#WESAC19

wave energy
SCOTLAND

HIE
Highlands and Islands Enterprise
Iomairt na Gàidhealtachd 's nan Eilean

Blue Horizon

NWEC3, WESAC19

Chris Retzler

Technical Director

Who we are…

- A Research, Design and IP Generation Company
- Currently 7 full-time, 2 part-time personnel
- Located on UoE King's Buildings Campus
- Principal source of funding: WES NWEC3

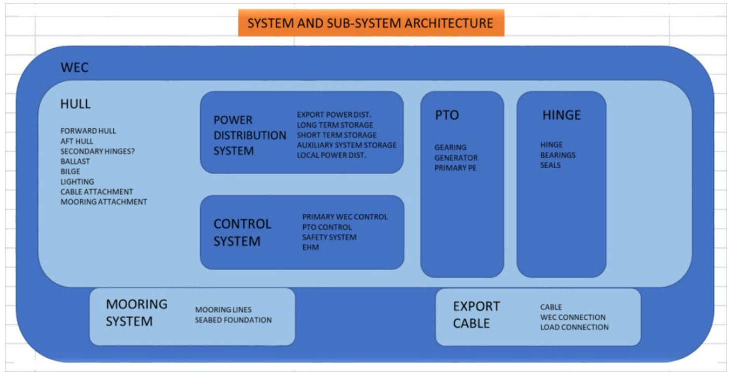
Design Triangle

Mocean core skills in numerical and experimental modelling

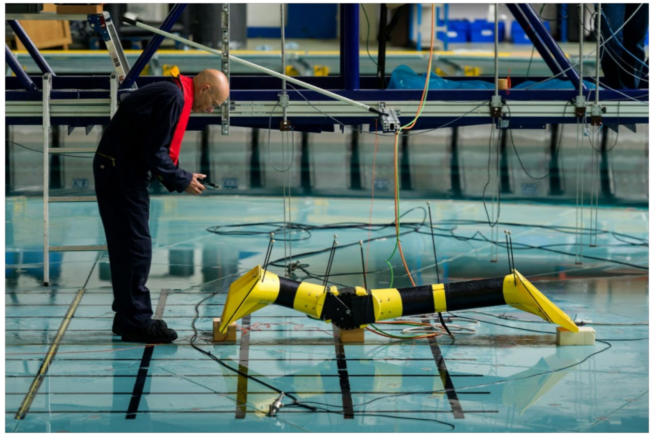
Growing expertise in engineering specification

High engagement with external consultants and subcontractors

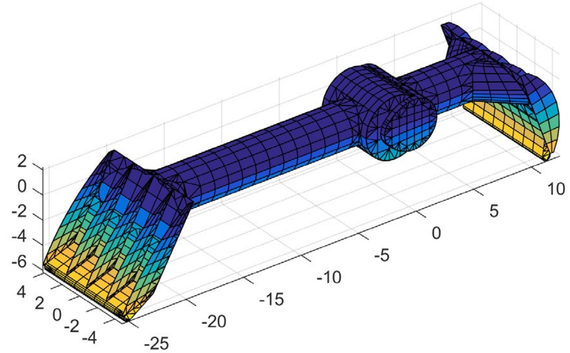
Engineering Requirements



Wave Tank Validation

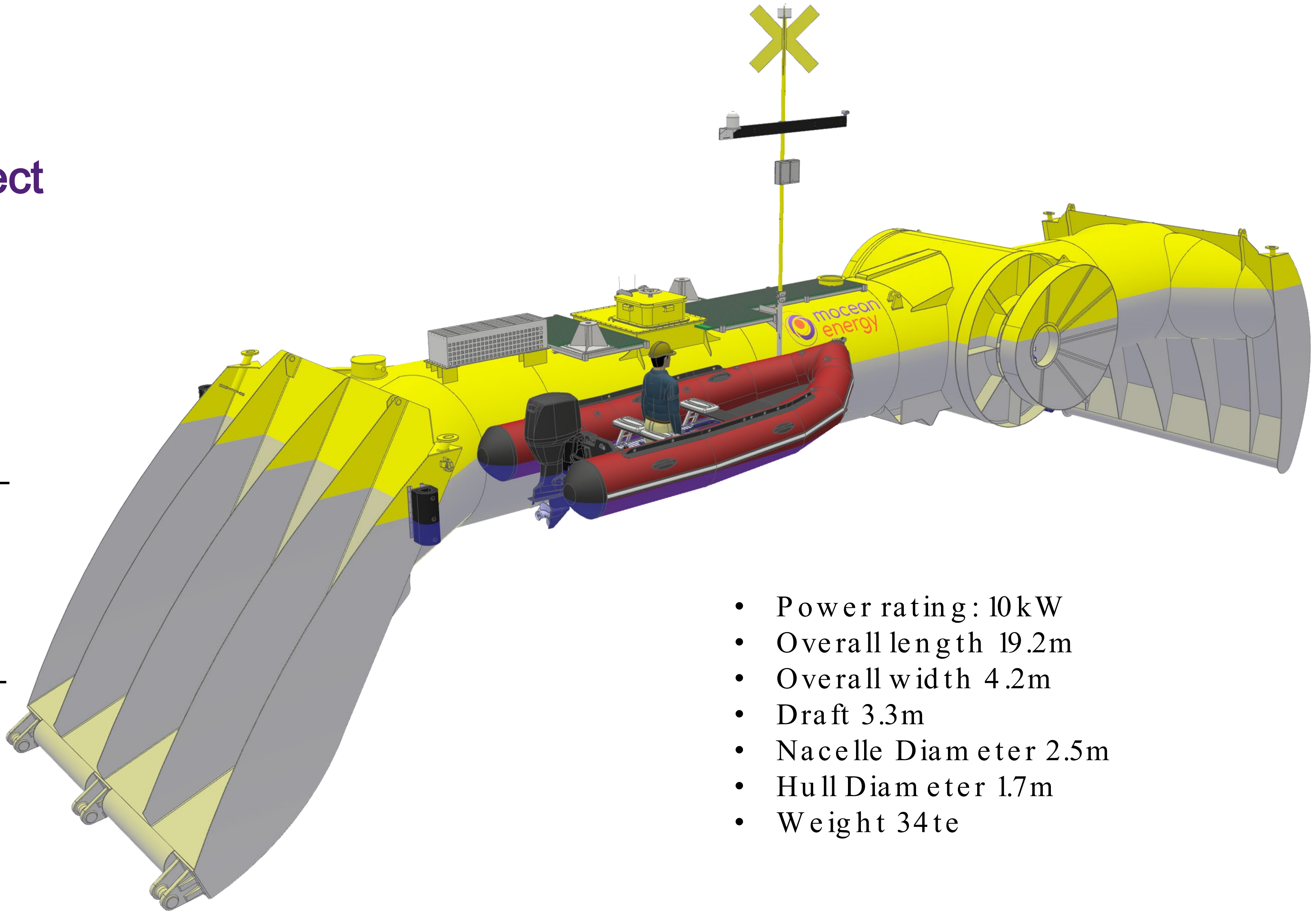


Numerical Optimisation



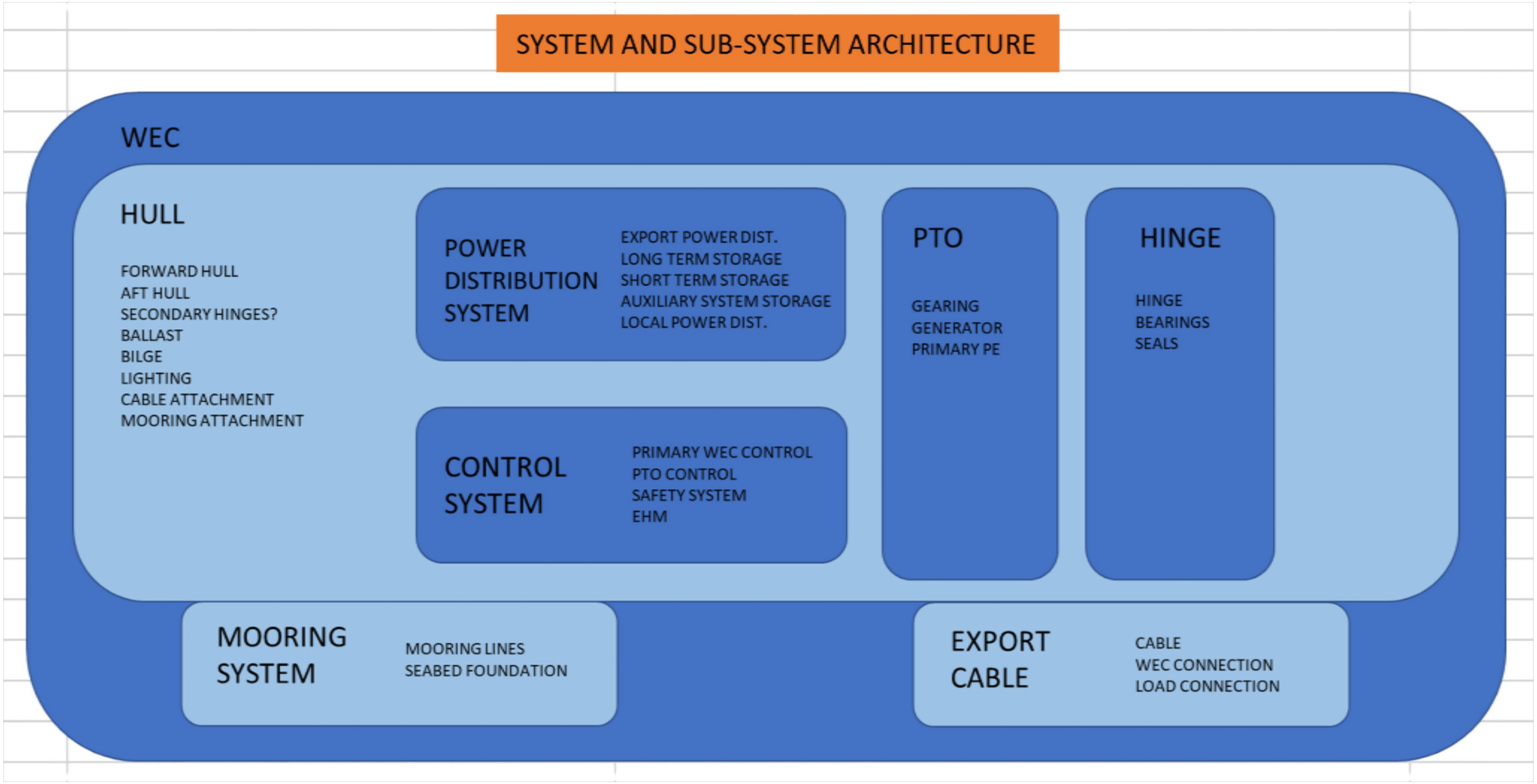
Blue Horizon Project

- Design, build and test a ½ -scale prototype – the M100P
- Project runs Jan 2019 – December 2020
- Fabrication in Fife, completion due 2020 Q2
- Testing in Orkney Q3 – Q4 2020



- Power rating: 10kW
- Overall length 19.2m
- Overall width 4.2m
- Draft 3.3m
- Nacelle Diameter 2.5m
- Hull Diameter 1.7m
- Weight 34te

Blue Horizon Architecture



Blue Horizon – 12 Subcontractors

BLACKFISH ENGINEERING DESIGN AND PRODUCT DEVELOPMENT

THE UNIVERSITY of EDINBURGH

SUPPLYDESIGN BESPOKE ELECTRONICS

LEASK MARINE

MAESTRO GLOBAL STRUCTURAL ANALYSIS

FDL

sequentec specialist electronic systems

aquatera environmental services and products

ajs Production Ltd

OCEANEERING®

industrial systems and control

ORCADES MARINE Management Consultants Ltd

Blue Horizon – Project Structure

- WEC Programme management and QHSE
- Structure: Design, Fabrication, Assembly
- Power Take Off
- Power Control System
- Communications, data capture and storage
- Licensing, permitting, surveys, verification
- Mooring, Operations and Maintenance

Programme Management, Health, Safety and Environment

mocean energy

OCEANEERING®

- Mocean   is the project owner and manager
- Oceaneering's role is to advise on the project's Health and Safety provisions, risk assessments and procedures
- H&S is paramount and drives the definition of procedures for operations during the test programme, in turn has driven the design to incorporate all H&S provisions

