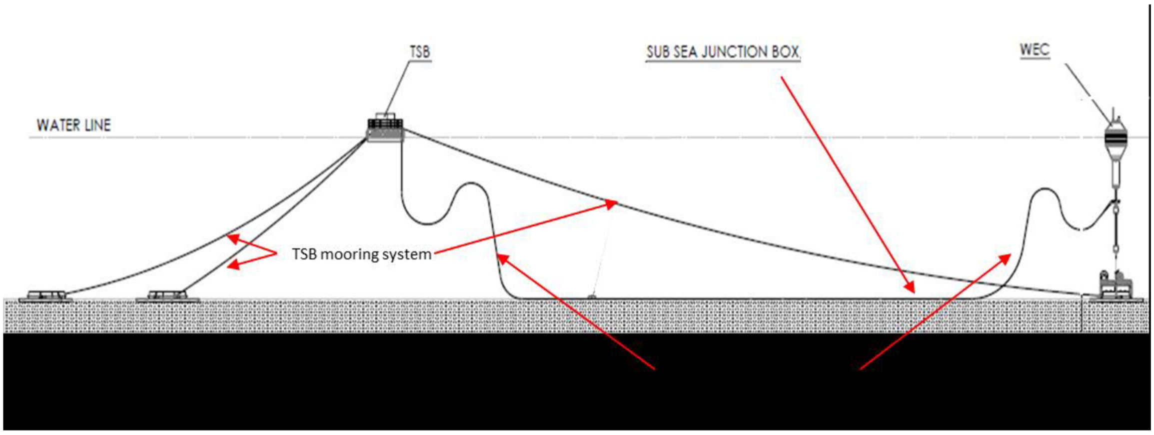
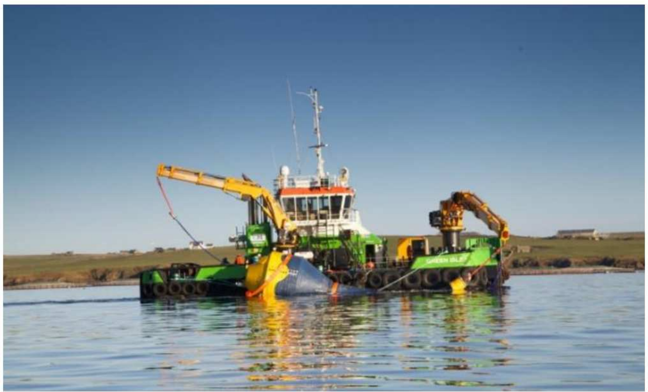


Figure 8. Overview schematic of installed WEC and TSB

For deployment, typically the WEC was transported to Scapa Pier by lorry and craned directly into the water by a multicat work vessel, which was subsequently used to tow it to the test site. A summary of the deployment sequence is given by

Figure 9 below. The tow to site took approximately an hour from Scapa Pier. Once the multicat was attached to a 3-point moorings, the mechanical connection to the mooring system was made. Subsequently, the electrical umbilical running to the TSB was retrieved and the electrical connection made with the WEC. The junction box was lowered to the seabed and the WEC winched into position. The multicat came off the moorings, retrieved them and departed site. In order to retrieve the device, the process was reversed.

A. WEC lift into water by the multicat's on-board crane



B. Tow to site

Electrical connection

D. WEC installed

Figure 9. WEC installation sequence

3. STAGE 3 PROGRAM OVERALL CONCLUSION

The dry and ocean test campaigns of the C3 WEC have confirmed the design principles and performance of this new type of load-shedding phase controlled WEC. The effect of detuning this compact point absorber type WEC in storm to minimizing loading and then tuning it in regular wave conditions to amplify power absorption has been proven. This new function brought to wave energy can be compared to wind turbines pitching the blades to control the loads.

Key performance verification of the Stage 3 program includes:

- Performance of detuned ***Survival mode*** verified. The transparent storm protection mode based on frequency detuning was found very effective in minimizing motion and loads on the device in storm waves.
- Performance of ***Tuned (resonant) mode*** verified. WaveSpring phase control delivered the projected amplification of motion and power capture performance.
- **Power production** in ocean was consistently slightly higher than predicted by the simulation models.
- Wave spring **phase control** technology had robust operation and delivered 99% efficiency at rated loading. The amplified C3 motion has been provided without real time wave information, proving the ability of WaveSpring to control the timing of the buoy motion without information on wave height, period, direction or timing of individual waves.

Figure 10 C3 WEC operating in waves up to 4m in detuned survival mode

Dry test data from the HIL-rig covered the full range of relevant sea states, ocean test data covered most of the sea states that can be encountered in Scapa flow.

As a result of the C3 dry and wet testing with related model calibration, the forecasted performance of full-scale C4 and C5 machines has been slightly increased compared to the targets set before starting Stage 3.

Dry testing has been found effective for characterizing and stabilizing a WEC prior to ocean deployment. The rigorous HIL-rig testing delivered a WEC that had satisfying availability during ocean testing, that performed the specified functions and met the projected performance.

