Blue Horizon

WES Novel Wave Energy Converter Stage 3 Project

Public Report

Mocean Energy Ltd

This project has been supported by Wave Energy Scotland

Executive Summary

This report provides information about the lessons learned of the Mocean WEC: Blue Horizon project funded under the Stage 3 Novel Wave Energy Converter (NWEC) program by Wave Energy Scotland (WES).

A lessons learned process was undertaken to review the success of the delivery of each of the project stages;

- Detailed design
- Build and Commissioning
- Operations, maintenance and testing
- Decommissioning

This report is the culmination of a collaborative effort informed by Mocean Energy and key partners involved in the project execution. For each of the project stages respondents were asked to consider both positive and negative experiences throughout the lifetime of the project.

Lessons learned to date from the project include insights into project managing, Systems engineering, Structure, Generator, Power electronics and electrical systems, Control system, Communications-data-wiring, Mooring and marine ops, Fabrication and assembly, Operations and maintenance, Testing, and Numerical modelling.

The feedback will be used within Mocean Energy to improve effectiveness and efficiency of future projects, and to inform the process of delivering and testing a Wave Energy Converter (WEC).

We hope that this attempt to share insights and lessons will prove helpful to wave energy professionals, and be relevant to those involved in project delivery across the broader energy and public sector.

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1 Introduction

Mocean Energy concluded the Mocean WEC: Blue Horizon project to complete the detailed design, build, and testing of a sea-going prototype Mocean WEC, funded by WES through its Novel WEC Programme. Blue X, the WEC, comprises forward and aft hulls, patented wave channels, a PTO nacelle and power control subsystems in the forward hull.

The primary purpose of testing has been to gather performance data and learnings from deployment of the device in order to inform further development of Mocean's Wave Energy Converter designs. In addition to the power performance of the WEC, the test programme assessed the behaviour and practicalities of the mooring system and the electrical connection.

With the technical and commercial experience and credibility gained from this project, Mocean aims to commence the more ambitious development of larger WEC, which will eventually be suitable for deployment in grid-connected wave farms.

2 Description of Project Technology

The Mocean WEC is a hinged raft that differs radically in shape from the classic symmetric twin-pontoon configuration. During the course of the NWEC 3 project, Mocean constructed and operated a prototype WEC "Blue X". The design process used a Mocean developed software that calculates the force on and resulting motion and power of a WEC that can be configured parametrically. The unique geometry of the Blue X evolved through an optimisation that adjusts parameters to maximise captured energy while penalising the size of the WEC and PTO.

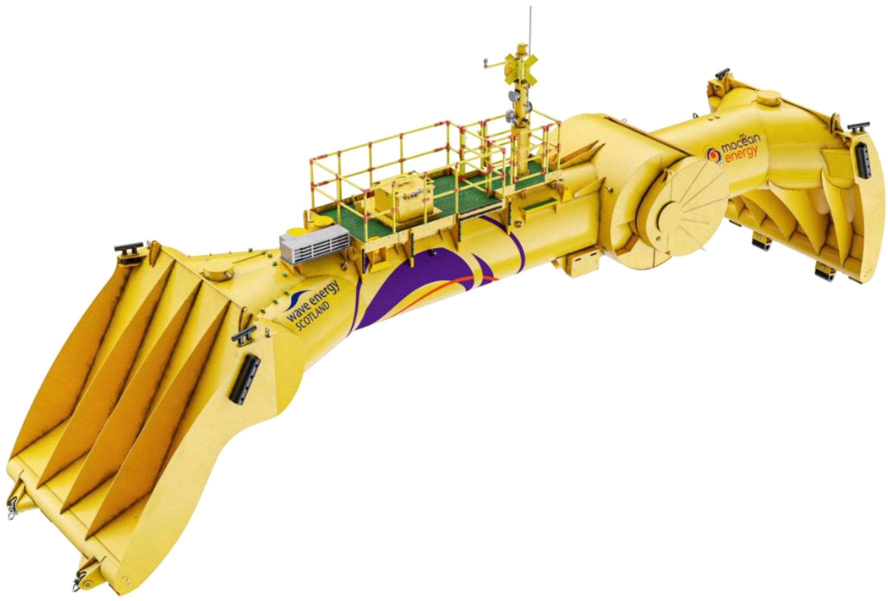

Figure 1 Blue X

The Blue X geometry has two slender tubular hulls either side of the hinge – with the key innovation being two sloping, deeply-submerged plates at the fore and aft ends of the WEC, which are 3 times the width and depth of the tubular hulls. Overall, the forward section is twice the length of the aft. The combination of the asymmetrical sections and the submerged plates delivers performance that is 3 times greater than the classic hinged raft.