Power Take -off: C -GEN generator

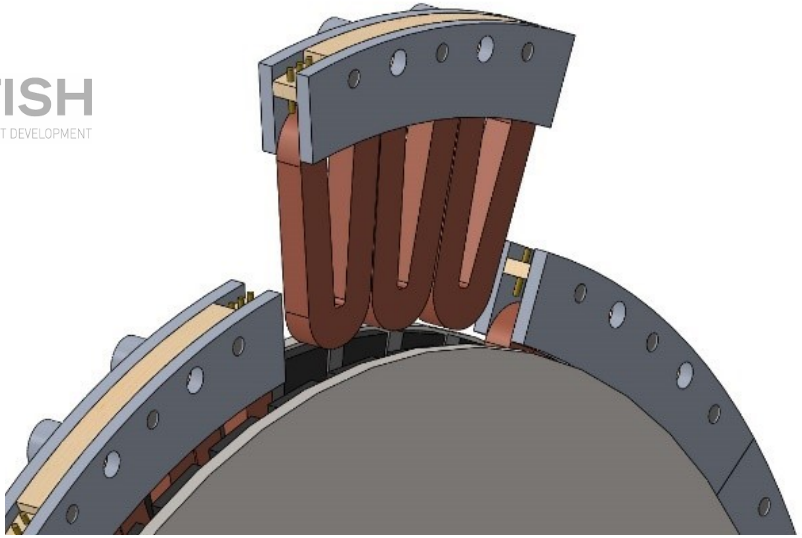
THE UNIVERSITY of EDINBURGH

F D L

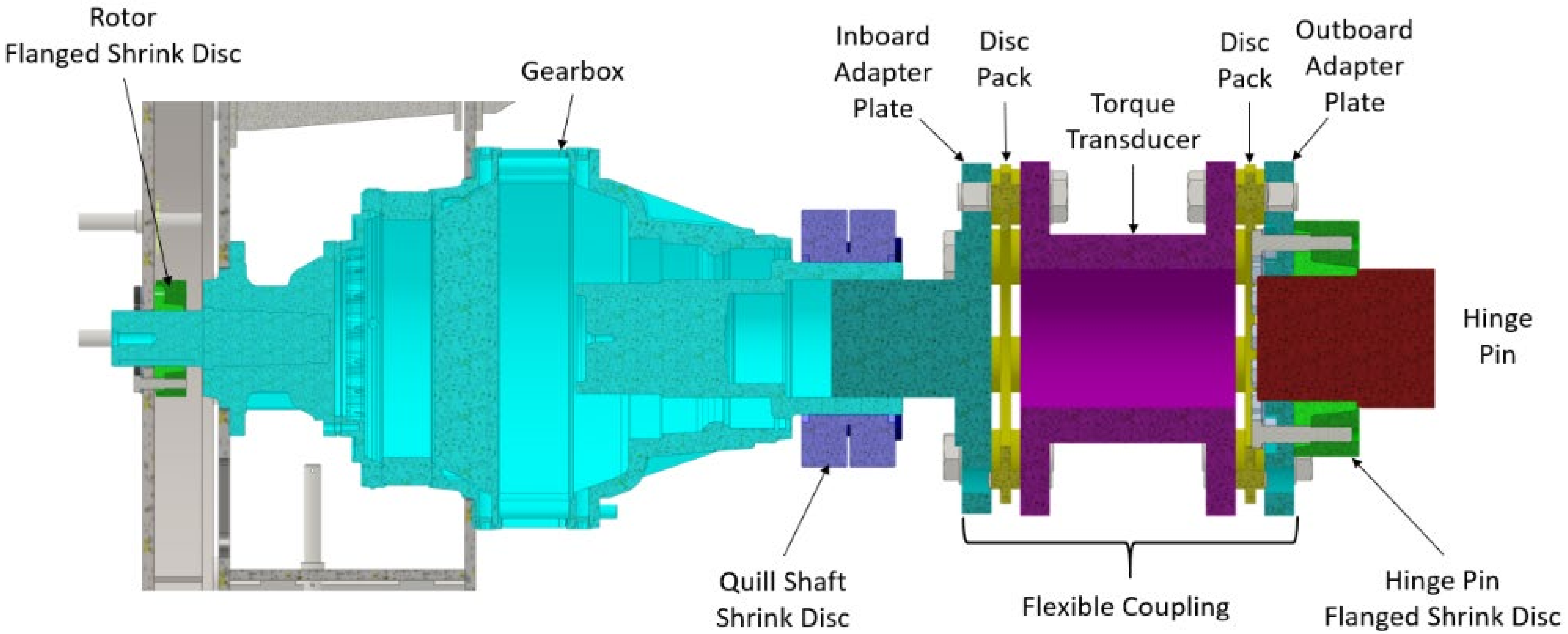
BLACKFISH
ENGINEERING DESIGN AND PRODUCT DEVELOPMENT

415V rms 3 phase
axial flux PMG

10kW continuous
power; 30kW peak

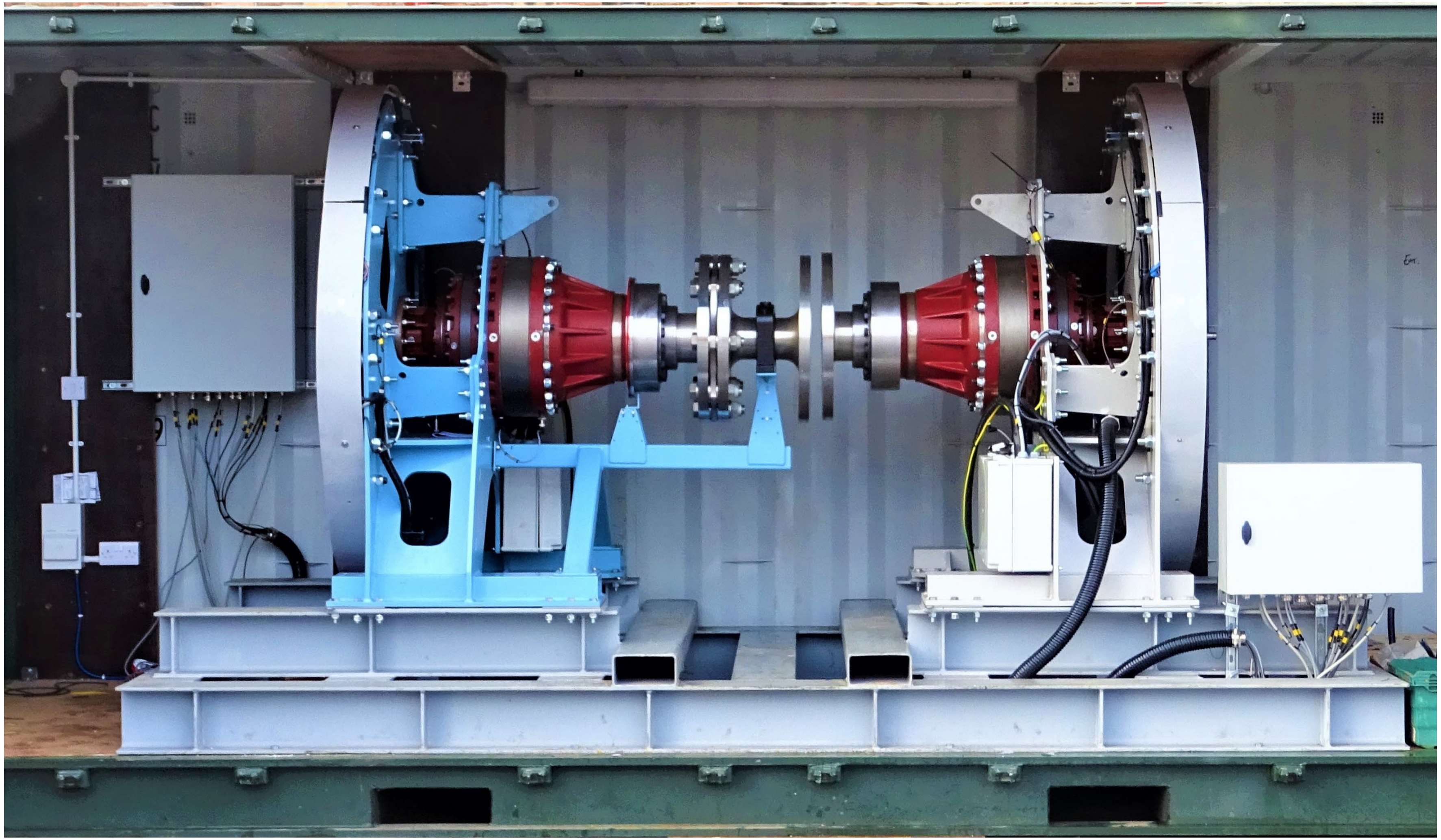


PTO Drive Train – not to scale



Power Take -off: Back -to -Back Rig

- Two C-GEN/gearbox assemblies; one driven as a generator by the other as a motor.
- Max hinge torque: 65kNm
- Max generator speed: 30rpm
- Gearbox ratio: 15.34
- All components in blue frame are complete and ready for transfer into WEC once testing is complete.
- Testing has begun at SDL, Rosyth

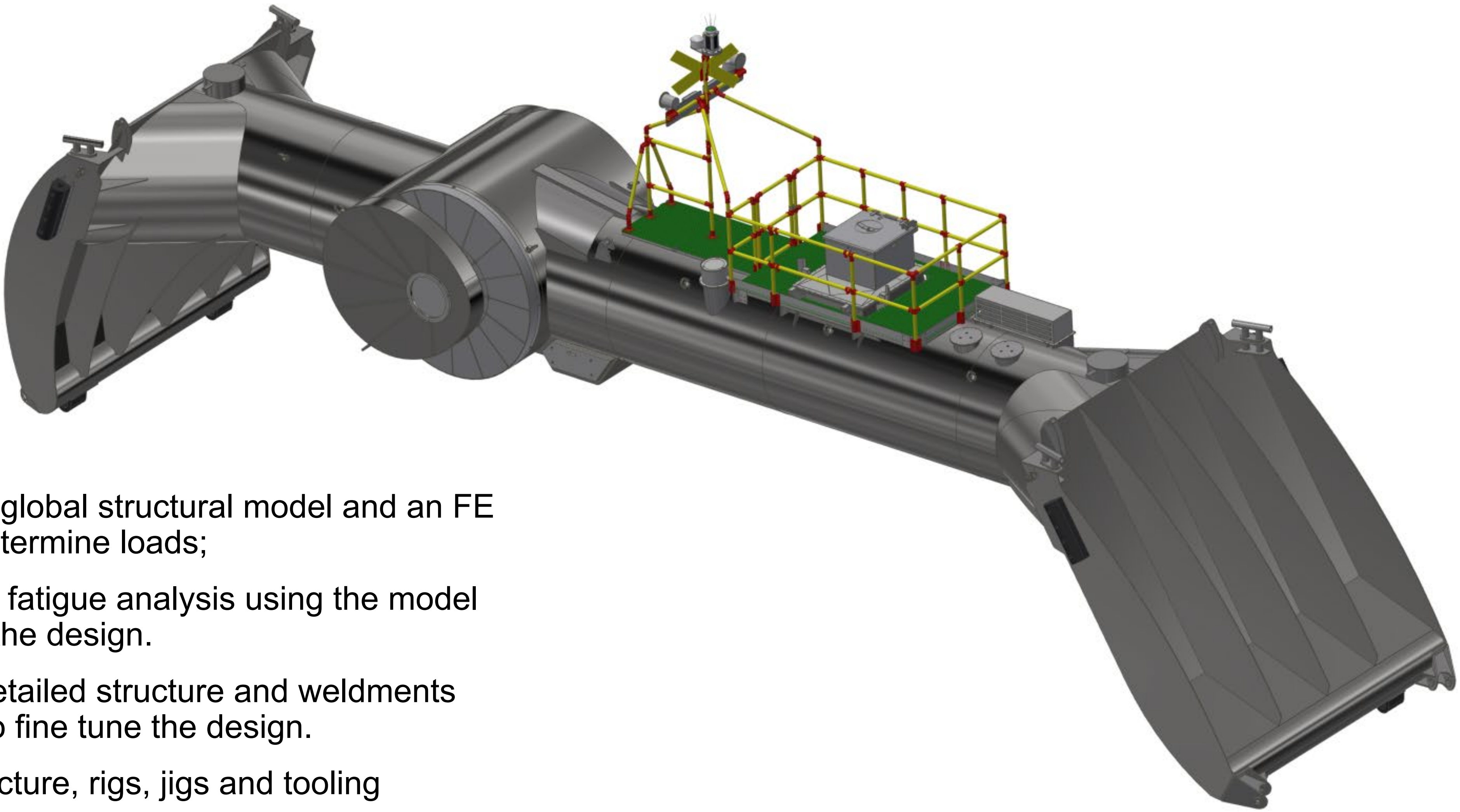


Design, Fabrication, Assembly

MAESTRO Global Structural Analysis

BLACKFISH Engineering Design and Product Development

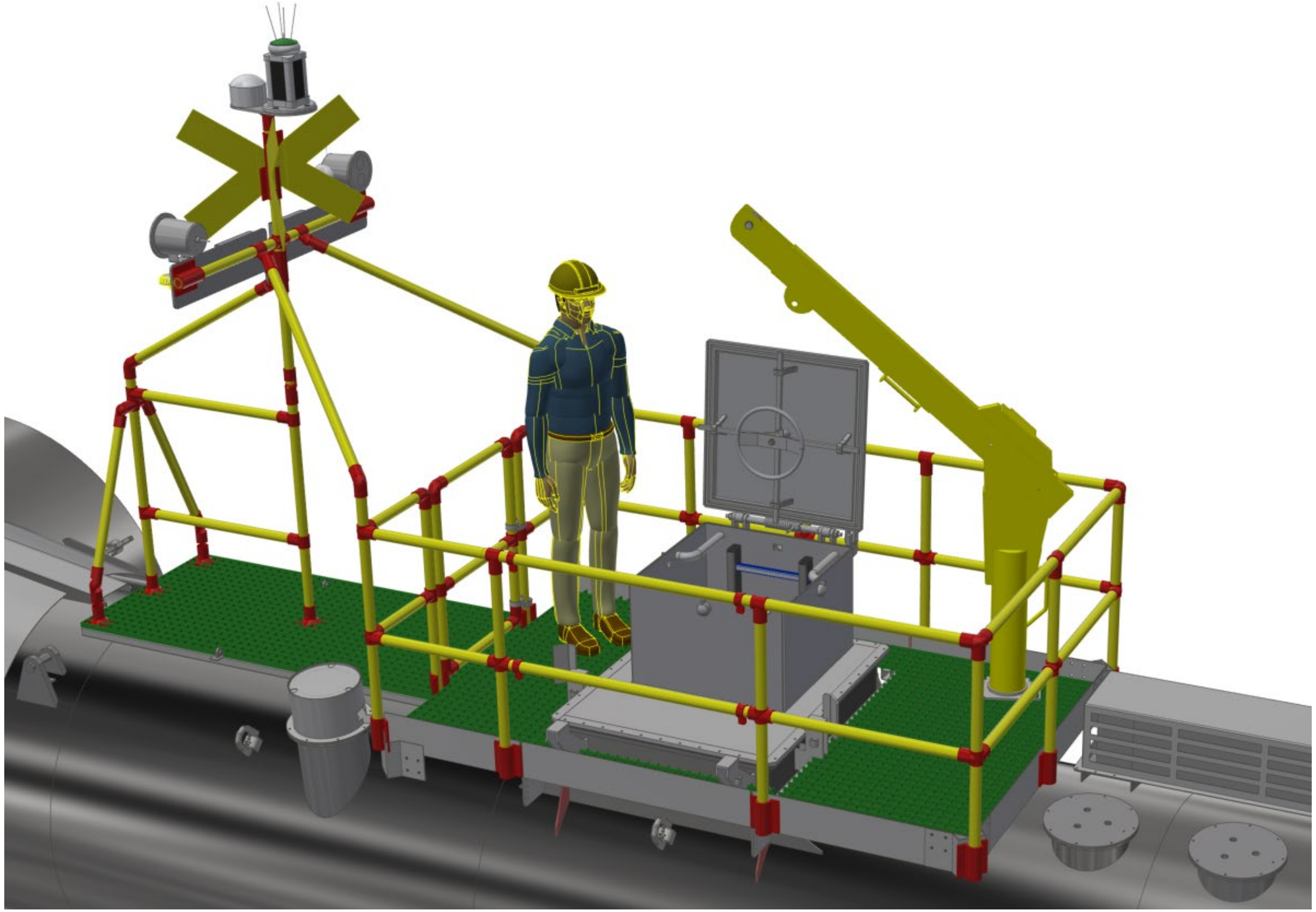
AJS Production Ltd



- Maestro developed an FE global structural model and an FE hydrodynamic model to determine loads;
- They performed a spectral fatigue analysis using the model and iterated it to optimize the design.
- Blackfish developed the detailed structure and weldments using FE stress analysis to fine tune the design.
- AJS to fabricate WEC structure, rigs, jigs and tooling

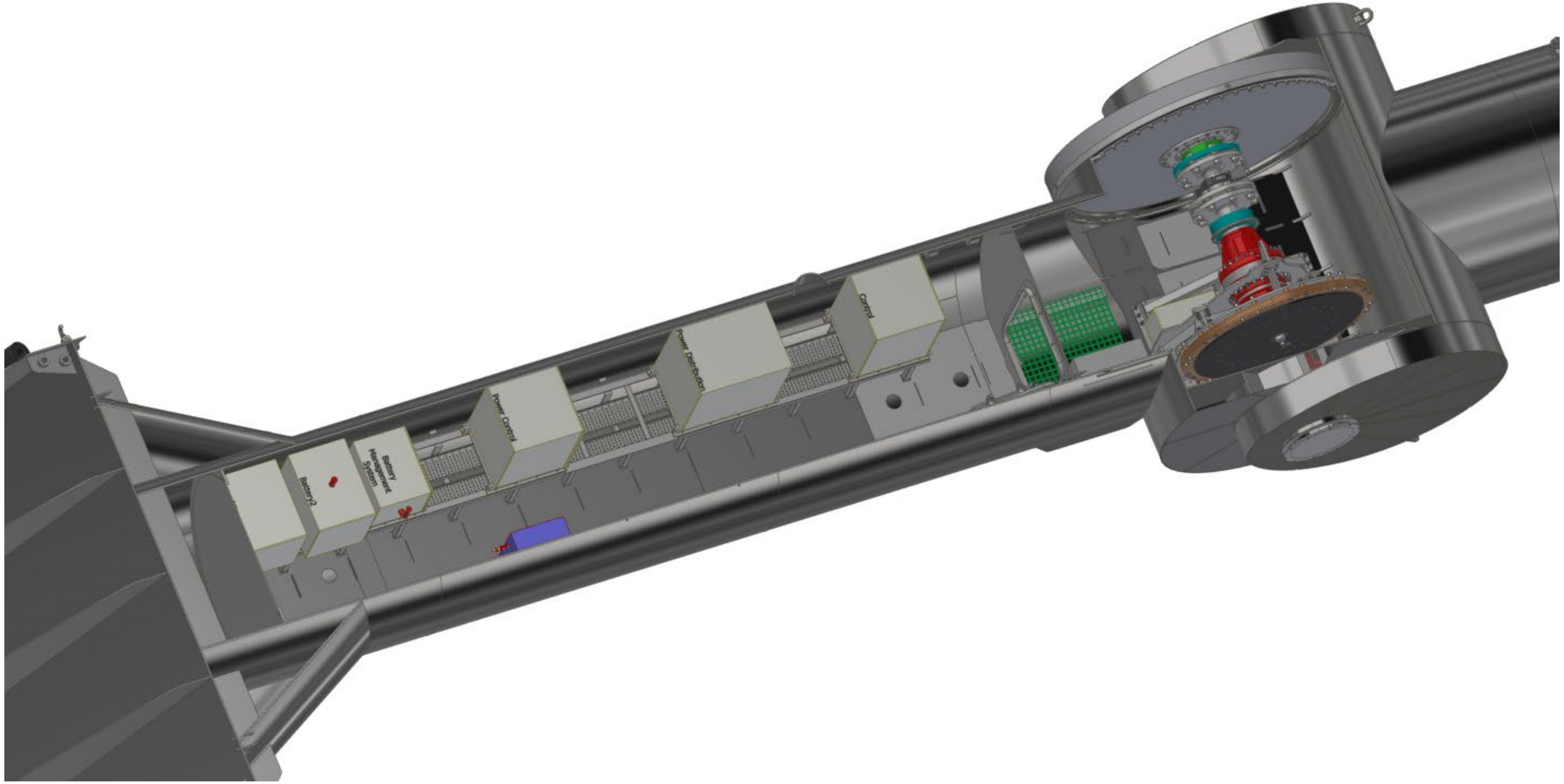
Access

- Access via hatch; davit arm lifts in equipment and provides person rescue in emergency
- Cylindrical caps cover the electrical penetration plates.
- Mast carries navigation aids, cameras and sensors and a weather station
- Dump resistor on forward deck provided as the electrical load.



Internal View

- Hull holds Cabinets including:
    - Batteries + management
    - Power control and distribution
    - WEC control
- Nacelle contains the PTO
- Cameras and sensors are distributed through hull and nacelle and include torque, speed, temperature, humidity, motion, bilge level etc.