A majority of engineering efforts spent during the ocean test campaign was focused on the auxiliary sub-systems including the microgrid, the tidal adjustment system and the anchor before said subsystems delivered the specified functions with reliability. A key lesson learned for next ocean deployment is to perform more rigorous pre-qualification on such auxiliary subsystems prior to integrating them with the WEC(s).

Both dry and ocean testing have resulted in valuable lessons-learned and in conceptual design improvements which help pave the way to achieving the Stage 4 objectives.

The results from Stage 3 provide to following key metrics and projections for the next stages of product verification and commercialization of the technology:

Figure 11 Summary of key metrics and projections for the technology in Stage 4 and onwards

High level **outcomes** of the Stage 3 program included:

1. Verified that the CorPower WEC technology provides a step-change improvement in absorption performance, conversion efficiency and CAPEX over current state-of-the art in wave energy.
2. Verified the reliability, operability and scalability of the solution.
3. Validated a clear and realistic path to LCOE below 150 GBP / MWh after having less than 200MW installed.
4. Took advantage of the best available guidance and methodology with respect to risk management, test methods and standards from the European Marine Energy Centre (EMEC).
5. Developed and commissioned an advanced rig for dry Hardware-In-the-Loop (HIL) testing of resonant WECs. The rig demonstrated the capability of accurately simulating wave loading over the full range of sea states, and the instrumentation and associated data processing provided detailed characterization of WEC performance.
6. Developed methods for dry qualification of all key WEC functions in the HIL-rig prior to wet-testing, which resulted in a relatively mature and stable C3 prototype with good availability during ocean testing.
7. Verified the target metrics for the C4 full scale WEC, by detailed numerical models that were calibrated by the dry test and wet test data.

4. STAGE 3 GATE REVIEW – TARGET OUTCOMES & KEY METRICS

This section presents the Stage gate review and discuss HiWave main results and outcomes. The following subsections assess the HiWave project results using the different target outcomes and related metrics.

4.1. AFFORDABILITY

The affordability of a project can be determined using a number of metrics. In this project, it is primarily evaluated using Levelized Cost of Energy (LCOE), which indicates the average cost of the electricity produced over the lifetime of a project. The LCOE is a widely used indicator to evaluate the attractiveness of energy generation from a defined source and to compare it to other alternative energy sources. To define the LCOE of a specific project, the cost to build, install, operate, decommission the asset, together with the total energy output of the assets over it lifetime are used. LCOE is defined in terms of the present value of CAPEX, OPEX, Decommissioning costs and Energy yield, see equation (1):

$$LCOE = \frac{PV(CAPEX) + PV(OPEX) + PV(Decommissioning\ costs)}{PV(Energy\ yield)} \quad (1)$$

4.1.1. LCOE

The LCOE work in the HiWave project has been undertaken using an economic model developed by the University of Edinburgh (UEDIN), which is referred to as the HiWave Model, building on experience developed through UEDIN’s work on previous European funded projects including SIOcean, DTOcean and OPERA.

The CPO LCOE model’s results correspond closely to the HiWave Model’s results, with neutral scenario learning rates applied. It is estimated by both models, with neutral scenario learning rates, that a LCOE of:

- €150/MWh could be reached by 120MW cumulative installed capacity (generation 9)
- €100/MWh could be reached by 500MW cumulative installed capacity (generation 11)
- €50/MWh could be reached by 7.4GW cumulative installed capacity (generation 15)

The LCOE results thus validate that there is a realistic path for the CPO WEC farm concept to offer LCOE below 150GBP/MWh after having less than 200MW installed, meeting the affordability target of the HiWave project. The projections for achieving €100/MWh and €50/MWh are considered very competitive within the ocean energy sector, and shows a path for ocean energy to compete with other more established renewable energy sources.

The following parameters have been used in these LCOE projections:

Based on LCOE Model v1.28	**Generation**	**G1**	**G2**	**G5**	**G7**	**G8**	**G9**	**G10**	**G11**	**G12**	**G13**	**G14**	**G15**	**G16**	**G17**
Project Lifetime	**Years**	n/a	n/a	21	22	22	23	23	23	24	24	24	25	25	25
Installed capacity (cumulative)	**[GW]**	0,00025	0,0009	0,007	0,029	0,06	0,12	0,23	0,5	0,9	1,8	3,7	7,4	15	29
Installed # devices (cumulative, approx)	**[#]**	1	3	22	84	166	331	634	1 240	2 392	4 696	8 983	17 556	34 312	67 825
Farm size assumed	**[MW]**	0,25	0,9	10	15	50	50	80	200	300	400	700	1000	1500	1500
Discount rate	**[%]**	n/a	n/a	9%	8%	7%	7%	6%	6%	6%	5%	5%	5%	5%	5%