Nominal Power	10 kW
Energy Storage	33 kWh
Communications	4G, VHF, Wi-Fi
Dimensions	19.3m(L) x 4.6m(W) × 7.6m(H)
Total Mass	38 Te

Table 1 Blue X specification

A notable characteristic of the prototype is that is designed to operate without connection to an umbilical. This design requirement was put in place to facilitate the testing at the performance test site. The rotation of the aft hull with respect to the forward hull drives a gearbox and then a generator. Power from the generator is then conditioned and used onboard the WEC to power local system. Power beyond that needed to power on-board systems is stored in 30 kWh of batteries. Once the batteries are fully charged, excess power is dissipated through an onboard dump resistor. Key onboard systems that use power include: the control, communications, cooling, instrumentation, and navigation lighting.

3 Scope of Work

The ambition of the Mocean Stage 3 project was to gather information on the Mocean WEC performance, engineering and operation to:

1. Lead to the **next stage of technical development** (i.e. next-stage WEC designed in concept),
2. **Raise funding** (private investment matched to awarded grant for post-Stage-3 project),

Mocean's project objectives for NWEC stage 3 were to:

1. **Collect data** on power absorption, motions, and loads from the scaled WEC under operation over a range of power-producing and survival seas to be used for numerical model validation and engineering.
2. **Demonstrate the feasibility of operations** (and collect data where appropriate) including: construction and assembly, transportation, lifting, maintenance, towing, and installation.
3. **Engineer a functional system**, supported by relevant operations, that survives all likely environmental and operational conditions, provides the ability to control torque at the hinge, produces electricity from waves, is capable of operations without umbilical connection, and facilitates frequent inspection and maintenance.
4. **Follow a plan** that prioritises risk reduction, anticipates system failure, accounts for contingencies, and adheres to Quality & HSE (QHSE), regulations, budget, and schedule.
5. **Show progress towards a commercial product** to interested parties including Wave Energy Scotland, the Scottish Government, investors, customers, and the public.

Apart from the Levelized Cost of Energy (LCOE) of Blue Horizon (the MW-scale WEC for utility grid power), other measures of the WEC performance in the four critical areas listed below, were identified as project target outcomes:

- **Affordability** – Subsystem CAPEX, OPEX, manufacturing cost, installation cost, maintenance cost, time to manufacture/assemble, etc.
- **Performance** – Power (input into PTO), power (output from PTO), wave to wire efficiency, subsystem mechanical/electrical conversion efficiency, total time operational, MAEP, etc.

- **Availability** – System/component Mean Time To Failure (MTTF), system/component Mean Time To Repair (MTTR), Mean Time To Install (MTTI), maintenance strategy, transportability, modularity, tow speed, redundancy, number of components in bill of materials, install/maintenance operational limits, etc.
- **Survivability** – Operational limits, reliability of survival systems, maximum allowable force, etc.

4 Project Achievements

4.1 Manufacturing

The detailed design stage started in the January of 2019, and fabrication was completed in the spring of 2021 in Fife .The manufacture of the 38 tonne wave energy converter was a significant achievement requiring a multi-disciplinary team.

Key activities :

- Engineering design and the production of engineering drawings and procedures
- Fabrication and painting
- Electrical and mechanical installation and commissioning
- Logistics and launch
- Marine operations
- Third party verification and consenting
- Project management (timeline and budget)

Figure 2 Blue X during manufacture

4.2 Operations

Following the completion of manufacturing, several operations took place and were demonstrated; lifting, commissioning, transportation, towing, installation, maintenance, recovery.

In detail, Blue X was constructed at Cowdenbeath and transported by road to Rosyth for final assembly and commissioning in April 2021. At Mocean's Rosyth site, Mocean carried out the first lifts of the complete WEC. The wet commissioning and trim adjustment in the water by the addition of ballast was completed by May, before Blue X was transported by road and ferry to Kirkwall in Orkney. As built WEC mass and mass distribution was very close to design, resulting in minimal ad hoc ballast.