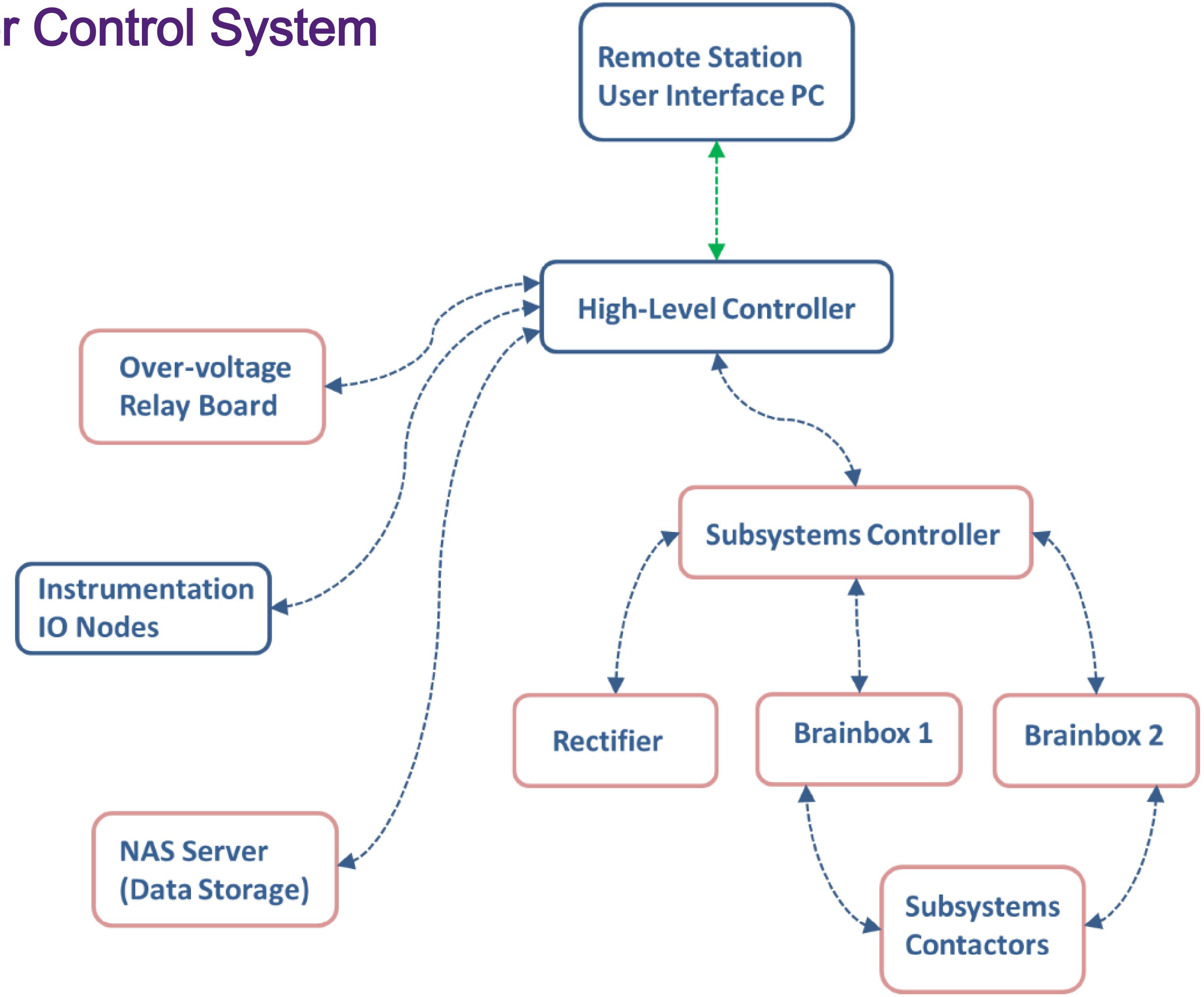


Power Control System

SUPPLYDESIGN
BESPOKE ELECTRONICS

industrial systems and control

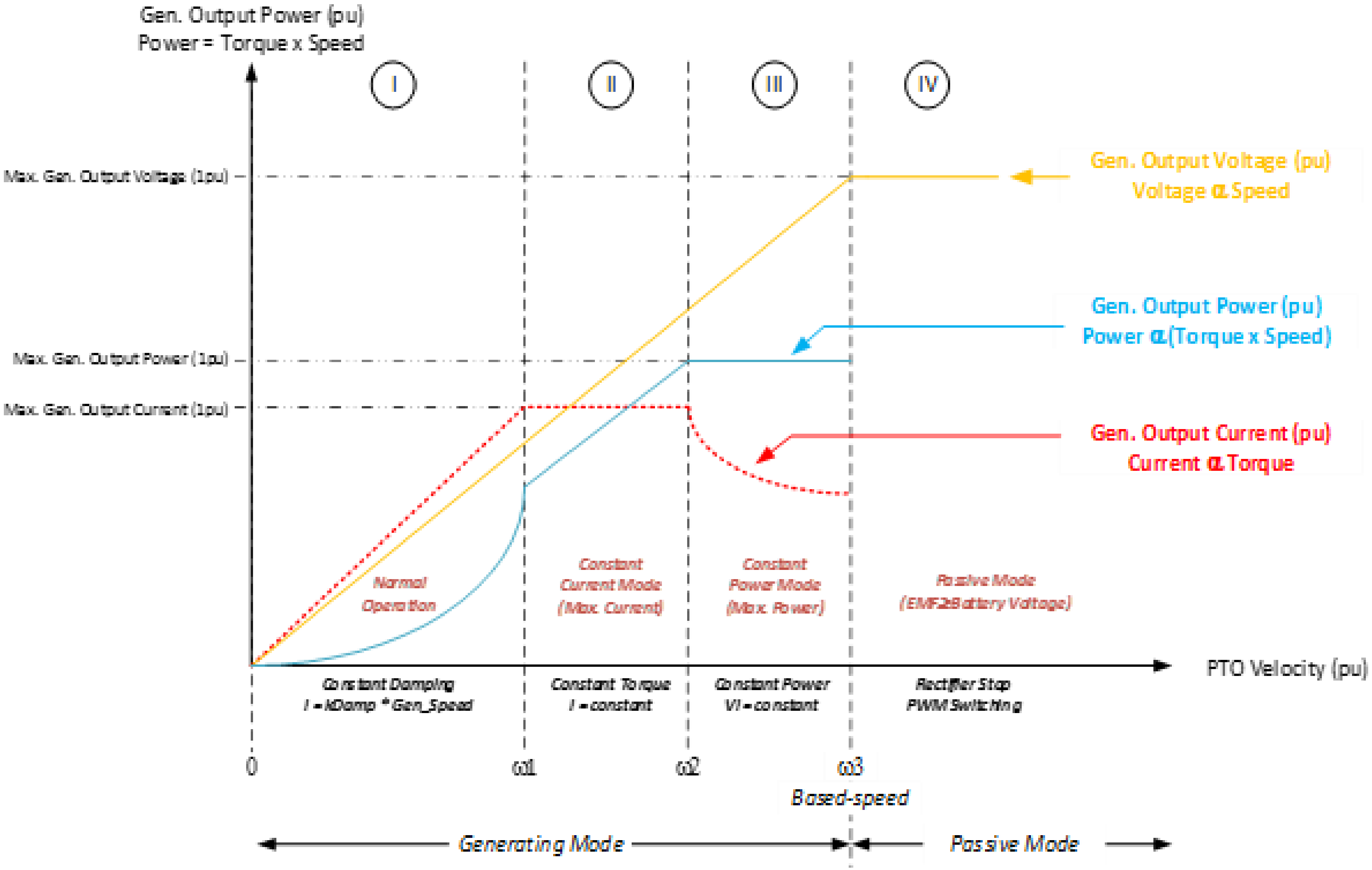
sequentec
specialist electronic systems



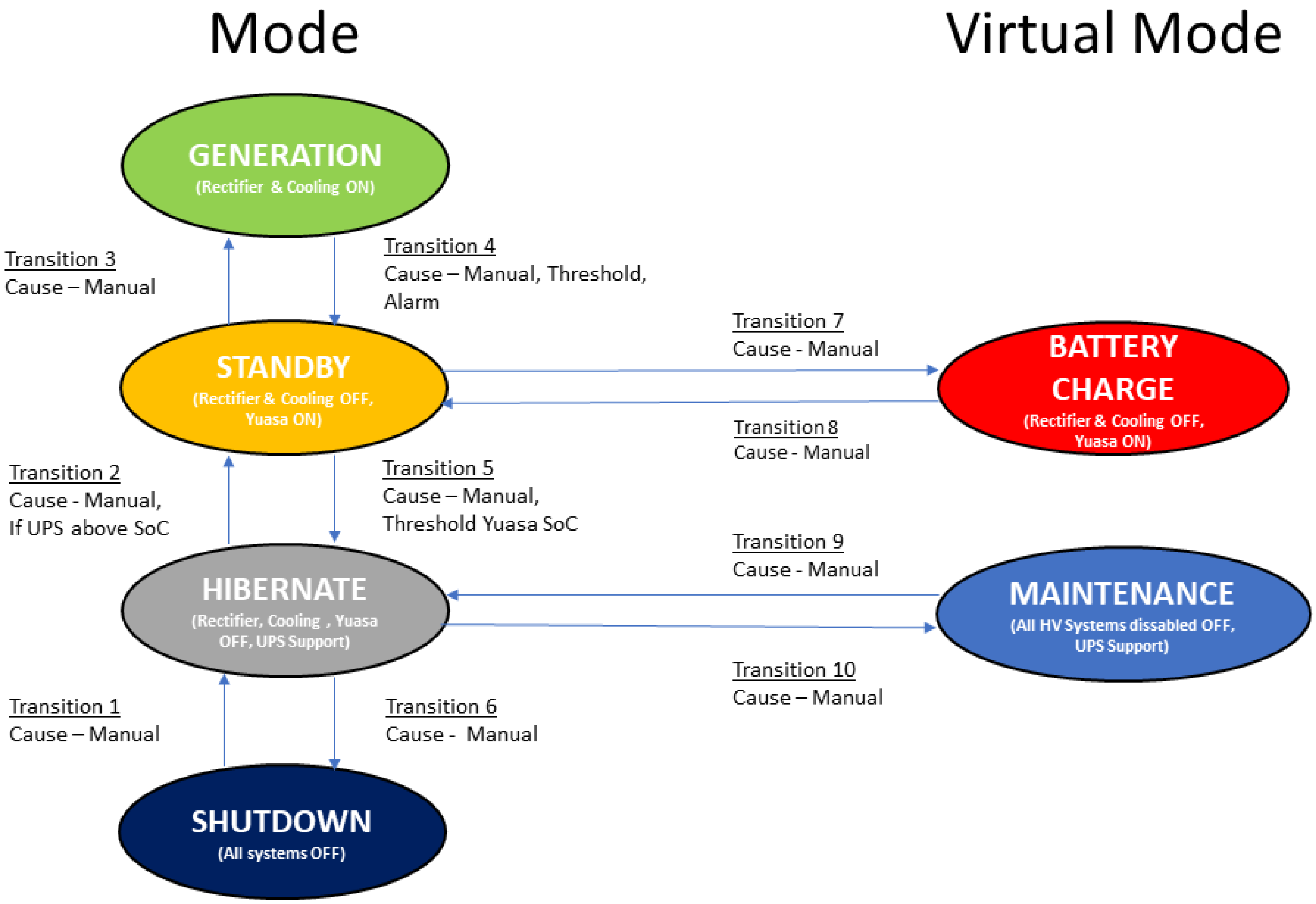
- User Interface (remote access) – ISC
- HLC (on board high-level controller) – ISC
- SSC (on board sub-systems controller) and rectifier – SDL
- Comms and data storage - SEQ

Power Operating Modes

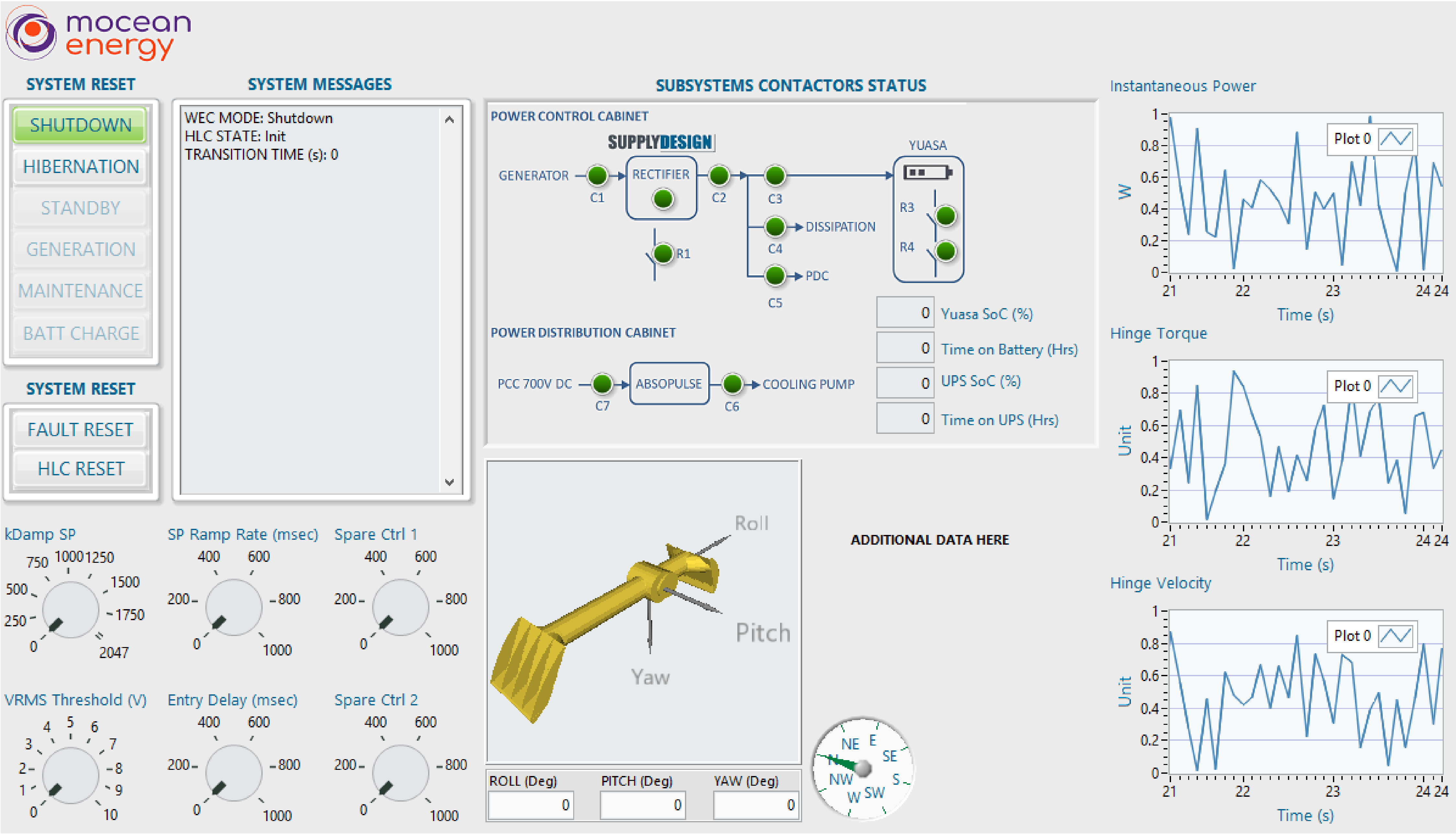
SUPPLYDESIGN
BESPOKE ELECTRONICS



System Operating Modes



Remote Interface

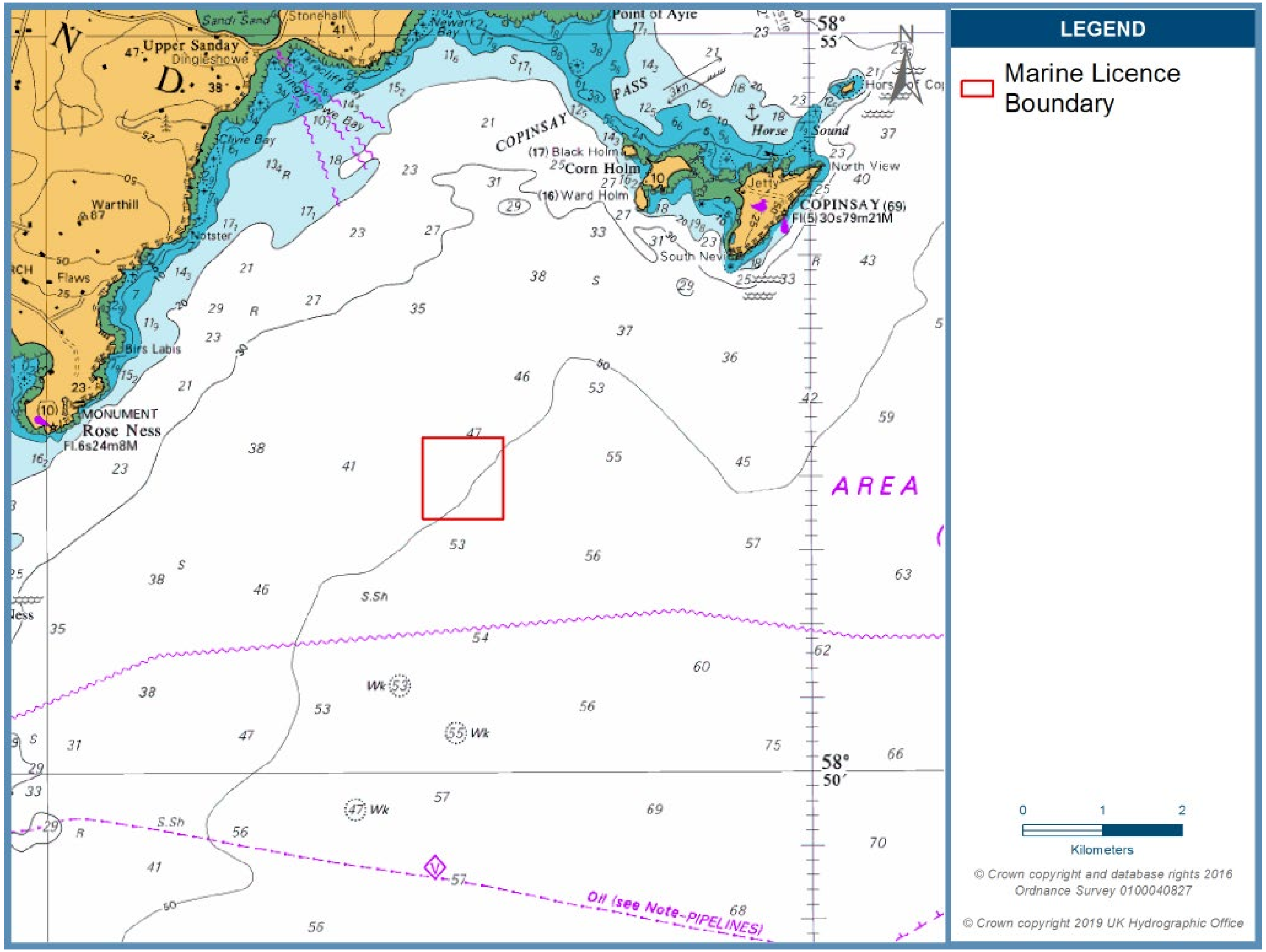


Scale selection, Site Selection

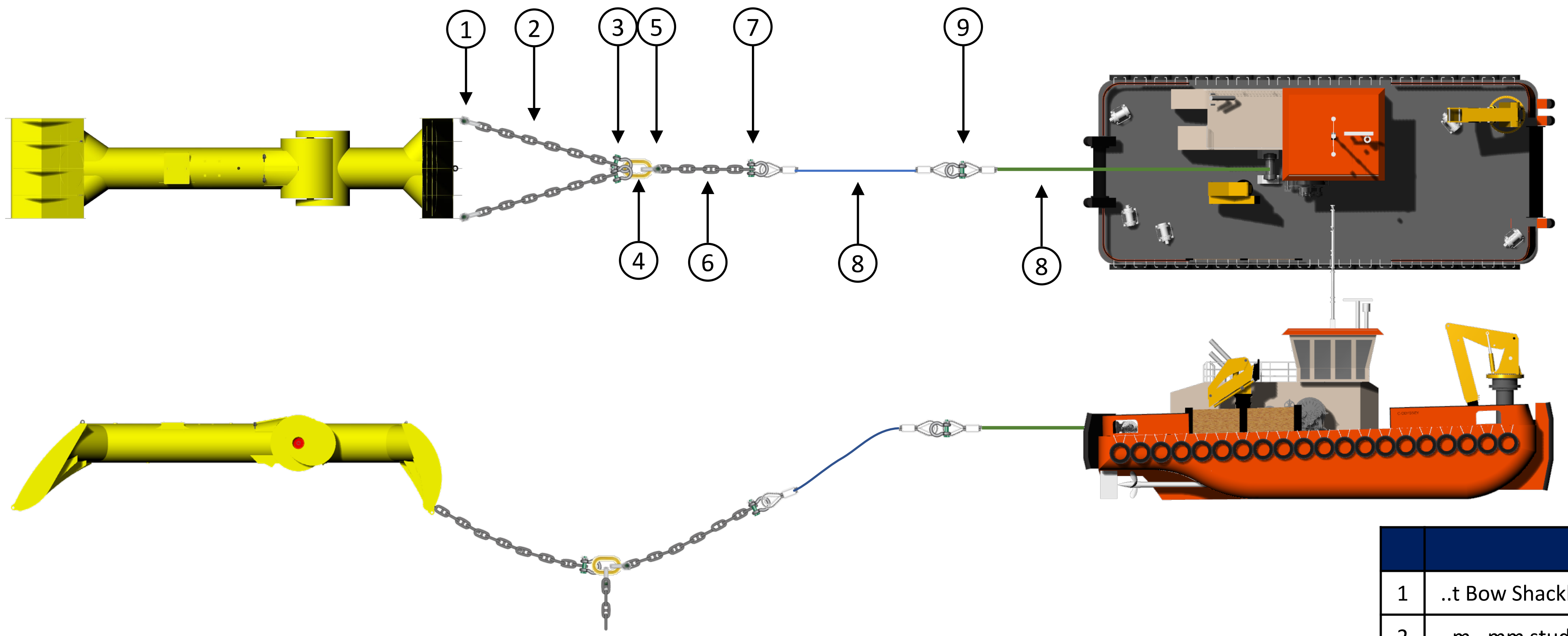
- The M100P prototype is ½ scale; the scale was chosen to be as large as possible to provide a convincing demonstration of the technology – but limited by cost.
- The appropriate half -scale, power -performance waves must be selected appropriately.
- The prevailing wave conditions at the EMEC Bilia Croo site were found to be too long and high for the M100P. Conversely, the waves at the EMEC Scapa Flow site were found to be too small.
- Alternative sites were assessed; GIS mapping used to identify appropriate conditions.
- A site east of the mainland was selected. Operations will be conducted from Kirkwall.