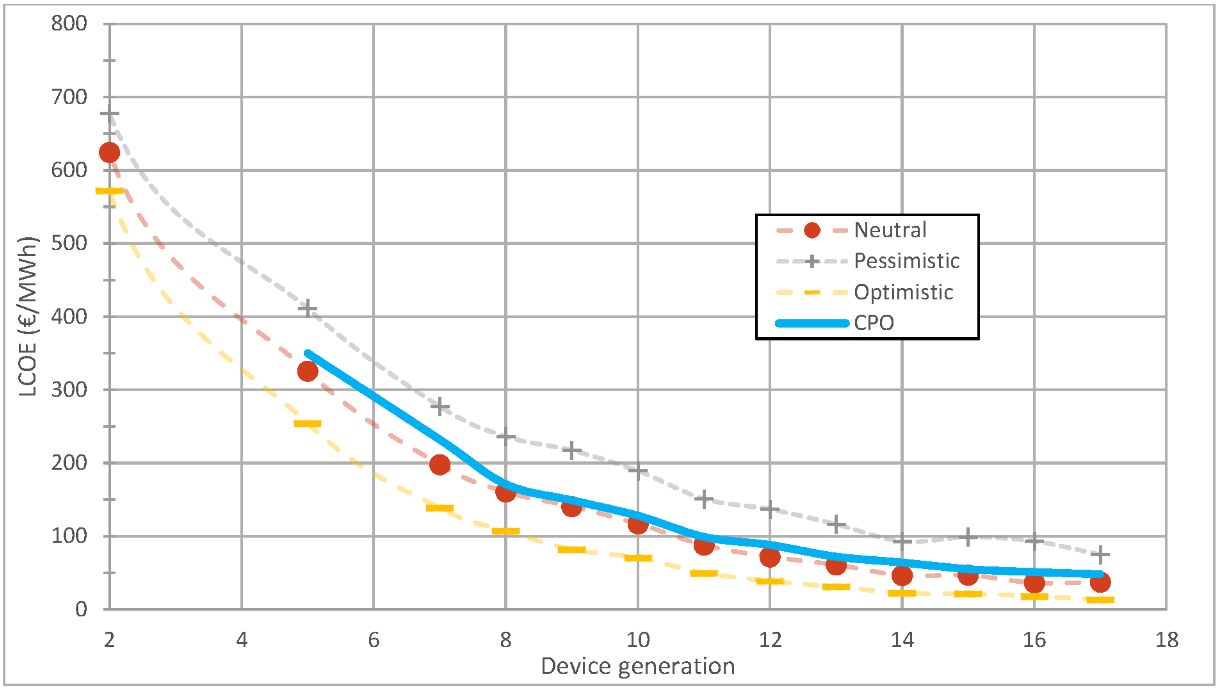


Figure 12 LCOE for UEDIN neutral, pessimistic and optimistic scenarios compared with CorPower Ocean Forecast

4.1.2. CAPEX

As presented above, the CAPEX of WEC farm project have a direct impact on the affordability of the project. With the HiWave project CPO was aiming to prove its WEC concept of using the proprietary Cascade Gear unit, Pre-tensioning Module, WaveSpring-module and Generator configuration with dual flywheels.

- A total of 9,117,108SEK were spent for the procurement of the C3 PTO unit (excluding Mooring system and umbilical), equivalent to 974,726€ or GBP707,495 (conversion using average exchange rate of 2015 from the European Central Bank). Note that this amount includes the procurement of the C3 hull.
- Non-recurring engineering (NRE) costs related to the fabrication of a first-of-a-kind single device are included in the costs figures, which at this stage of development represent a significant share of the CAPEX, meaning that a 2nd unit of the same kind would have a significant CAPEX reduction;
- The LCOE work undertook in the HiWave project looked at future cost projections. Results have shown a total WEC CAPEX of 1,84M€ or 1,63MGBP for the first full-scale unit, the C4 WEC and 4,1M€/MW or 3,3MGBP/MW after 58MW installed base (equivalent to generation 8).

By designing, procuring, manufacturing and testing its C3 PTO kit CPO was able to reach the CAPEX target of the HiWave project. Proving its WEC technology in 1:2 scale in ocean testing has also established the path for attaining the stage 4 targets of reduced CAPEX (First full scale unit < 2M GBP and CAPEX / MW <5 M GBP after 50MW installed base).

4.1.3. OPEX

As presented above, the OPEX of WEC farm project have a direct impact on the affordability of the project. With the HiWave project CPO was aiming to prove its concept of having small light-weight devices allowing the use of low cost vessels, reducing the O&M-cost.

A total of 6,155MSEK were spent for the OPEX associated with the HIL-rig and ocean testing of the C3 WEC unit, equivalent to 600,6k€ or 529,2kGBP. OPEX includes the spending for marine operations, insurance (land & ocean operations, transport, etc.), WEC transport from Sweden to test site in Scotland, test site lease, NRE and O&M related services and contracts, etc;

- The LCOE work undertook in the HiWave project looked at future cost projections. Results have shown a total OPEX of 160kEUR/MW/year after 230MW installed (equivalent to generation 10) and

91kEUR/MW/year after 460MW installed (equivalent to generation 11), being respectively 4,5 and 2,9% of the total project CAPEX.

By successfully installing, commissioning and operating the C3 WEC unit during the ocean demonstration project CPO has been able to get close to the expected OPEX target of the HiWave project (C3 OPEX <500kGBP, exceed by less than 6%). Proving its WEC concept in 1:2 scale in ocean testing has also established the path for attaining the stage 4 targets of reduced OPEX (OPEX < 4% of farm CAPEX after having 1000 units / 270MW installed).