The WEC was transported as a whole unit on a low-loader trailer from Rosyth to Orkney via the Aberdeen freight ferry as part of the detailed route planning, which took into account dimension limits and road suitability.

Figure 3 Blue X on site at Scapa Flow

It was then launched from Hatston Pier and towed to EMEC's Scapa Flow scale test site, as shown in Figure 3, to begin its test phase in mid-June. Blue X was installed at the test site over the course of two days; the first day was the mooring installation, and the second day was the tow and WEC hook up.

Following the installation at Scapa Flow, Blue X operated successfully for the 5-month testing period on site at Scapa Flow before recovery to the quayside in November 2021 after 154 days at sea. The WEC was briefly recovered to Copland's Dock (Stromness, Orkney) for an electrical upgrade half way through the 5-month testing phase where operations and maintenance, such as lifting, detachment and reattachment of WEC from moorings, were further demonstrated and improved. All these operations were completed in a timely manner, highlighting the inherent maintainability of the system and the validity of Mocean's approach to managing O&M.

4.3 Performance

Blue X has completed 154 days at sea, delivering steady outputs of up to 5 kW and safe instantaneous peaks of 30 kW, and operating in sea states up to 2.3 meters Hs. For the validation of the data collected from the WEC, the sea state was measured with a waverider buoy while the WEC response and its output power were continuously measured.

A Third Party performance assessment was carried out by EMEC to report on the independent calculation of at-sea WEC power production performance. The review confirmed Mocean's findings. Additionally, monthly analysis of the test data and comparison with numerical models assisted in validating Mocean's technology and improve future designs.

4.3.1 Overvoltage

It was found that during large wave events the overvoltage protection system would cause the generator to temporarily go offline, which caused a detrimental impact on overall energy production. This issue was resolved with an electrical upgrade part way through testing which allowed the generator to operate at reduced voltage in more energetic sea states.

4.3.2 Battery charging

A battery charger issue caused the device to be offline (i.e. not generating) for approximately 2 weeks during testing. Simultaneously, the operations team was requested to self isolate due to COVID-19, thus accessing the WEC at sea was not feasible and mitigation operations could not take place. As a result of the above issues, the device's AIS transponder was offline – a Notice to Mariners was issued to make other shipping in the area aware that our device remained on station. All other navigational equipment including navigation light and passive radar deflector remained operational. The device remained deployed in Scapa Flow and the issue was resolved without removing the device from site.

4.4 QHSE

The completion of the project was achieved by following a plan that prioritises risk reduction, anticipates system failure, accounts for contingencies, and adheres to Quality & HSE (QHSE), regulations, budget, and schedule.

Funded by the European Commission European Maritime and Fisheries Fund and led by the European Marine Energy Centre (EMEC) in Orkney, a research project was conducted to gain knowledge on the environmental response of the Blue X installation at Scapa Flow under the Strategic Environmental Assessment of Wave energy technologies (SEAWave) project. As part of the project, EMEC deployed an hydrophone to measure ambient noise from the Mocean device and to understand the quantum of added noise, while the University of Plymouth, alongside the University of Exeter, had deployed baited cameras and midwater cameras to assess to what extent the device acts as an aggregation site for fish. University of Plymouth shared the outcomes of their research, finding that Blue X and its moorings acted as aggregator by providing cover to small fish, even after a short time (2 months) of deployment.

A maintenance manual was produced as part of the maintenance strategy, and additional failure investigation reports and an issue register were created to document any system failures, investigations and resolutions. The experience gained in accessing the WEC at sea and carrying out confined space access at sea, provided valuable feedback to improved the quality of operations

It is worth noting that lifting, transport, and marine operations were reviewed prior and during HIRAs, attended by an HSE advisor and shown to be viable.

4.5 Lessons Learned

Mocean have established a comprehensive Lessons Learned database which aims to capture positive and negative observations and apply them to future WECs.