Licensing, permitting, surveys, verification

- The M100P will be installed at a location south-east of the island of Copinsay, shown as the red square.
- The site has been chosen from the GIS study as optimal with respect to traffic, fishing, protected areas, water depth, seabed conditions, waves and currents and access to ports and safe anchorages.
- Permitting and licensing is underway

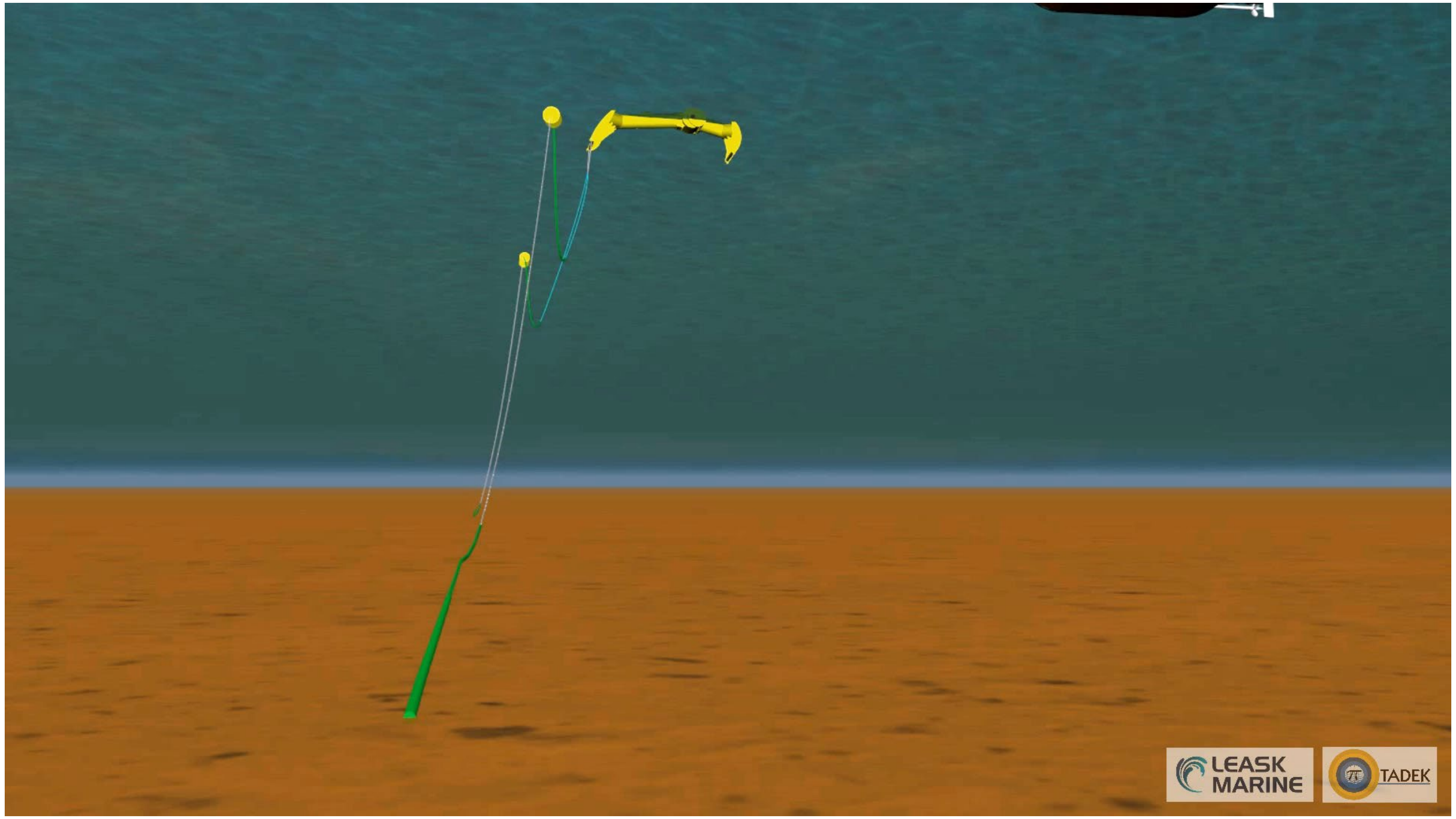


Operations: Tow to site



	Description	Qty.
1	..t Bow Shackle	2
2	..m ..mm studlink Chain	6
3	..t Bow Shackle	2
4	Masterlink	2
5	35t Bow Shackle	2
6	20m 80mm Grommet c/w thimbles eys and masterlink	1
7	35t Bow Shackle	1

Mooring



Project status

Completed so far

- Design work 85% complete – topside structures to follow
- Back-to-Back Test Rig operative
- WEC fabrication begun – first tubes rolled
- Licence and lease application in
- Operational planning underway

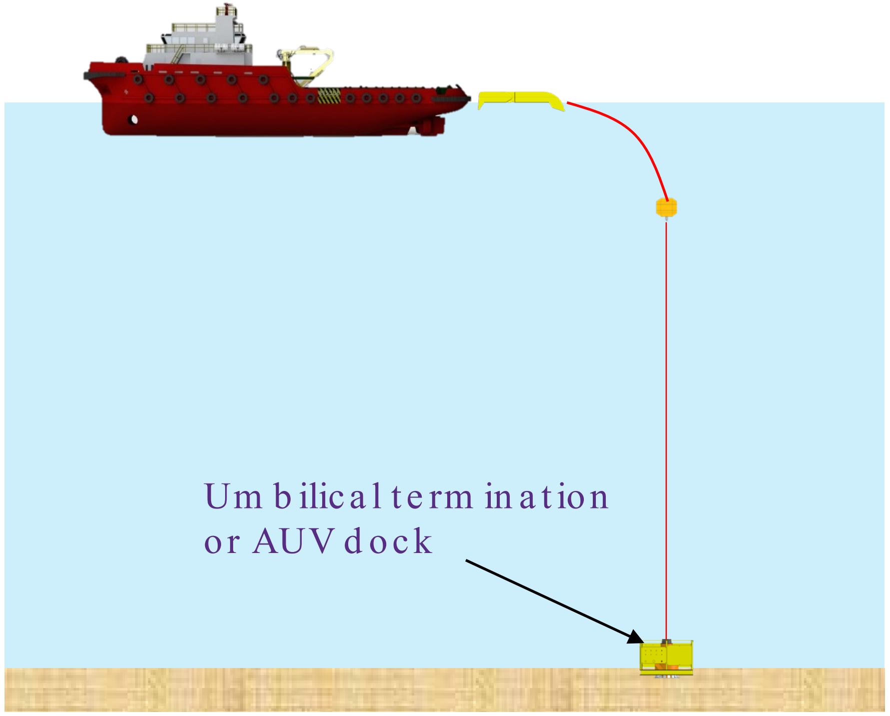
And in 2020…

- Test launch WEC, road transport to Orkney
- Operations team move to Orkney
- Testing scheduled to begin in May 2020

Blue Star

- *Blue Star* is a hinged raft wave energy converter.
- It will provide power and communications to offshore O&G applications.

Power	2-4 kW average generation in North Sea. 50 kWh onboard battery to deliver higher power levels as required.
Dimensions	Fits in shipping container 15 tons
Comms	4G Tampnet Satellite
Mooring	Simple mooring / umbilical with AUV dock or UTA as gravity anchor
Operations	Operations designed to be safe, inexpensive and fast



Other Markets

There are numerous applications for different products in other markets.

Ocean Science and Survey

Offshore Platforms

Utility Scale Power

1% of worldwide nearshore wave resource worth £12B

Remote Resorts and Communities

Offshore Aquaculture

ARTEMIS INTELLIGENT POWER

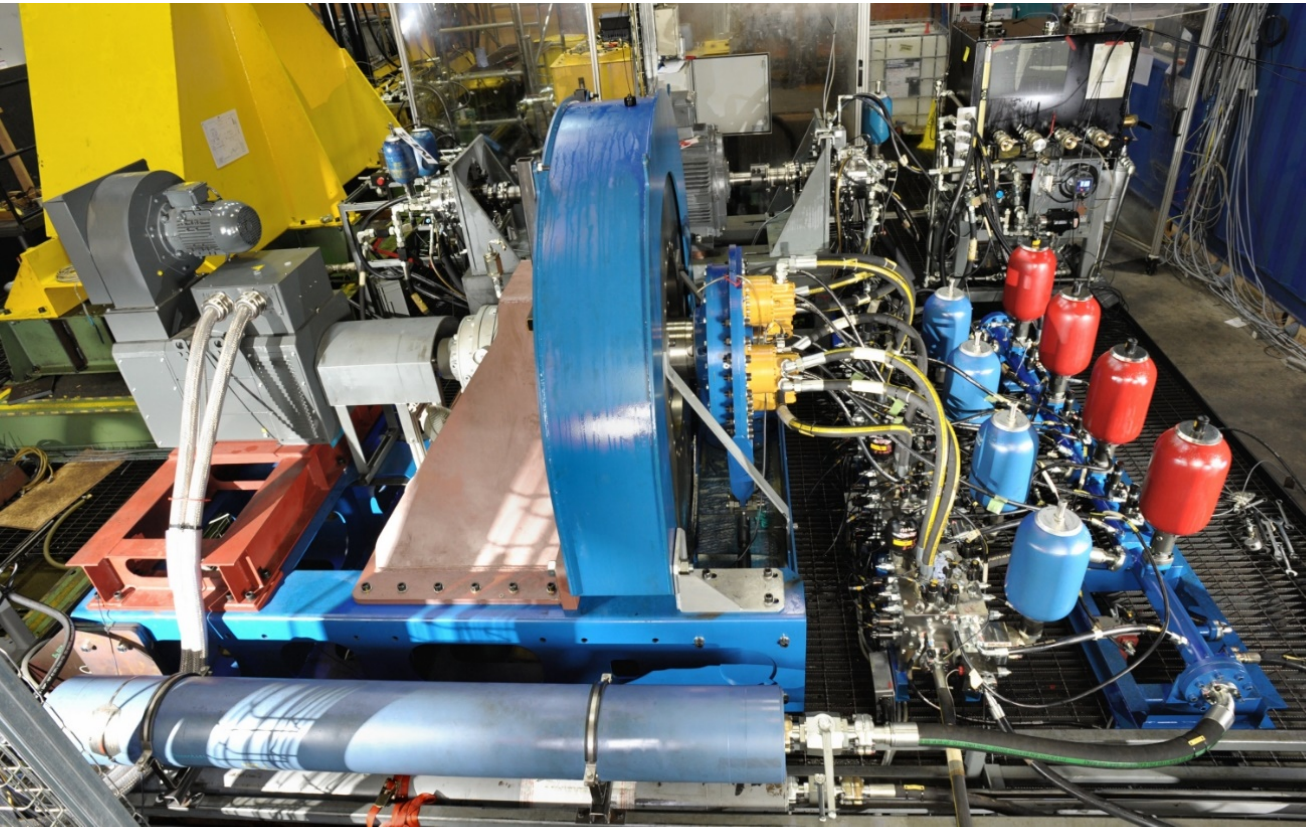
wave energy SCOTLAND

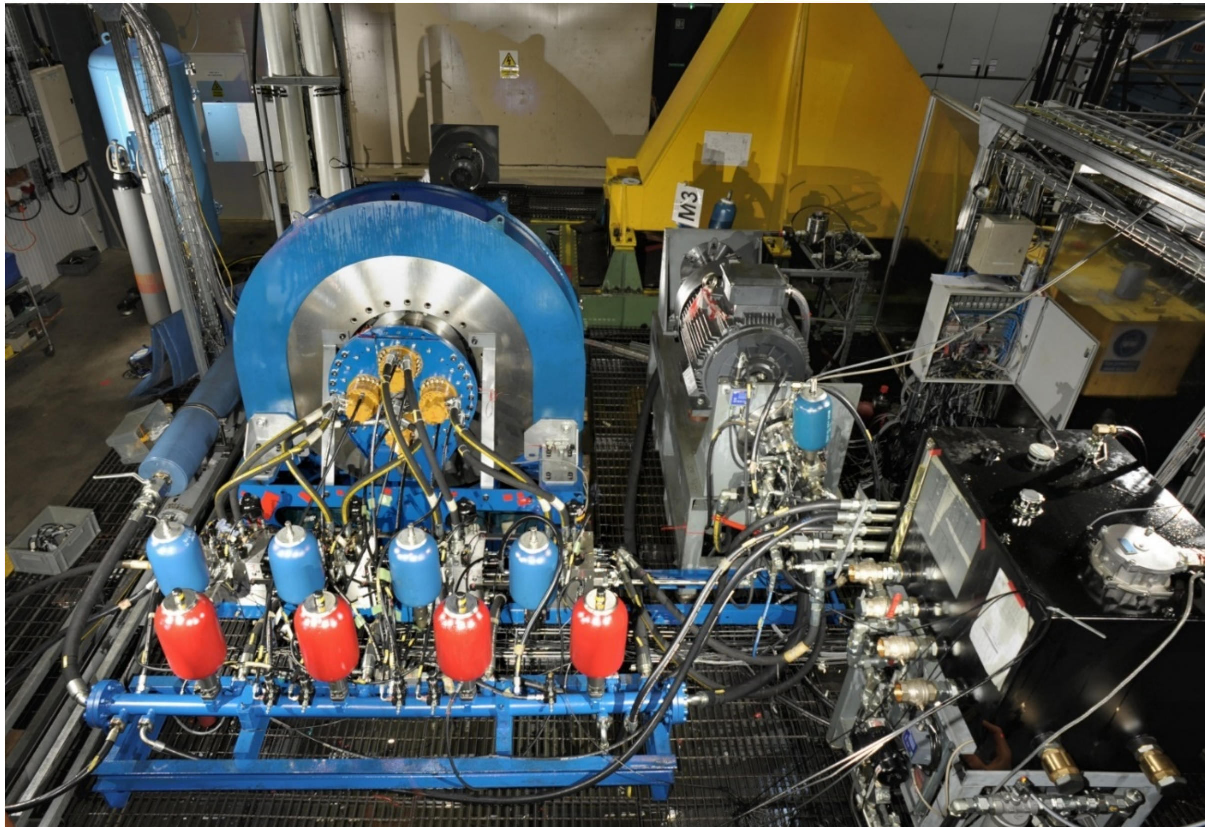
Quoceant Innovation Offshore

QUANTOR

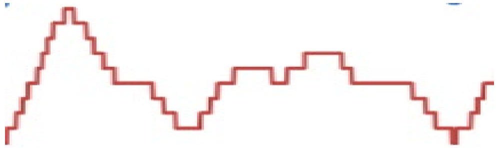
Hybrid digital hydraulic power-take-off

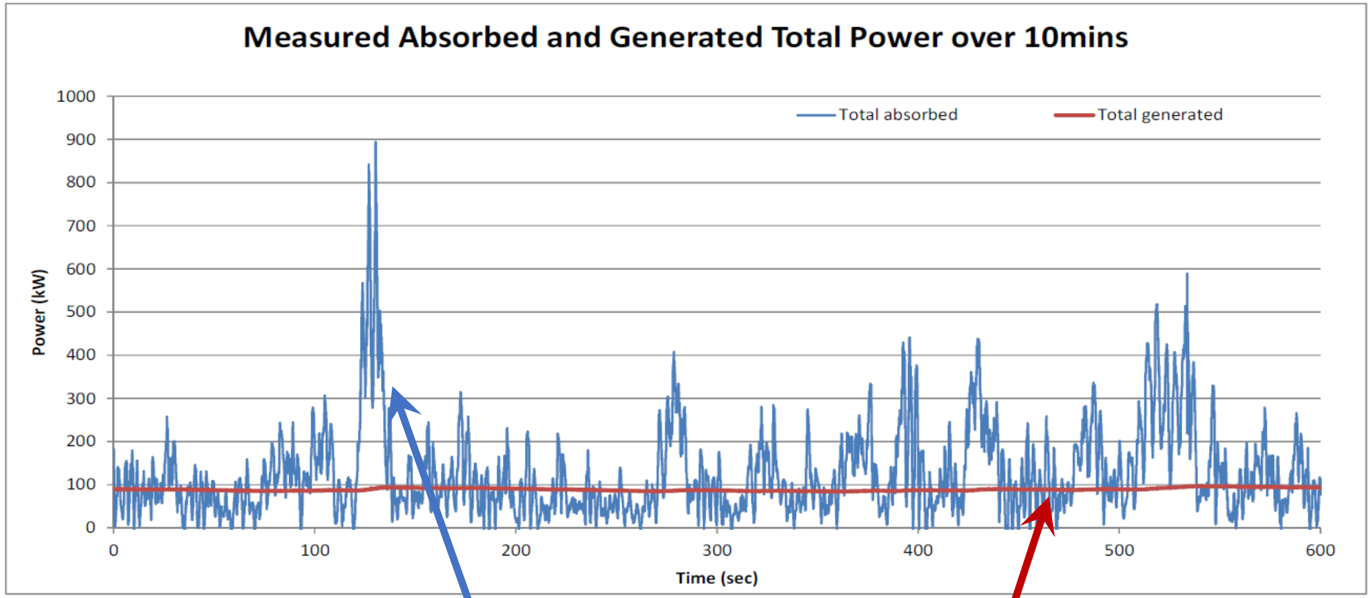
WES annual conference, 5th December 2019