4.2. BANKABILITY

A key enabling factor to becoming successful is to ensure that CPO can provide a bankable wave energy product, requiring performance, reliability and cost data for the technology in array operation with third party certification. The verification package provided will be a critical component of the Stage 4-5 program to enable project developers to present attractive offerings in the financial markets and achieve financial close on larger scale commercial arrays. For the Stage 3, the objective was to reach a Statement of Feasibility from a 3rd party certification body, as the first step toward prototype certification and type certification required to achieve warranty provisions desired for commercialization.

DNV GL was awarded by Iberdrola Engineering & Construction for the “Prototype Certification (WES Stage 3)” tender. The 3rd party activities of this project were to provide an independent and systematic review of the design and manufacturing leading to assurance of ½ scale Prototype integrity as well as fulfilling the objectives of the HiWave Project (delivering of a highly reliable PTO solution using innovative control technology offering a step-change improvement in performance and cost to the wave energy sector).

DNV GL has verified the Certification Basis, Technology Assessment, Failure Mode Identification and Selection of Qualification Methods and evaluated the main challenges of the technology. The CorPower Ocean technology has been considered feasible and thereby suited to further development and future certification according to DNV-OSS-312 with due consideration of the Certification Plan.

4.3. MANUFACTURABILITY

CPO have partnered with a number of SMEs, large companies, universities and research institutions to ensure that both the vertical and horizontal value chain is approached. In the HiWave project we have had the benefit of working with many supply chain partners considered leaders in their respective fields, who have contributed significantly in terms of both knowledge and experience to the company. The demonstration activities in Orkney have added unique knowledge from local ecosystem who have had first-hand experience from more ocean energy deployments than anywhere else in the world, which, in turn, has provided the project with invaluable lessons learnt. Key partners across the European value chain include:

Figure 13 CorPower partners

During Stage 1 & 2 and with the completion of Stage 3, CPO has been able to reach the expected manufacturability target of the HiWave project by developing successful manufacturing procedures and partnerships that will carry over to Stage 4 and beyond.

For the Stage 4 program CPO will introduce a new methodology of parallel dry testing of PTOs (drive train) using a land-based test rig with simulated wave loading and ocean testing of the wet kit (buoy, moorings, anchor, connectivity) to debug and stabilise the respective sub-systems before final integration and to ocean test the full WEC system, thus de-risking the ocean deployment phase. The wet-kit demonstration will be performed through the UMACK project, project being the first Scottish-Swedish partnership secured for the Stage 4 demonstration. The UMACK project is co-funded by Scottish Enterprise and the Swedish Energy Agency through the Ocean Energy ERA-NET Cofund, and will involve CPO, TTI Marine Renewable Ltd, The University of Edinburgh, Sustainable Marine Energy Ltd and the European Marine Energy Centre.

4.4. INSTALLABILITY

During the first three offshore installations, detailed record of timings of each step was kept to facilitate future planning and ensure scheduling estimates were kept. WEC installation was an activity repeated three times during the period January – April 2018 and it can be seen from Figure 14 that over the three installations, the difference between planned and actual timings reduced and, with explanation for steps that took longer, the time it took to complete each step typically decreased. This occurs as the same key personnel were involved in the activity each time and minor modifications were made to equipment to improve the installation process.