The highest priority Lessons from the NWEC3 and NWET projects are in the areas of:

- Design with maintenance philosophy in mind
- Consenting requirements and timelines
- Mooring connections
- Confined space access
- Design with survivability in mind
- Change control
- Budgeting
- Timeline
- Multiple electrical partners
- Mass buoyancy trim
- Fabrication
- Commissioning
- Human resourcing
- Overvoltage protection

5 Summary of Performance against Target Outcome Metrics

Broadly speaking, metrics serve two purposes, which we could name as 'development indicators' and 'stamps of approval':

1. They allow internal developers to optimise their technology and assess its development trajectory
2. They contribute to decisions made by, and attempt to address the interests and concerns of:
    a. Public funding bodies
    b. Private investors

The metrics presented here relate to the 1MW rated Blue Horizon WEC for utility grid power.

5.1.1 Affordability

The LCOE analysis of Blue Horizon has been supported by renewables commercial service provider Exceedance via the Marine Energy Alliance (MEA) Interreg project. The report indicates that a significant LCOE step-change cost reduction has been achieved since the start of the NWEC programme. This is estimated as 8% compared to a baseline wave energy sector LCOE of €400/MWh, and 76% with respect to the LCOE estimate at the end of NWEC Stage 1.

Its findings include:

- Modelling of Blue Horizon with first of a kind capital expenditure costs gives a baseline LCOE of £318/MWh.
- Modelling a future farm of 100 Blue Horizon devices with "nth of a kind" CAPEX costs, as estimated once the wave energy sector reaches 1GW cumulative deployment, gives an LCOE of £117/MWh. This is well below the Wave Energy Scotland target of £150/MWh.
- The top 5 key cost drivers for the baseline model are: yield, total CAPEX, discount rate, total OPEX, and lifetime.
- Sensitivity analysis on total OPEX and discount rate on the future nth of a kind LCOE shows that the estimated figure of £117/MWh may sit within a range of between £104-130/MWh.

- A potential cost reduction pathway highlights that the main cost reductions will come from a reduction in Hull, PTO & Control, and Mooring & Umbilical costs, from a reduction in discount rate, and reductions in OPEX.
- The potential cost reduction pathway indicates the reductions in the aforementioned three key CAPEX items reduce the overall CAPEX by 50% from the baseline model to the future model, and accounts for an overall LCOE reduction of 30%.

- The importance of implementing both deployment-based and radical innovation (i.e. step-change) cost reductions to further improve cost of energy is being highlighted. Mocean has ensured all relevant learnings are captured in order complement its step-change improvements with deployment-based learning as it moves to future design iterations.
- Current best estimates suggest that the WES programme has facilitated a significant step-change both within the technology itself and in relation to current wave energy sector state-of-the-art LCOE.
- Mocean's approach to minimising LCOE by targeting fitness functions based on a combination of AEP maximisation and mass and torque minimisation appears to be broadly successful in lowering successive LCOE estimates. The intended correlation between AEP/mass and AEP/max torque 'development indicators', and LCOE as a 'stamp of approval' metric, exists but is not observable across all stages of device evolution.

The study had also showed that there are limits of using LCOE as a tracker for techno-economic performance progress due to the numerous assumptions within the metric and the dimensional nature of LCOE, therefore additional target outcome metrics were reviewed.

5.1.2 Performance

Blue X has completed 154 days at sea, delivering steady outputs of up to 5 kW and safe instantaneous peaks of 30 kW, and operating in sea states up to 2.3 meters Hs.

Power was generated during weather events and data were captured by the WEC, communicated and recorded. Following electrical improvements halfway through the testing period, performance was improved providing further information on power generation ability.

Within the deployment energetic waves were encountered and allowed successful demonstration of:

- Generation of electrical power, battery charging and discharge through the dump resistor.
- Operation of PTO protection equipment.
- Confirmation of the expected dynamic roll stability in waves.

5.1.3 Availability

Successful dry and wet commissioning at Rosyth showcase that as built WEC mass and mass distribution was very close to design, resulting in minimal ad hoc ballast. Lifting and transport (road and ferry) operations had been thoroughly reviewed and significantly contributed to issue free operations.

The tow speed is another important indicator of availability. Blue X was towed a long distance (36 nautical miles over 9 hours) using a low-cost MultiCat vessel at a reasonable average speed of 4 kts. Blue Horizon's current geometry has a similar shape and towing/hinge locking mechanism may enable faster towing speeds up to 5knots. A 'fast-tow' version of the WEC with a change in the wave channel would likely allow towing speeds of 5knots, but the AEP to towing speed trade-off needs further assessment.