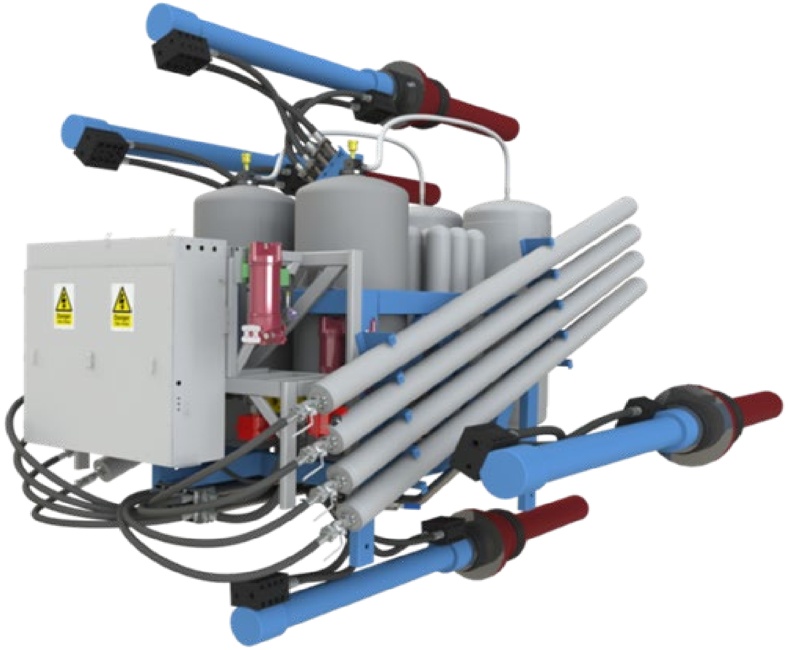




- *What is Quantor?*
  - ***Based on Pelamis PTO***
  - ***Highly effective and efficient, proven in the field, iteratively improved…***
  - ***…but with major flaw limiting control potential and general applicability***
  - ***Want to retain all advantages while introducing: continuous load control, rotary and winch capability***







Absorbed power from WEC to PTO

Output power from PTO to grid

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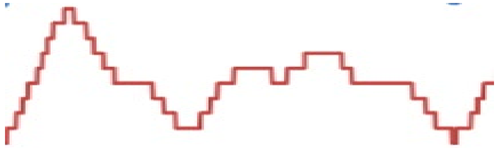
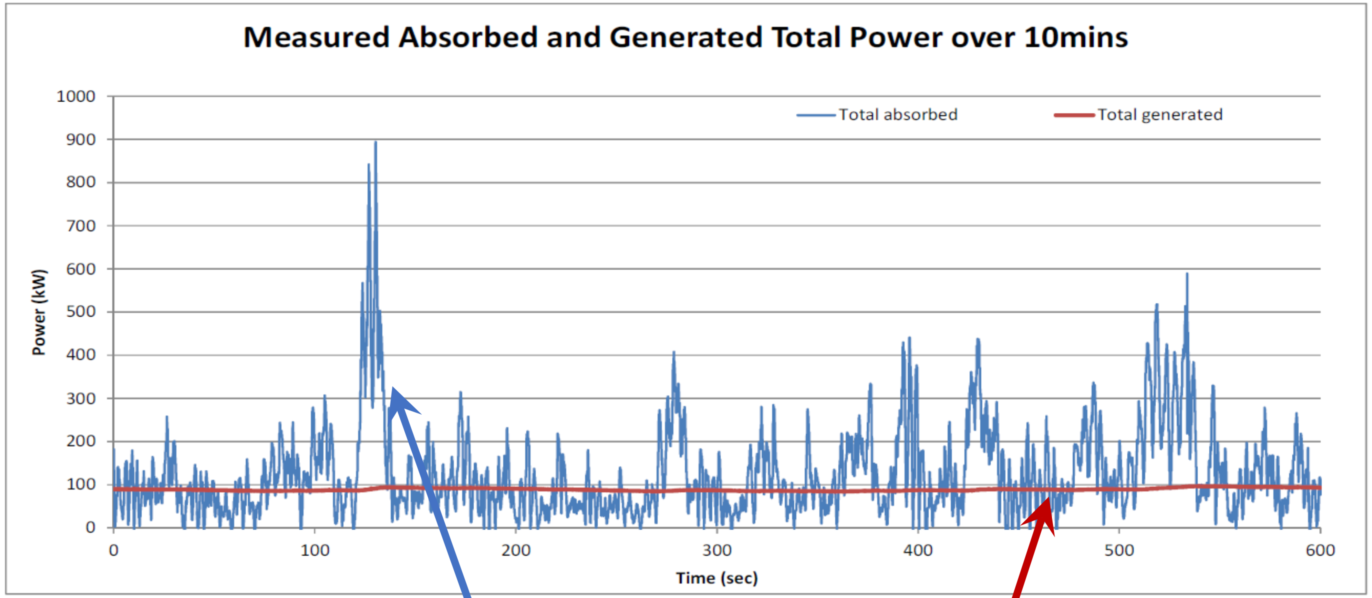
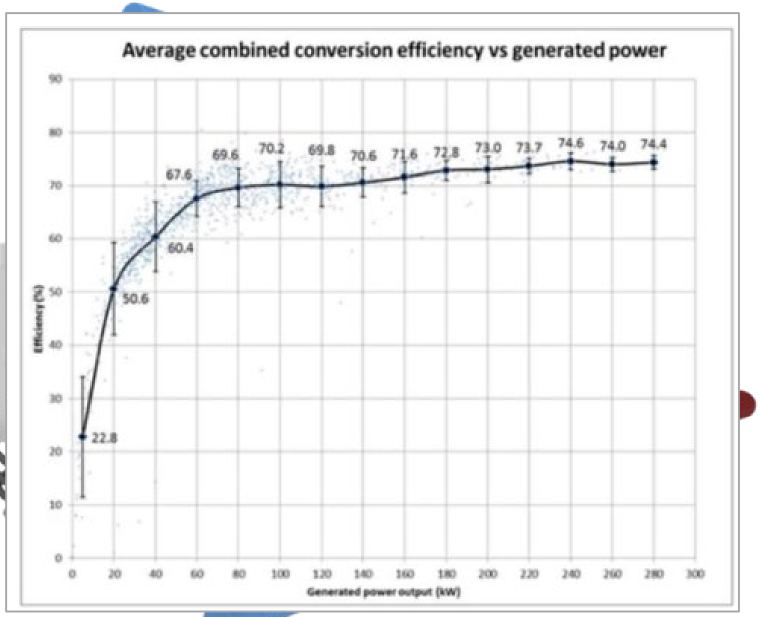
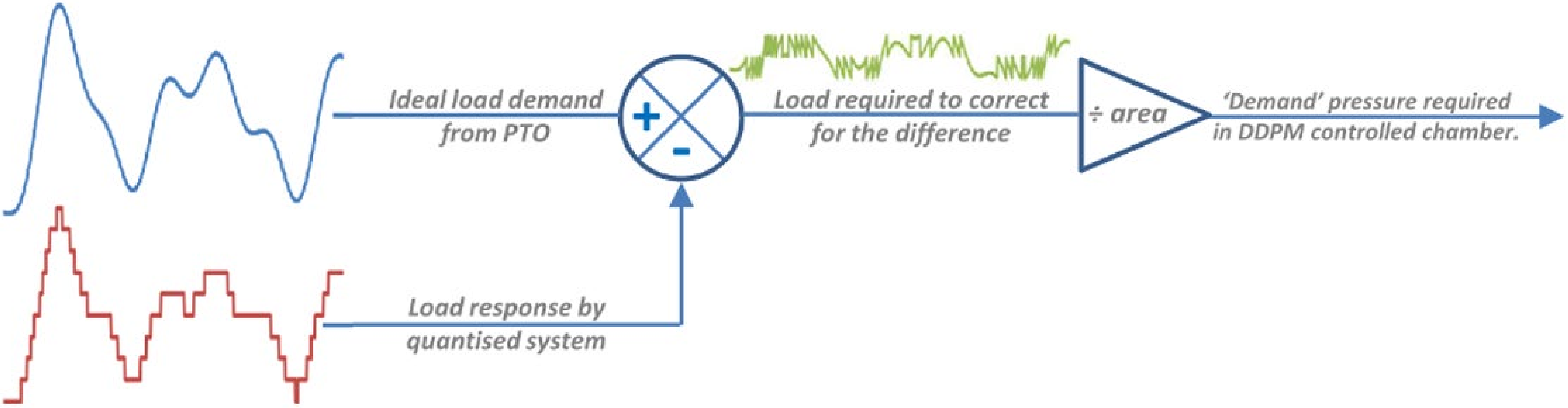


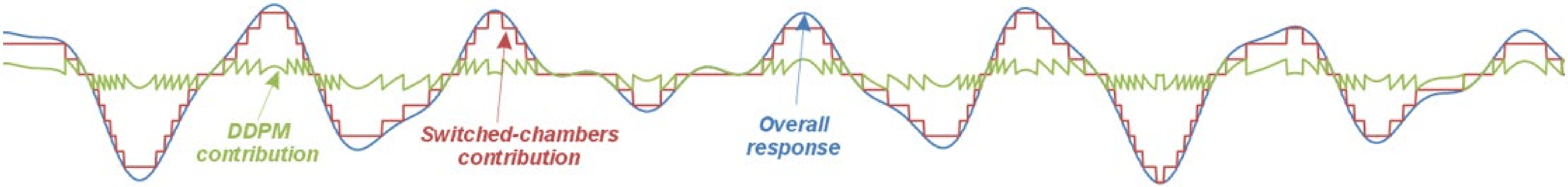


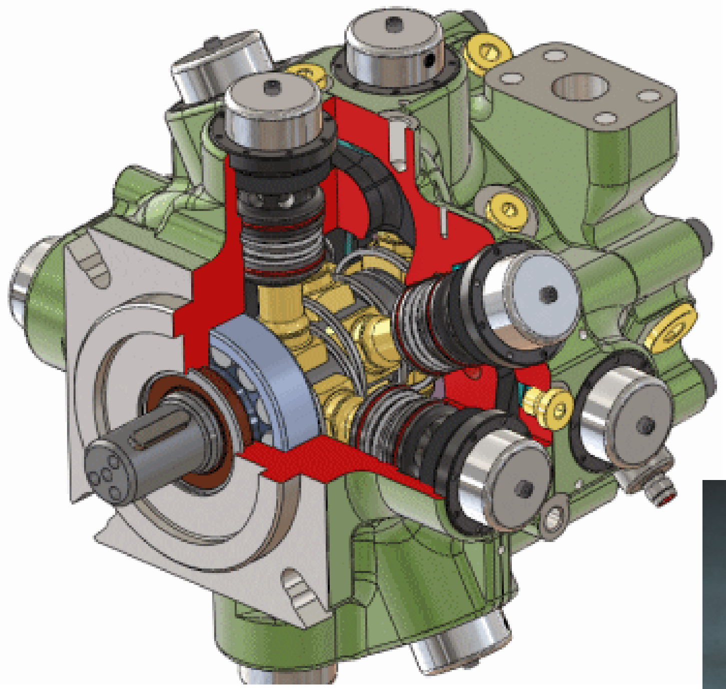


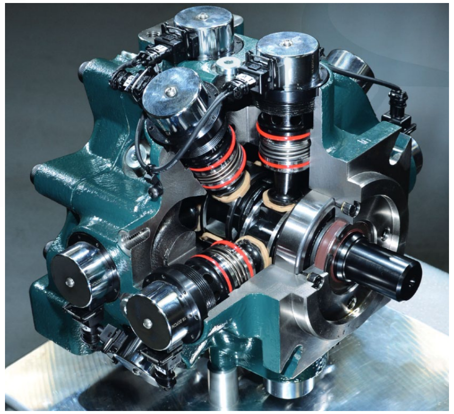
Absorbed power from WEC to PTO

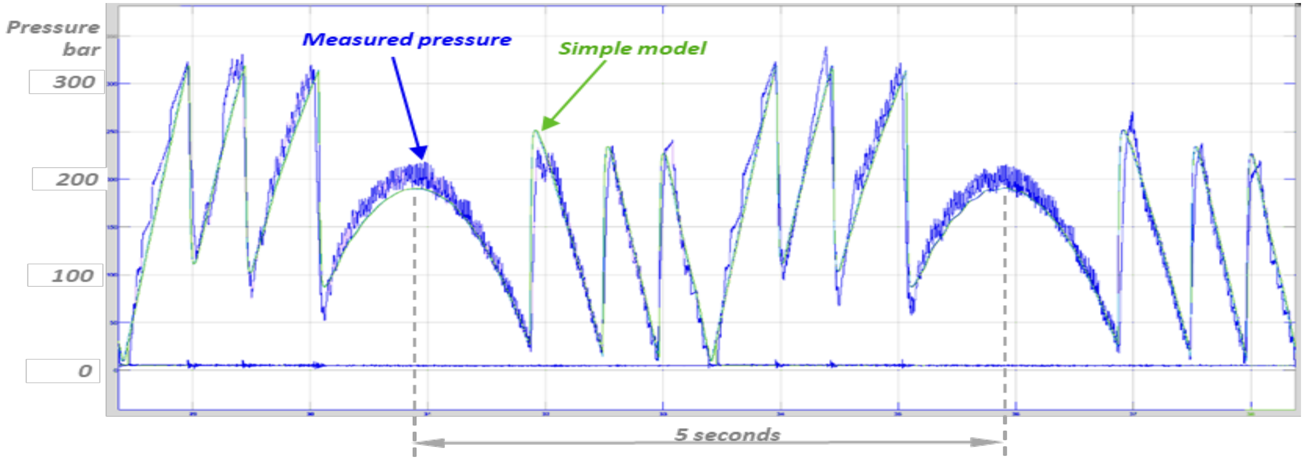
Output power from PTO to grid

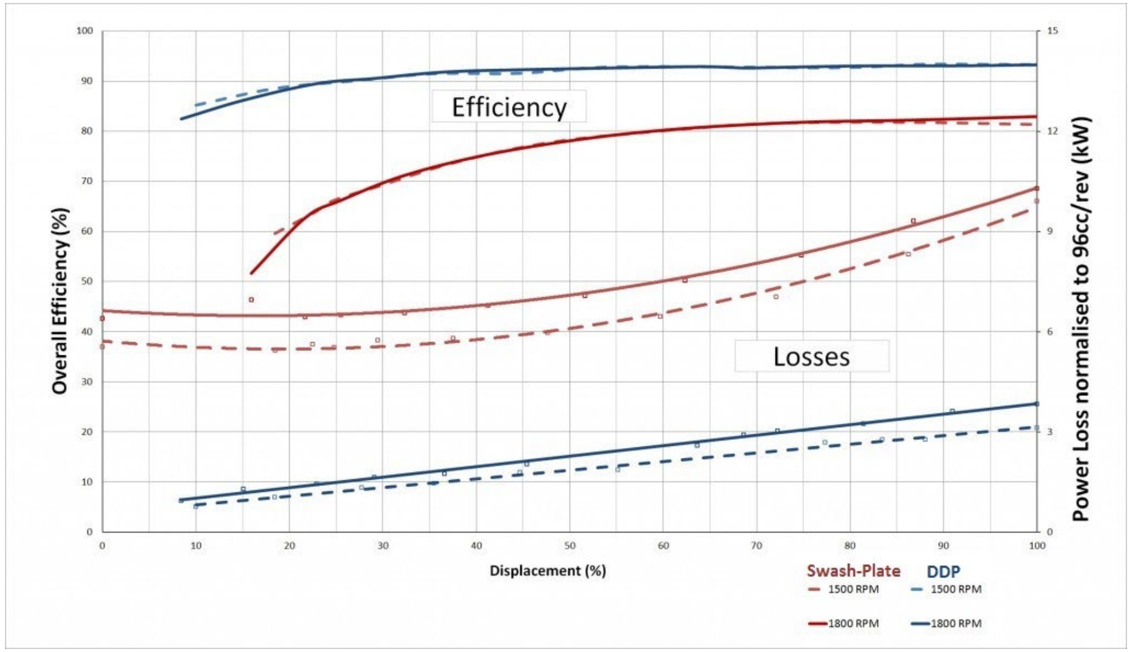

Ideal load demand from PTO
+
-
Load required to correct for the difference
÷ area
'Demand' pressure required in DDPM controlled chamber.
Load response by quantised system