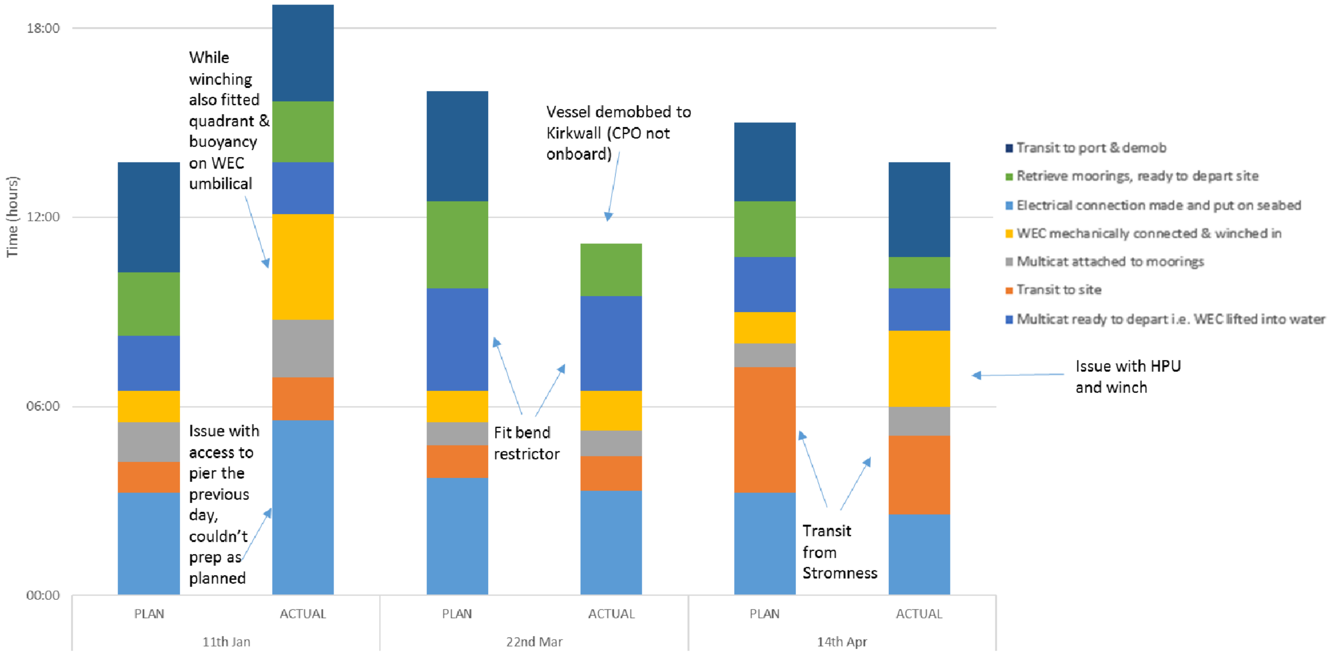


Figure 14 Stepwise C3 installation timings, comparing planned vs actual and learning through experience

To further analyse the actual timings required of each step and compare the three WEC installations on equal basis, the following assumptions were made:

- On the 22nd of March it is assumed that the transit to port and the demobilization occurred and took the same amount of time as during the third deployment, namely 3 hours;
- On the 14th of April it is assumed that the transit to site departed from the same location as the two first deployments, namely from Scapa peer instead of Stromness. Thus, it is assumed that the transit from site took the same amount of time as during the second deployment, approximately 1 hour.

The details timings and assumptions made for the analysis are presenter in the below table. Duration marked with (*) are the ones where actual durations have been modified and assumptions made, as presented above.

Based on the installation duration of the three WEC installations it can be seen that the second installation duration decreases by 24% compared to the first installation, the third installation duration decreases by 34,2% compared to the first installation and by 12,9% compared to the second installation.

Table 1 Stepwise C3 actual installation durations

Up to point	**11th Jan**	**22nd Mar**	**14th Apr**	
Multicat ready to depart i.e. WEC lifted into water	05:33	03:20	02:35	
Transit to site	01:22	01:05	01:05*	
Multicat attached to moorings	01:50	00:50	00:55	
WEC mechanically connected & winched in	03:20	01:15	02:25	
Electrical connection made and put on seabed	01:40	03:00	01:20	
Retrieve moorings, ready to depart site	01:55	01:40	01:00	
Transit to port & demob	03:05	03:00*	03:00	
Total Duration (hour)	**18:45**	**14:10**	**12:20**	
Compared to	n/a	1st deploy.	1st deploy.	2nd deploy.
Time improvement (%)	**n/a**	**-24,4%**	**-34,2%**	**-12,9%**

Figure 15 below illustrates the actual installation timings for the three WEC installations. For the second and third installations, the steps where assumptions were made are represented with a white background and coloured border in the histogram.

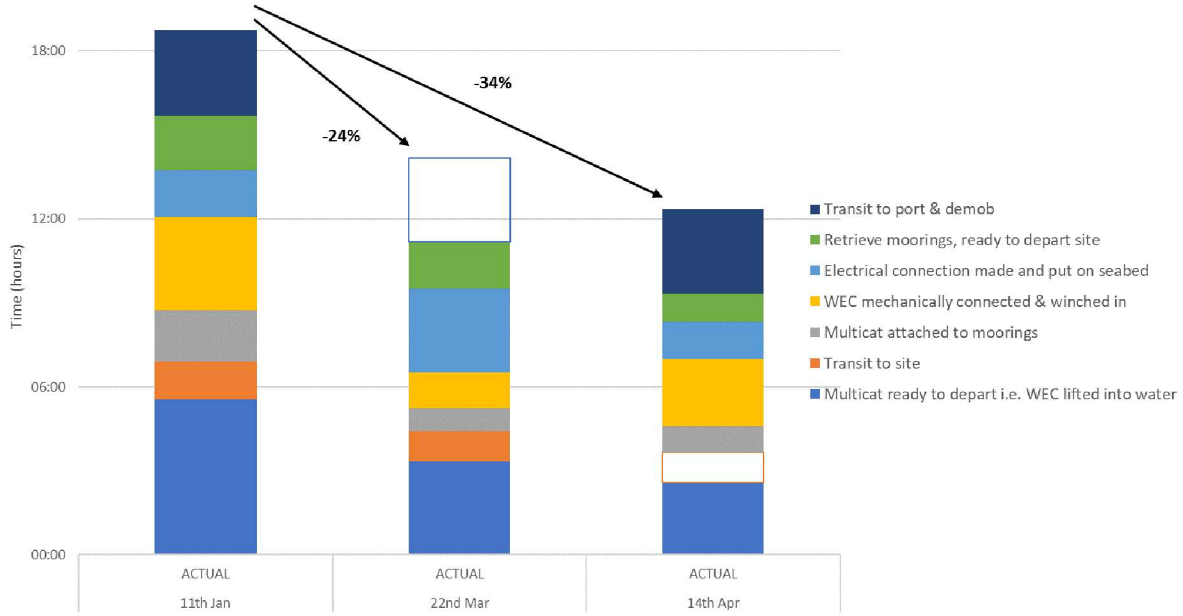


Figure 15 Stepwise C3 actual installation timings and overall installation duration improvement

The results presented above demonstrate that the CPO WEC concept has been able to reach the expected installation target of the HiWave project (cycle time trend showing a minimum of 30% improvement).