Blue X was installed at EMEC's Scapa Flow test site over 2 days; the first day was the mooring installation, and the second (long) day was the tow and WEC hook up. The recovery of the WEC and its mooring system was completed within a day by utilising the same resources as the installation operation.

During the testing period, the power control system was upgraded to allow automated mode changing for generation and improved monitoring operations.

5.1.4 Survivability

The design accommodates very large relative angles of rotation (+/- 135deg) of the two hulls, which effectively avoid structure-on-structure impacts. Steep wave conditions at Scapa demonstrated survival behaviour in sea states up to 2.3 meters H with Blue X diving through waves and automatically shutting down power take-off (PTO).

The up time of the communication system was 99.99%, excluding total system downtime, which enhanced reliability of the survival systems.

6 Recommendations for Further Work

6.1 Inspection and maintenance

Post-recovery inspections of Blue X have taken place to ensure learning is captured at the earliest opportunity and to allow maintenance to take place in good time prior to redeployment in 2022.

6.2 Renewables for Subsea Power (RSP)

Renewables for Subsea Power (RSP) is a collaborative project between Mocean Energy and partners to develop a complete system approach for providing remote power and communications using wave energy to subsea equipment. The RSP Phase 3 project is planned to commence in early 2022, starting with modifications to the WEC to integrate RSP systems such as a power export cabinet and umbilical. Blue X and subsea equipment will be deployed at a site east of Orkney later in the year and tested for at least four months. The WEC will be tested along with a HALO subsea energy storage system and a residential AUV. This site has been preferred due to the variety of wave conditions covering the desired range of test conditions.

Figure 52 Blue X and subsea equipment

The project aims to demonstrate:

- reliable power and comms to subsea equipment
- remote operation of production system through all equipment operating modes
- remote operation of AUV including docking, charging, data transfer and over-the-horizon control.

The test program will provide data from the WEC and HALO system over the deployment months; wave data, power generation, battery state of charge, comms bandwidth, and monitoring signals. Several survey missions will be performed to demonstrate the remote operation of the AUV.

6.3 Next generation WEC

The WES programme has provided a vast amount of learning and technology development that serves as a starting point for product-focused development projects.
As part of the transition from the WES programme to commercially oriented next-stage projects, Mocean will focus on two strands of research and development on the Mocean hinged raft WEC concept:

- a near-term commercial product, Blue Star, intended to support low-power high-value applications in the Oil and Gas (O&G) sector, and ocean sensing, with a power rating of 20 kW.
- a longer-term feasibility study of a utility-scale WEC, Blue Horizon, intended to supply grid connected electricity to islands or mainland locations, with a power rating targeted at 1MW.

The first phase of the Blue Star product development has already commenced and the FEED-short front-end engineering design is underway. During this phase, technical modifications based on learning from trials are incorporated into the design, manufacturing partners are established and a detailed costing and schedule for the next phase will be produced. Phase 2 will consist of the detailed design, build and commissioning of the new WEC and the sea deployment.

7 Communications and Publicity Activity

To show progress towards a commercial product to interested parties including the Scottish Government, investors, customers, and the public, Mocean engaged in communications and publicity activities, such as:

- Dissemination activities on each milestone (transportation, sea-testing, rewiring and operations, recovery) including press releases and interviews.
- Attendance in events and COP26, promoting the project outcomes and next steps for Mocean Energy.
- FEED process now under way with potential commercial partner to further develop Blue X device
- Numerous posts on Mocean's LinkedIn profile on the progress of the project
- Newspaper articles, i.e. Scotsman, The Times
- Site press visits and interviews; BBC Reporting Scotland, BBC Scotland - Our Planet Now, Orkney: Britain's Green Islands, Dutch RTL news, Sky News
- Mocean released videos of Blue X; Mocean Energy - Blue X - Part 1, Blue X in Action , Mocean's Blue X Experience, Blue X Launch , Presenting Blue X, Blue X - Big Waves in Scapa

8 Useful References and Additional Data

The Mocean website (www.mocean.energy) has some publicly available information on the technology.