DDPM contribution
Switched-chambers contribution
Overall response



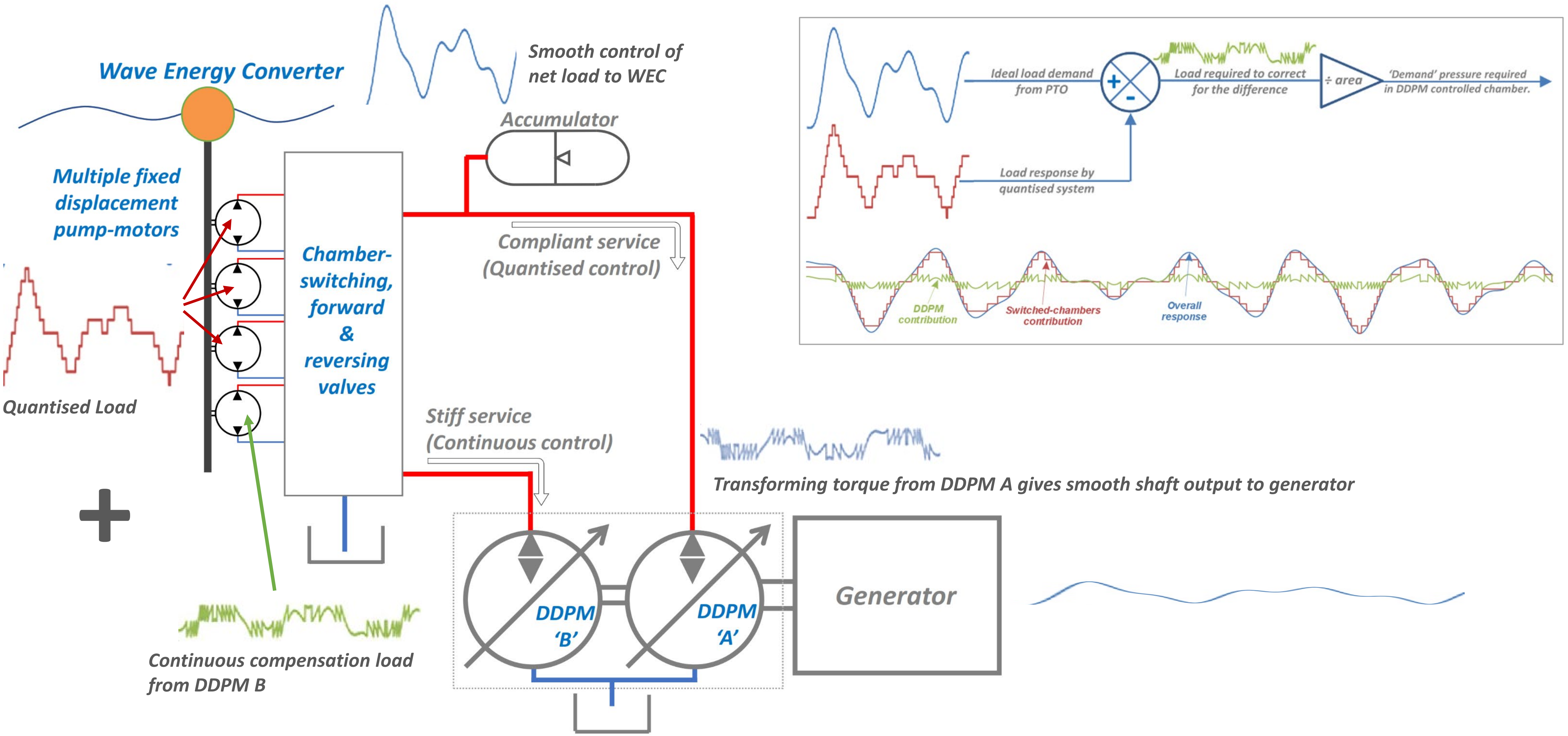


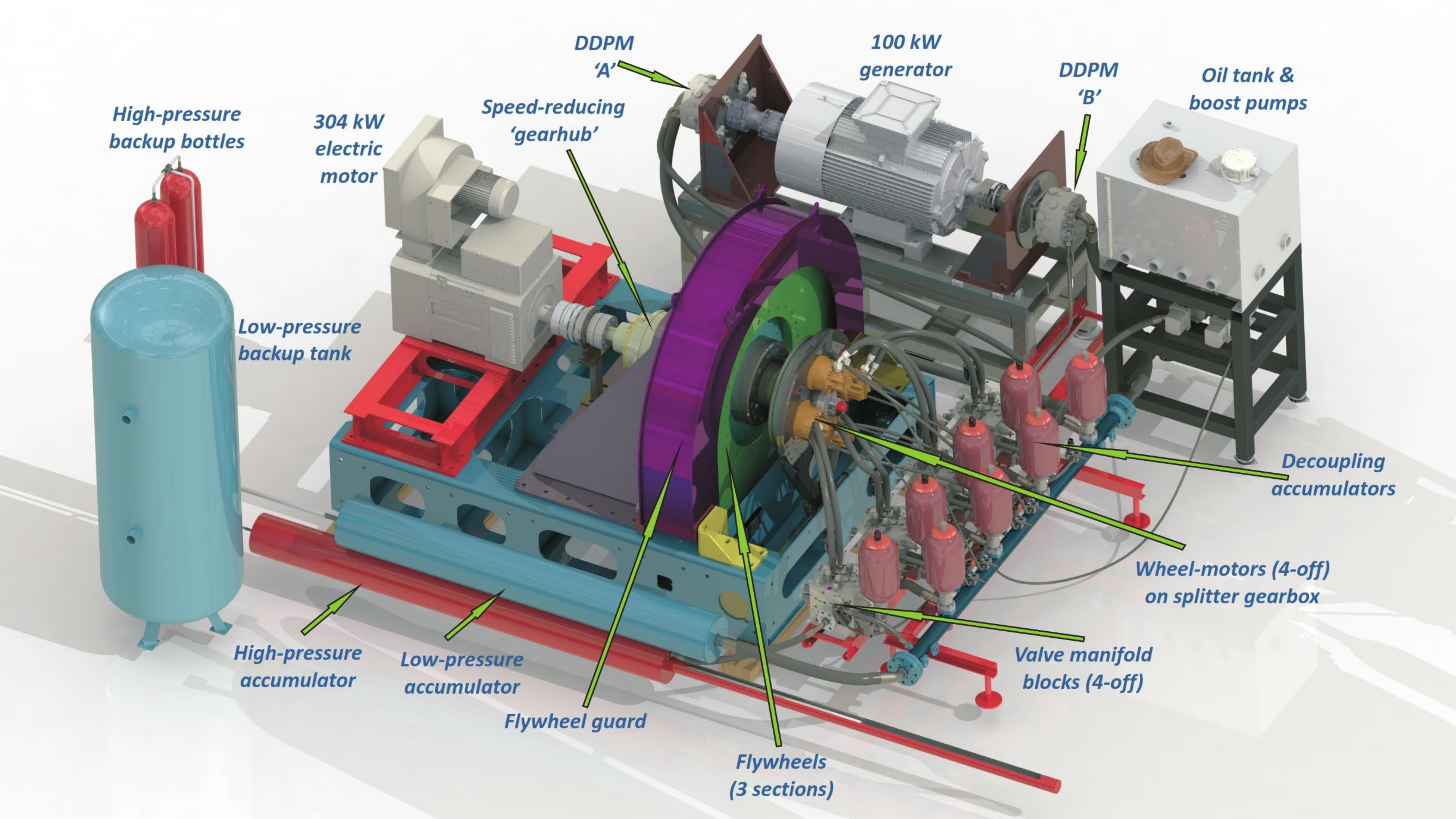




Digital Displacement Pump-Motor (DDPM) by Artemis.

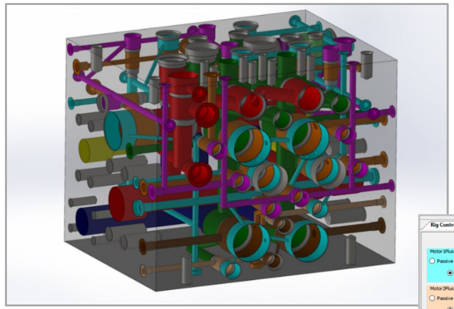
Provides highly responsive continuous pressure control at high efficiency

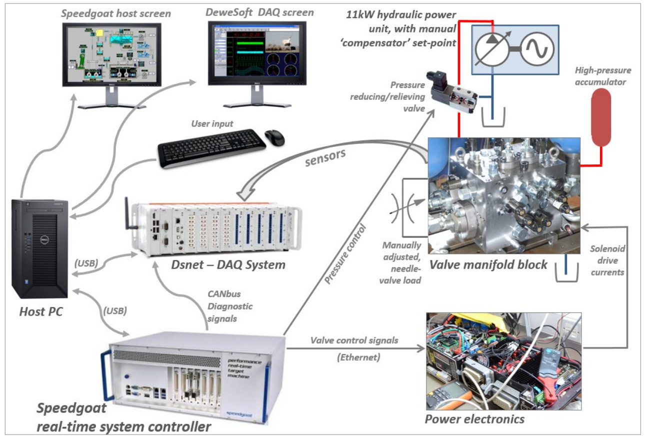

Wave Energy Converter
Smooth control of
net load to WEC
Accumulator
Multiple fixed
displacement
pump-motors
Chamber-
switching,
forward
&
reversing
valves
Compliant service
(Quantised control)
Quantised Load
Stiff service
(Continuous control)
Transforming torque from DDPM A gives smooth shaft output to generator
DDPM
'B'
DDPM
'A'
Generator
Continuous compensation load
from DDPM B
Ideal load demand
from PTO
Load required to correct
for the difference
÷ area
'Demand' pressure required
in DDPM controlled chamber.
Load response by
quantised system
DDPM
contribution
Switched-chambers
contribution
Overall
response

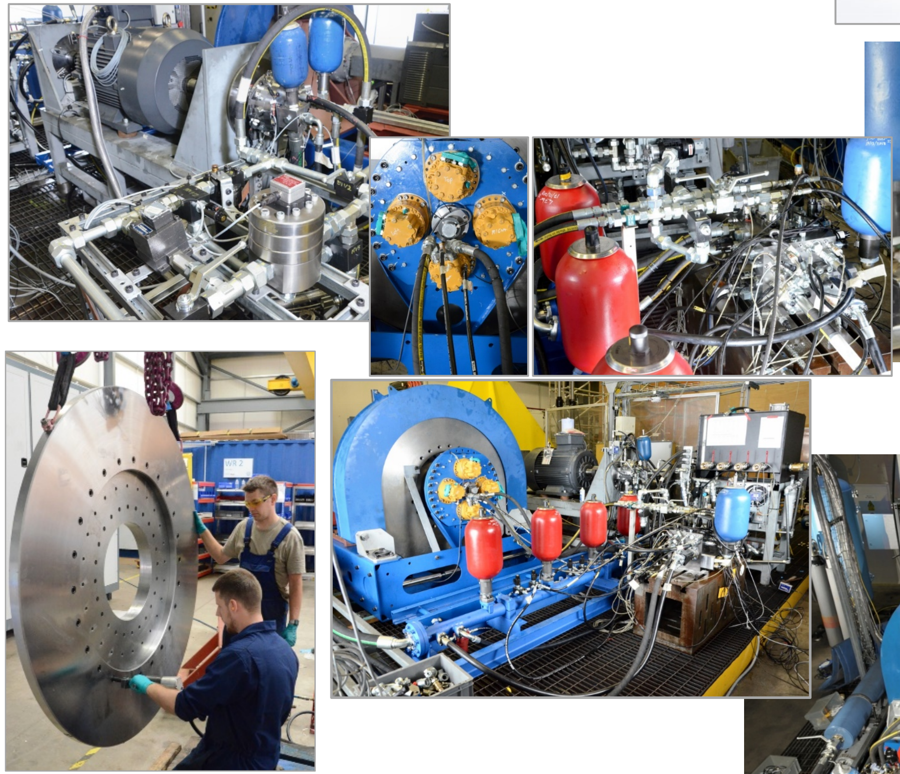

DDPM 'A'
100 kW generator
DDPM 'B'
Oil tank & boost pumps
High-pressure backup bottles
304 kW electric motor
Speed-reducing 'gearhub'
Low-pressure backup tank
Decoupling accumulators
Wheel-motors (4-off) on splitter gearbox
Valve manifold blocks (4-off)
High-pressure accumulator
Low-pressure accumulator
Flywheel guard
Flywheels (3 sections)

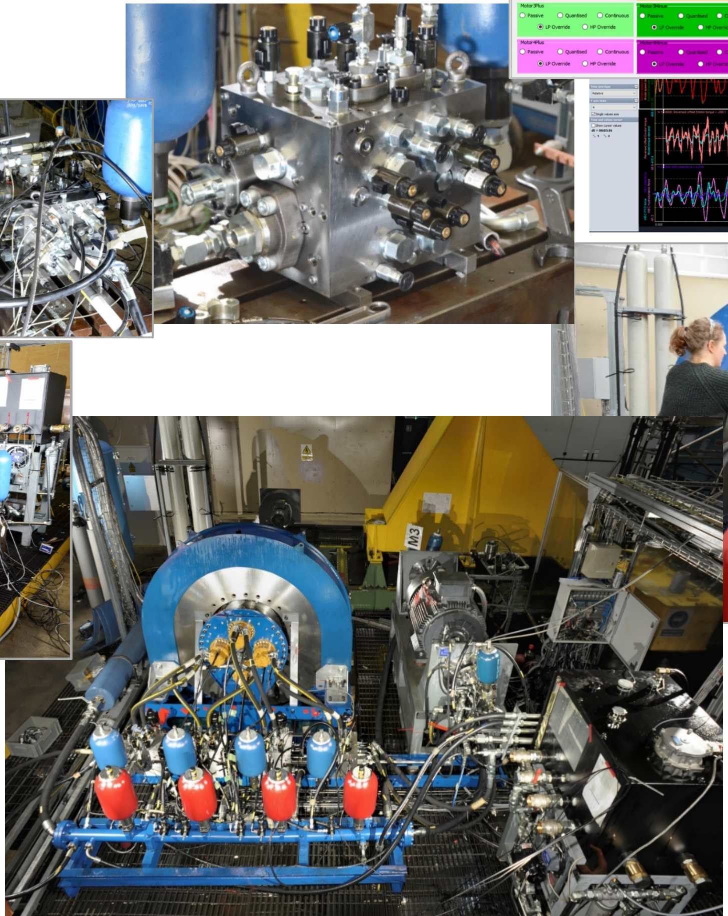
Early stages:

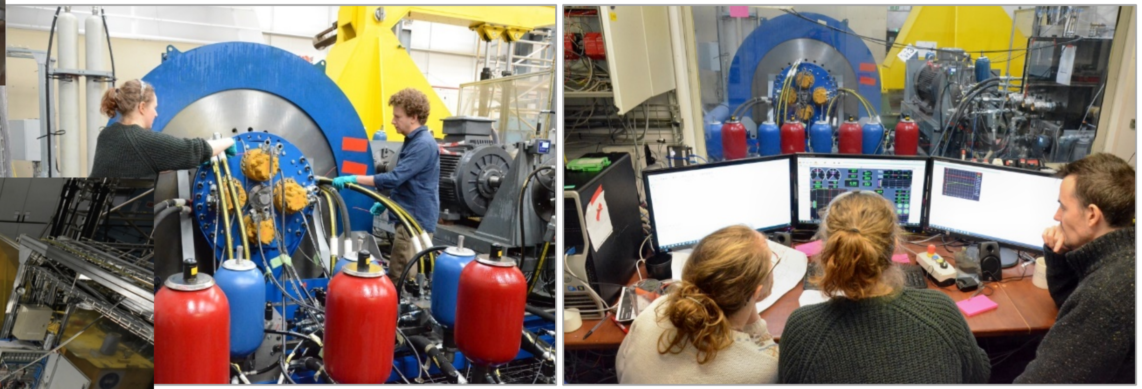
- *Development and demonstration*
- *Design, test, de-bug, evolve*