These results also validate that there is a realistic path for the CPO WEC farm concept to offer quick installation and retrieval procedures supporting the low OPEX targets.

Figure 16 Stage 3 WEC during first deployment at EMEC Scapa Flow test site

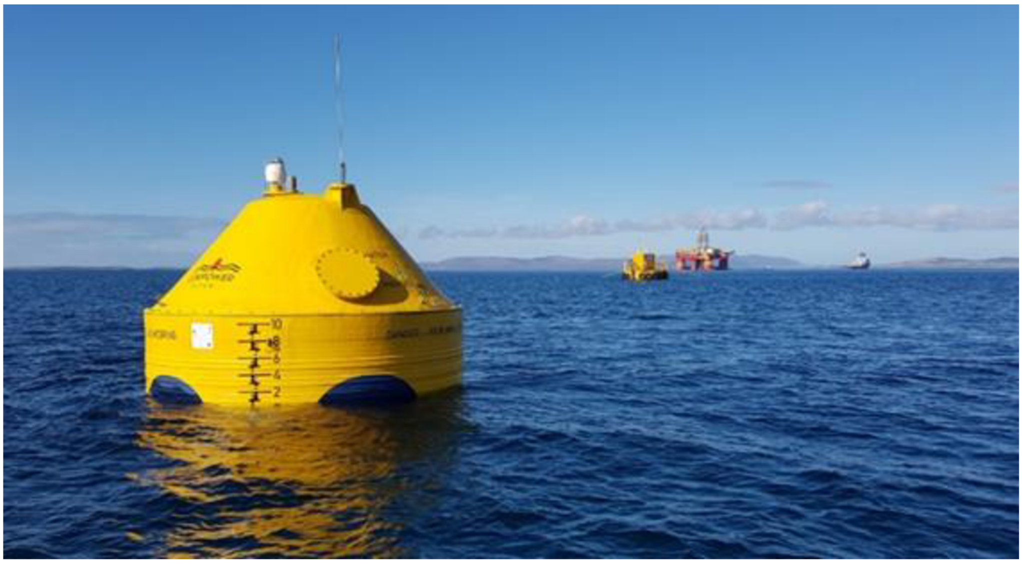


Figure 17 Installed C3 WEC at EMEC Scapa Flow test site

4.5. SCALABILITY

CorPower follows a structured five-stage verification process, established as best practice for ocean energy technology by International Energy Agency-OES, ETIP Ocean and Wave Energy Scotland. It involves step-wise validation of survivability, performance, reliability and economics starting with small scale prototypes in Stage 1, continued by sub-system testing and then fully integrated WECs in increasing scales up to array demonstration in Stage 5. The purpose of this process is to address risks in a managed way early on in the product verification process, while costs are still limited due to smaller device scale and team size.

Prior testing of multiple prototypes has already been completed during Stages 1 and 2 in Portugal, France, and Sweden in a process lasting from 2012 until 2015. The Stage 3 testing saw a large scale (1:2) Wave Energy Converter system taken through structured verification by rig testing in Stockholm, followed by ocean deployment at the European Marine Energy Centre in Orkney (Scotland).

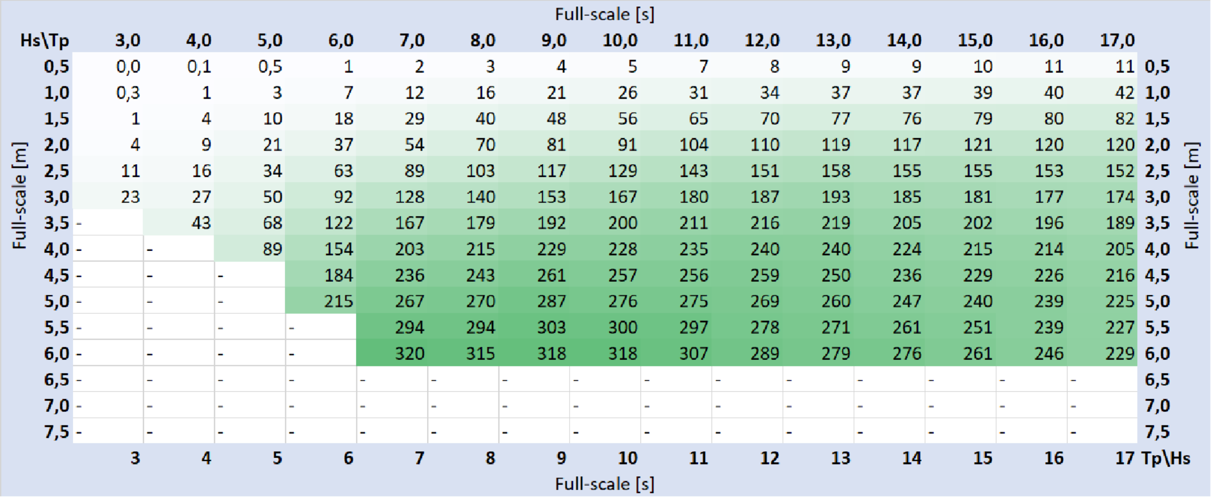
The successful demonstration of the half-scale C3 WEC confirms that the targeted up-scaling of the technology has been delivered through the HiWave project. The scalability from previous 5kW rated PTO to a 25kW rated PTO has been demonstrated in Stage 3. In the next planned step of scaling, the C4 WEC is projected to reach 300kW based on the calibrated models from Stage 3 program.

4.6. PERFORMANCE

The performance of the tuned (resonant) operation mode was verified during the ocean testing over the relevant range of sea states, up to 1.38m significant wave height (corresponding to 2.76m Hs in full-scale). The resonant motion is apparent, with the expected amplification of velocity and power capture verified. The sea states encountered in the ocean have consistently delivered slightly higher power production compared to the projections from the simulation models that had been calibrated after testing. In the more energetic sea states the power delivery was very close to expectations, a few percent higher than predicted by the models, typically + 2-3 %. In lower sea state the relative difference is larger. The results have provided further verification of the performance projections for the next full scale C4 system.

The projected full-scale performance has been derived using both lessons-learned from the half-scale design and testing, and planned design improvements for the full-scale prototype, with such improvements based on known and verified solutions.

Based on the measured performance of the C3 scale 1:2 WEC the numerical models of the CPO WEC technology has been accurately calibrated to a level where the difference between modelled and measured power production is less than 2-3% in the relevant range of operation. Using these calibrated simulation models, the following power matrix is projected for the next generation full scale devices. Please note that this Power Matrix of next gen WECs are expected to be updated during the detailed design phase planned for 2018-2019:



Full-scale [s]

Full-scale [m]

Hs\Tp	3,0	4,0	5,0	6,0	7,0	8,0	9,0	10,0	11,0	12,0	13,0	14,0	15,0	16,0	17,0	
0,5	0,0	0,1	0,5	1	2	3	4	5	7	8	9	9	10	11	11	0,5
1,0	0,3	1	3	7	12	16	21	26	31	34	37	37	39	40	42	1,0
1,5	1	4	10	18	29	40	48	56	65	70	77	76	79	80	82	1,5
2,0	4	9	21	37	54	70	81	91	104	110	119	117	121	120	120	2,0
2,5	11	16	34	63	89	103	117	129	143	151	158	155	155	153	152	2,5
3,0	23	27	50	92	128	140	153	167	180	187	193	185	181	177	174	3,0
3,5	-	43	68	122	167	179	192	200	211	216	219	205	202	196	189	3,5
4,0	-	-	89	154	203	215	229	228	235	240	240	224	215	214	205	4,0
4,5	-	-	-	184	236	243	261	257	256	259	250	236	229	226	216	4,5
5,0	-	-	-	215	267	270	287	276	275	269	260	247	240	239	225	5,0
5,5	-	-	-	-	294	294	303	300	297	278	271	261	251	239	227	5,5
6,0	-	-	-	-	320	315	318	318	307	289	279	276	261	246	229	6,0
6,5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6,5
7,0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7,0
7,5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7,5
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Tp\Hs

Full-scale [s]

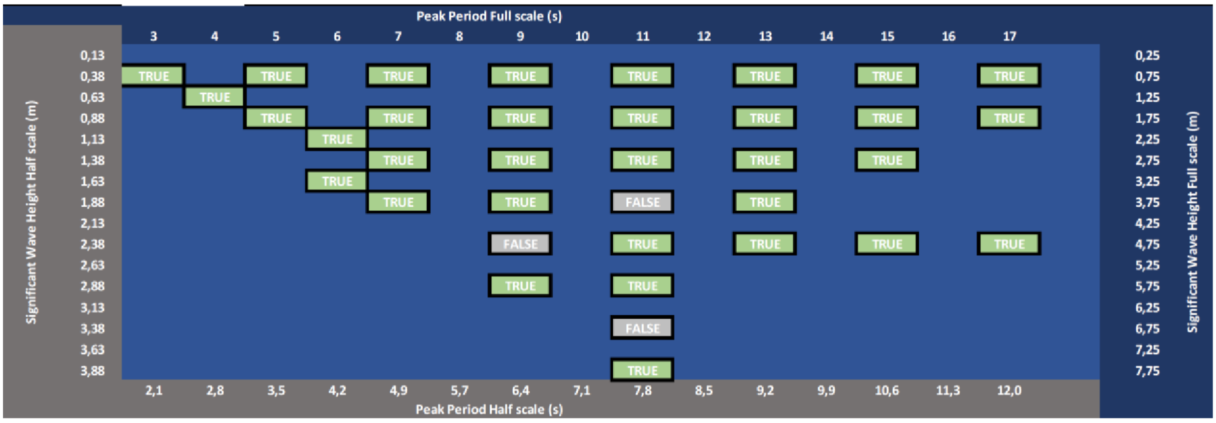
Full-scale [m]

Figure 18. Projected power matrix of a full scale WEC, based on models calibrated with measured C3 data [kW]

4.7. AVAILABILITY & SURVIVABILITY

High availability and reliability of WECs will be keys for enabling competitive wave energy projects, ensuring high energy yield and thus contributing to low LCOE.

The HIL test rig enables to test the WEC, applying realistic loads for a wide range of sea state. All sea states corresponding to the Scapa Flow target and full-Scale target have been performed on the HIL-rig setup in Sweden. The WEC has proven to have satisfactory performance in survivability mode, with thermal control and end-stop functions verified to perform to specification. In addition, the machine has been tested during final dry endurance testing over a period of 14 days, with 613 runs providing satisfactory availability meeting targets and allowing the decision to ship C3 to Orkney for ocean deployment. The dry testing of the WEC confirmed specified operation in the following sea states marked in green in below figure:



Peak Period Full scale (s)

Significant Wave Height Half scale (m)

	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
0,13																0,25
0,38	TRUE		TRUE		TRUE		TRUE		TRUE		TRUE		TRUE		TRUE	0,75
0,63		TRUE														1,25
0,88			TRUE		TRUE		TRUE		TRUE		TRUE		TRUE		TRUE	1,75
1,13				TRUE												2,25
1,38					TRUE		TRUE		TRUE		TRUE		TRUE			2,75
1,63				TRUE												3,25
1,88					TRUE		TRUE		FALSE		TRUE					3,75
2,13																4,25
2,38							FALSE		TRUE		TRUE		TRUE		TRUE	4,75
2,63																5,25
2,88							TRUE		TRUE							5,75
3,13																6,25
3,38									FALSE							6,75
3,63																7,25
3,88									TRUE							7,75
	2,1	2,8	3,5	4,2	4,9	5,7	6,4	7,1	7,8	8,5	9,2	9,9	10,6	11,3	12,0	

Peak Period Half scale (s)

Significant Wave Height Full scale (m)

Figure 19 Green sea states successfully verified C3 operation in dry testing

During the ocean deployment the C3 WEC has demonstrated satisfying availability for a first-of-a-kind prototype. In January 2018 the survival mode of the WEC was first tested in the ocean, with the most severe conditions endured including waves up to 2.56m (corresponding to 5.12m in full scale) and wind speeds up to 50 knots. In June the largest sea states were encountered, with the device operating in survival mode in 2.05m Hs, with individual waves close to 4m (corresponding to 8m in full scale). The load shedding function was found to perform well, with load levels that did not inflict damage to the WEC and the detuned motion of the device kept well within boundaries due to a combination of frequency detuning and high passive stiffness.

Figure 20 C3 operating in survival mode, 2.05m significant wave height, Scapa Flow, Orkney

Video analysis of the C3 motion in survival mode shows how the detuning of the frequency response makes the device very stable, demonstrating minimal surge, heave and pitch motion despite wave trains with large elevation passing the system. This wave transparency feature is key for minimizing the loads inflicted on the system in storm conditions. The survival function introduced with C3 can be compared to a wind turbine pitching the blades to reduce loads in storms, a function which is available on most commercial wind turbines of today.

The following sea states were encountered in Scapa flow, providing verification of survivability up to 2.05m Hs:

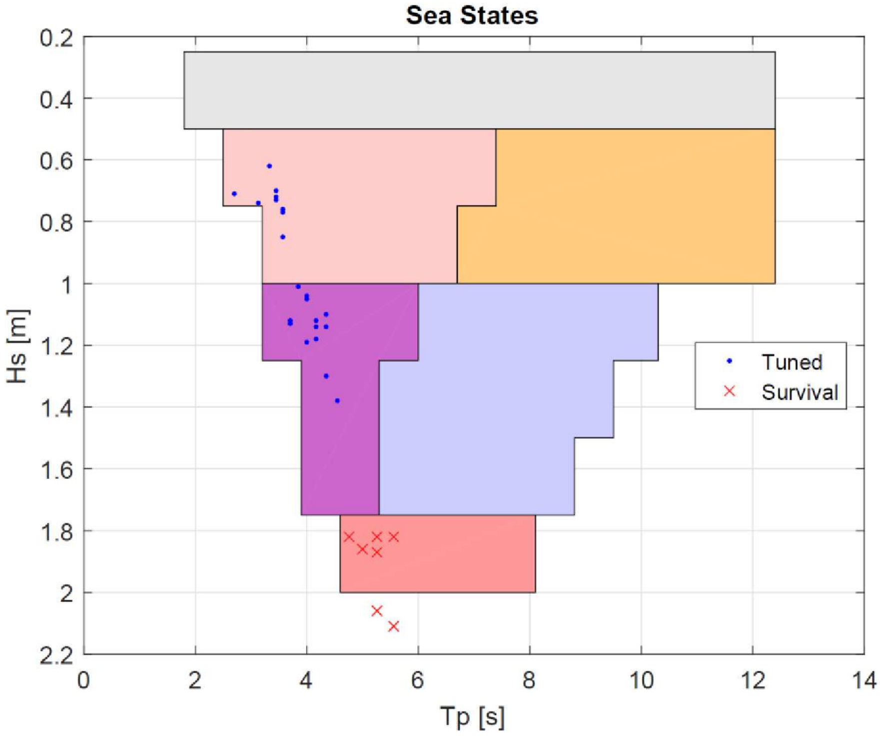


Figure 21 Sea states verified with C3 operation in Scapa flow

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The below reports provide further studies on the CPO WEC technology and related aspects:

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