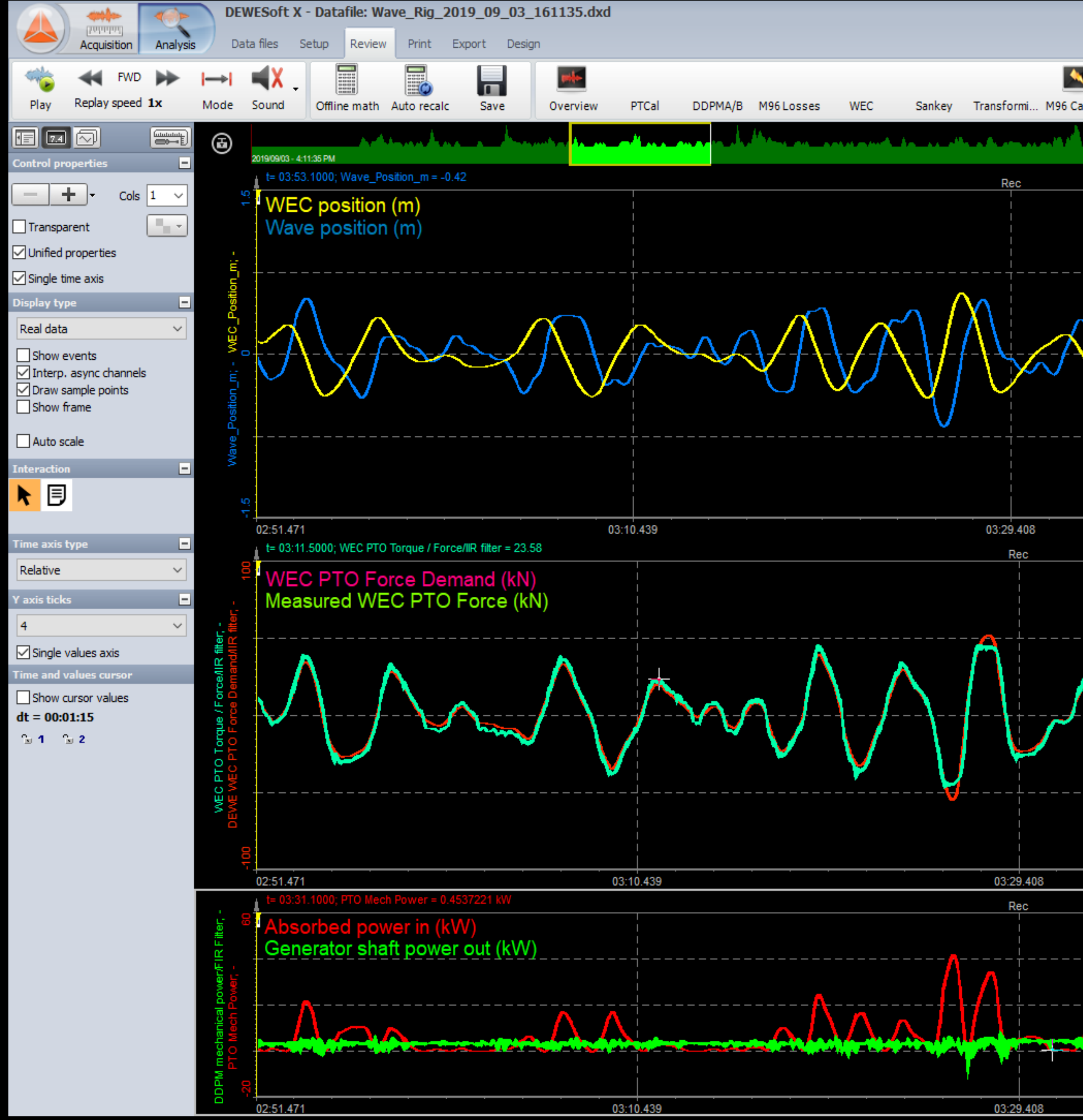


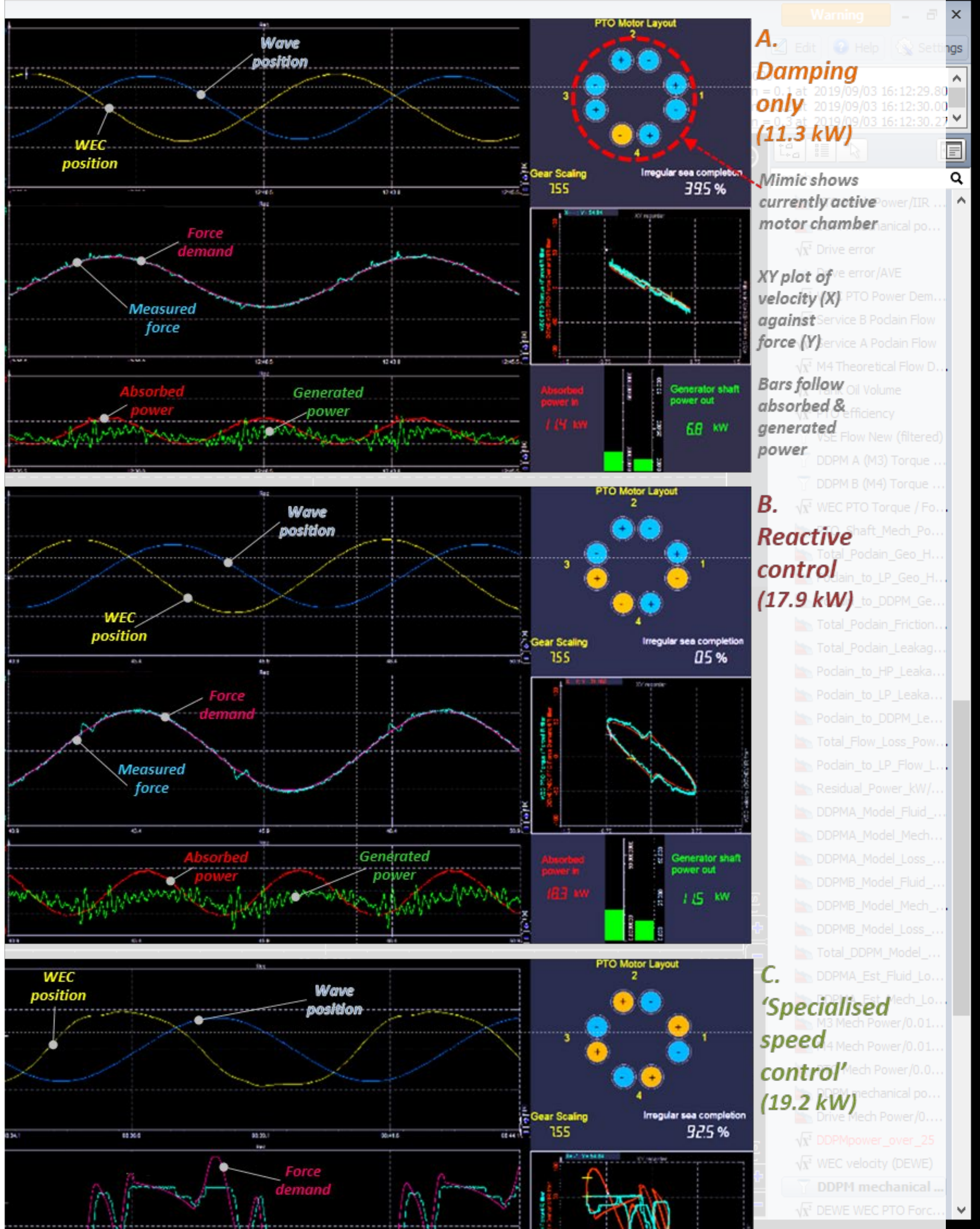


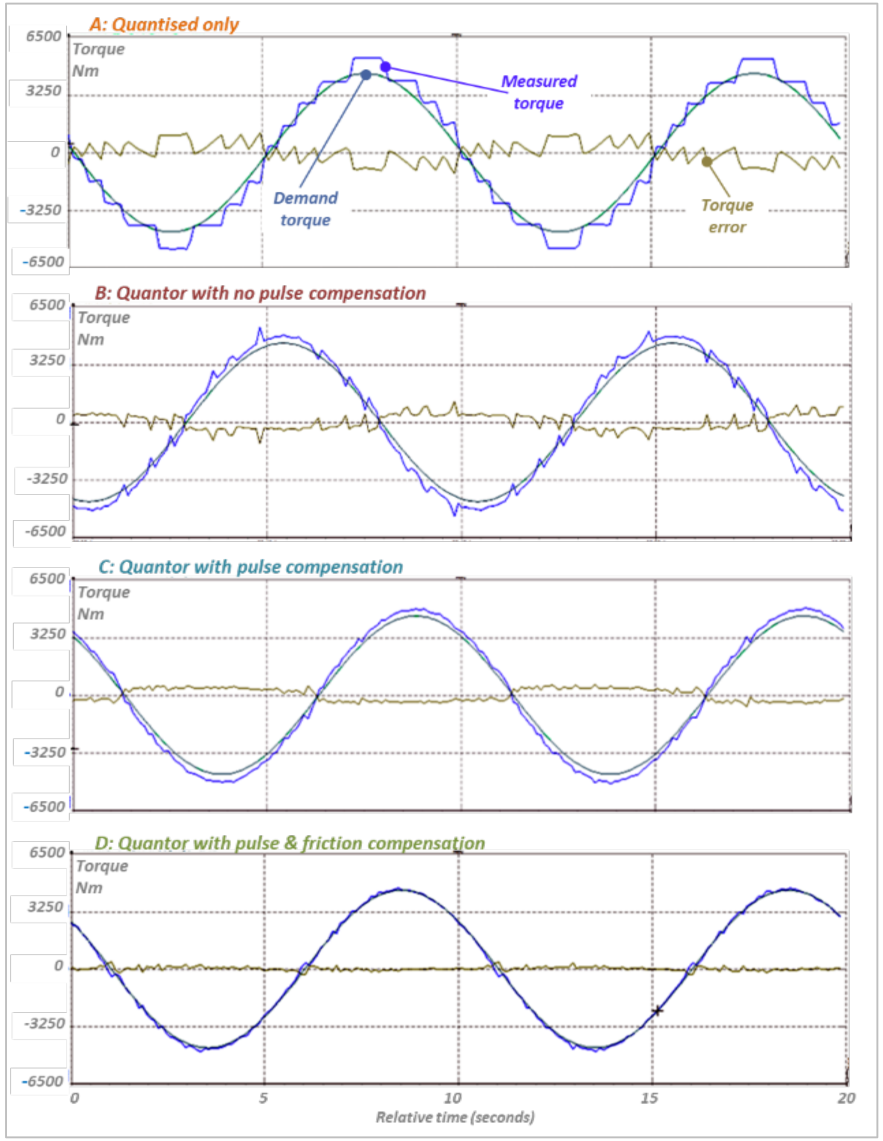


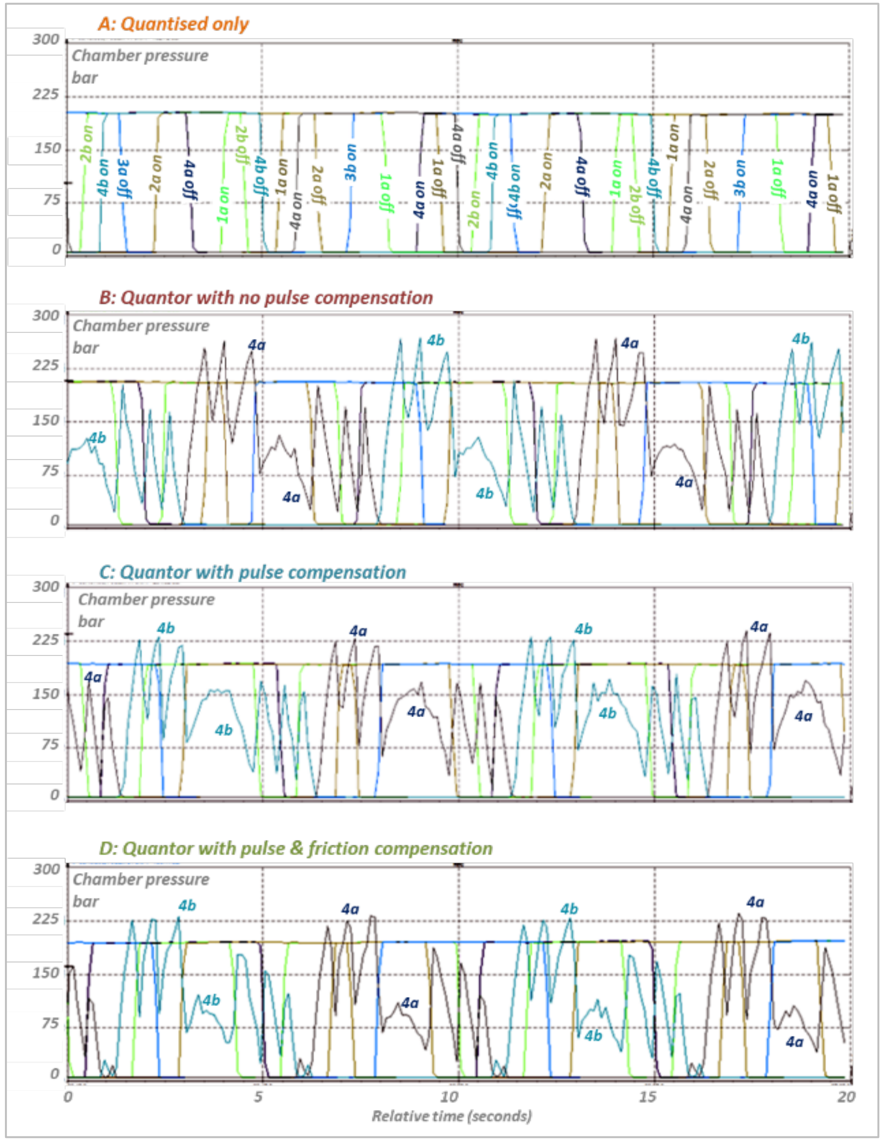
Later stages:

- *Quantify performance*
- *Validate models*


DEWESoft X - Datafile: Wave_Rig_2019_09_03_161135.dxd
Acquisition
Analysis
Data files
Setup
Review
Print
Export
Design
Play
Replay speed 1x
Mode
Sound
Offline math
Auto recalc
Save
Overview
PTCal
DDPMA/B
M96 Losses
WEC
Sankey
Control properties
Cols
Transparent
Unified properties
Single time axis
Display type
Real data
Show events
Interp. async channels
Draw sample points
Show frame
Auto scale
Interaction
Time axis type
Relative
Y axis ticks
Single values axis
Time and values cursor
Show cursor values
dt = 00:01:15
t= 03:53.1000; Wave_Position_m = -0.42
WEC position (m)
Wave position (m)
02:51.471
03:10.439
03:29.408
t= 03:11.5000; WEC PTO Torque / Force/IIR filter = 23.58
WEC PTO Force Demand (kN)
Measured WEC PTO Force (kN)
t= 03:31.1000; PTO Mech Power = 0.4537221 kW
Absorbed power in (kW)
Generator shaft power out (kW)


A. Damping only (11.3 kW)
Wave position
WEC position
PTO Motor Layout
Gear Scaling 155
Irregular sea completion 39.5 %
Mimic shows currently active motor chamber
Force demand
Measured force
XY plot of velocity (X) against force (Y)
Absorbed power
Generated power
Bars follow absorbed & generated power
B. Reactive control (17.9 kW)
Wave position
WEC position
Gear Scaling 155
Irregular sea completion 0.5 %
Force demand
Measured force
Absorbed power
Generated power
C. 'Specialised speed control' (19.2 kW)
WEC position
Wave position
Gear Scaling 155
Irregular sea completion 92.5 %
Force demand



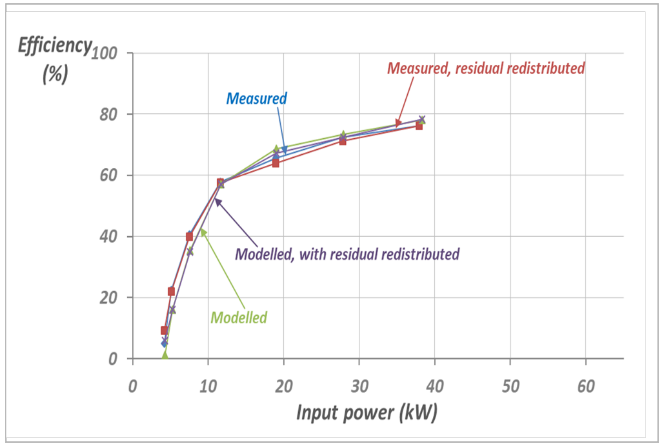


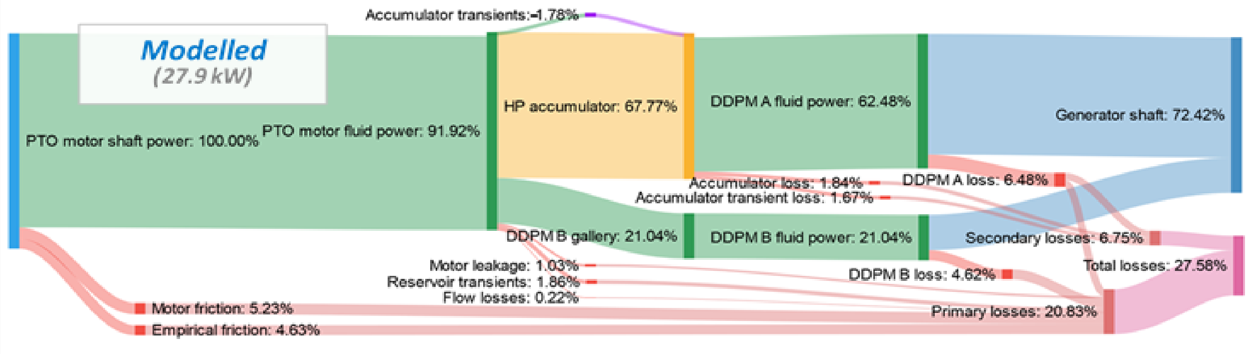
Quantify performance:

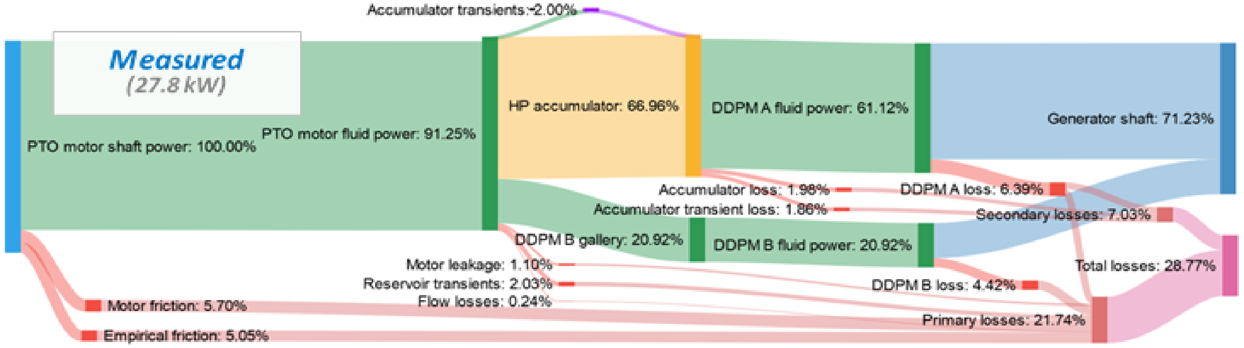
Smooth 4-quadrant torque control

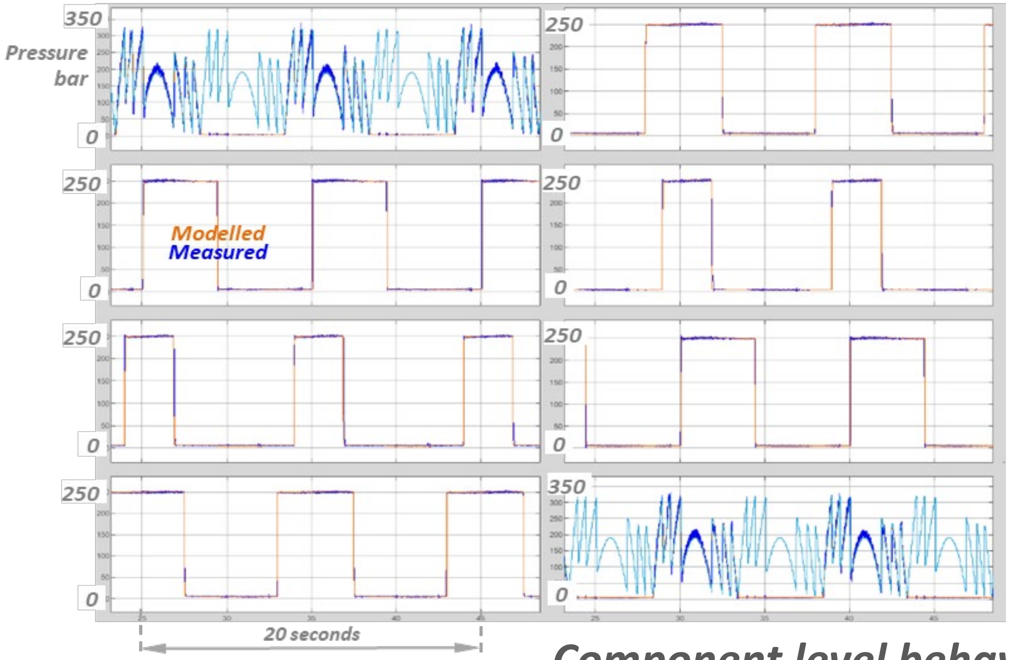
Validate models

Efficiency and Loss breakdown

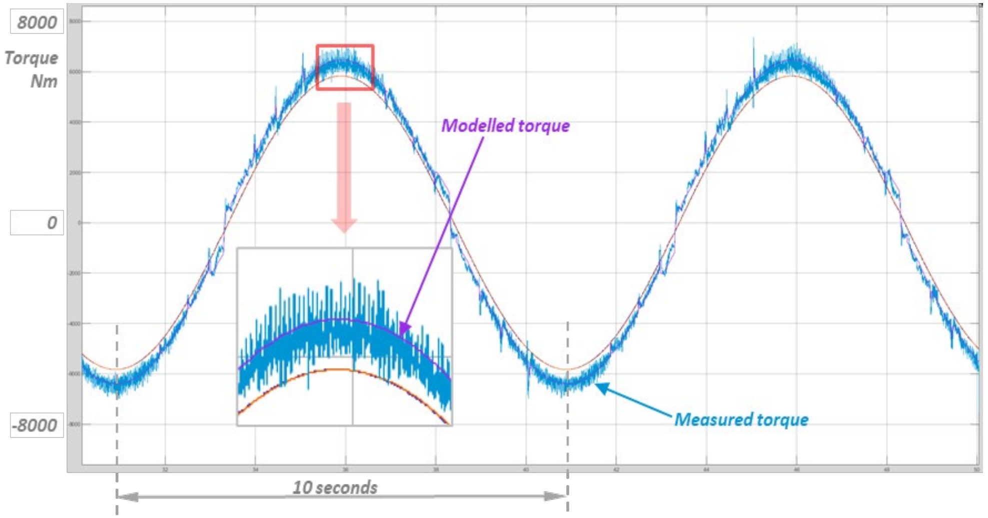






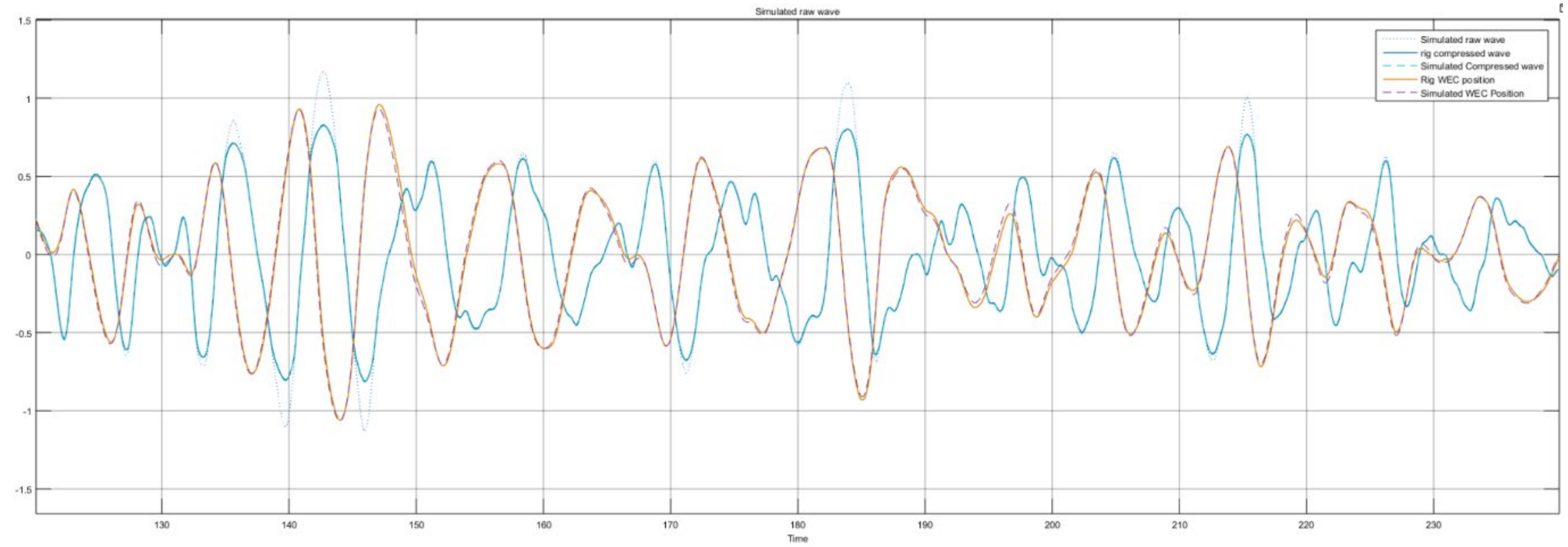


Component level behaviour

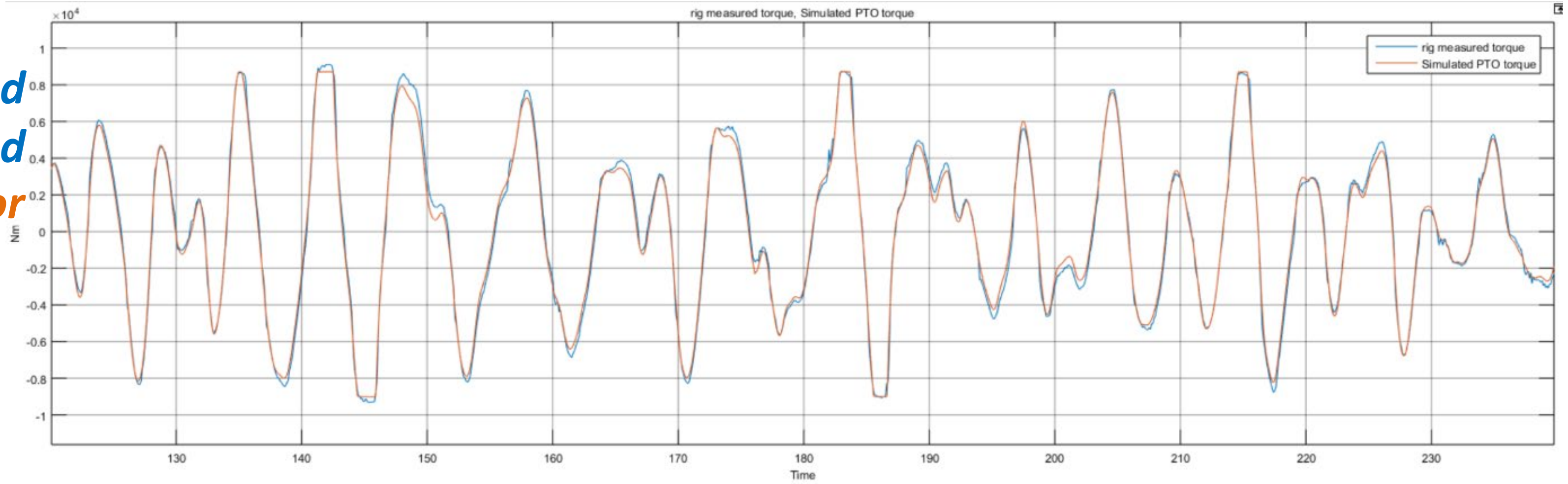


Comparison of simple model WEC response - given only the water surface

Wave and WEC response
Quantor



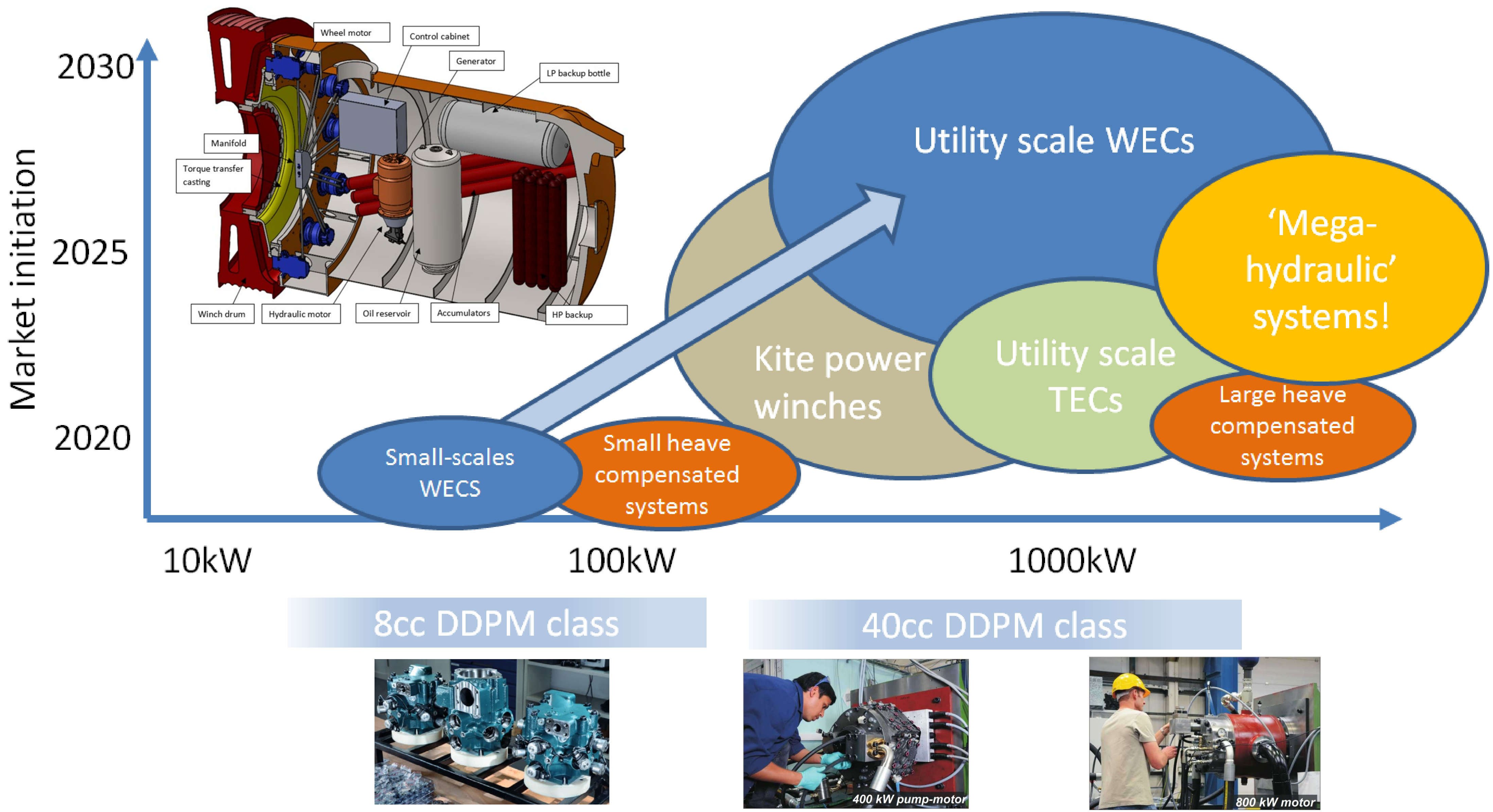
Torque measured and modelled
Quantor



ARTEMIS INTELLIGENT POWER

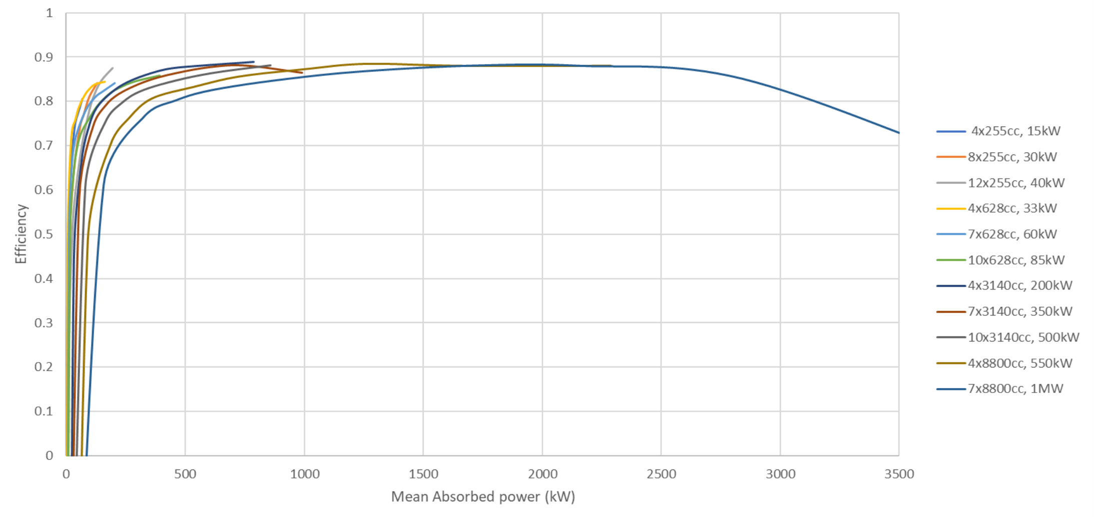
wave energy SCOTLAND

Quoceant Innovation Offshore

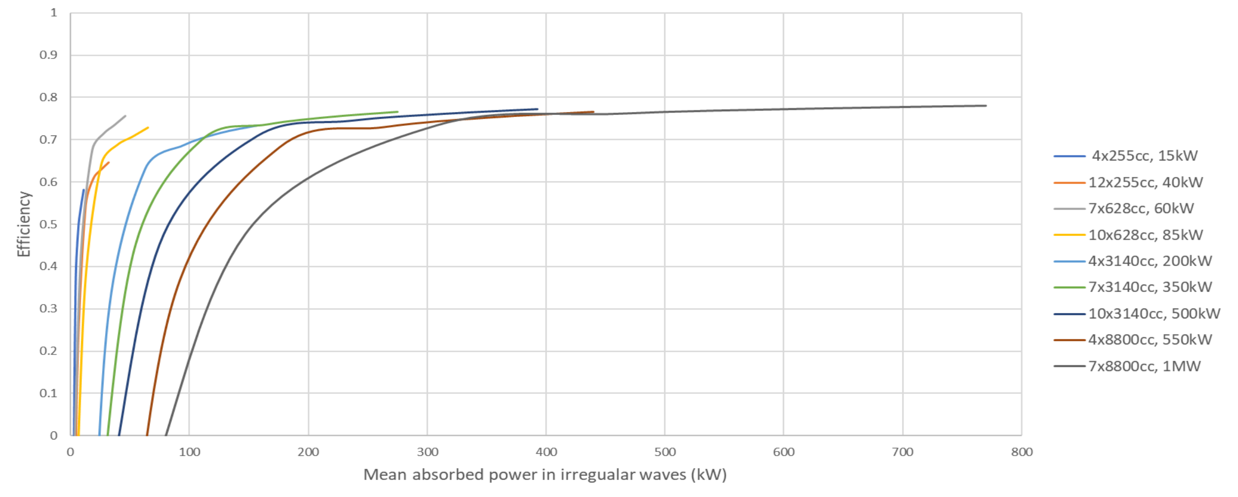


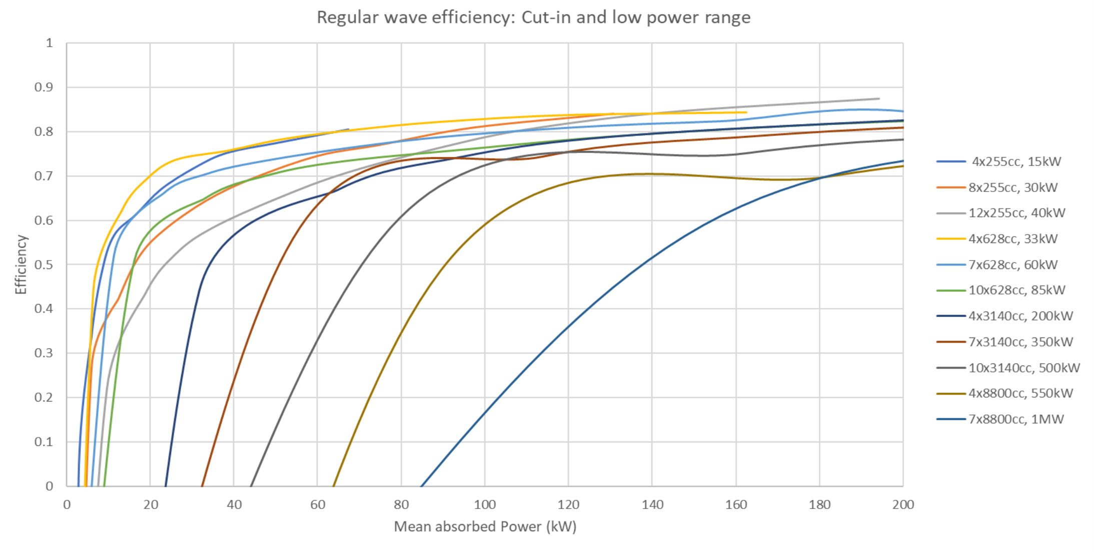
Projected performance

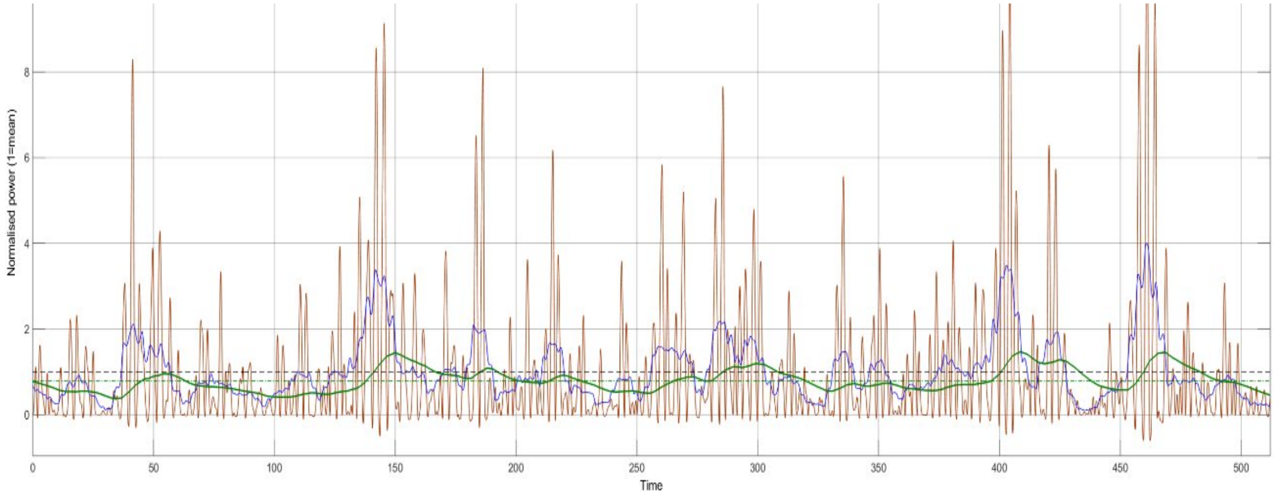
Regular wave efficiency curves



Weighted Irregular wave estimates







- *A control system, design framework, and components for the new state of the art Quantor PTO system scalable and capable for the full range of WEC applications.*
  - *4 quadrant continuous control with largely fixed losses, as required for spectral power regime*
  - *Robust and fault tolerant*
- *A small-scale test rig (~350kW instantaneous power => ~30kW avg) able to:*
  - *provide realistic and repeatable testing for control and hardware development;*
  - *provide validation of quantified performance data for a given set of components.*
  - *represents WEC dynamics - 'a wave tank for PTO';*
  - *couple the PTO and whatever WEC controls are applied to a given WEC dynamics (in one degree of freedom) – allowing high level control testing.*

- *Demonstrated functionality and validated performance for Quantor.*
- *Detailed performance models and generalisable control, adaptable to different architectures and scales.*
- *Initial FEED designs for application of Quantor into different WEC types and sizes.*
- *Generalised cost and performance metrics.*

- *100kW & MW-scale DDPMs*

ARTEMIS INTELLIGENT POWER

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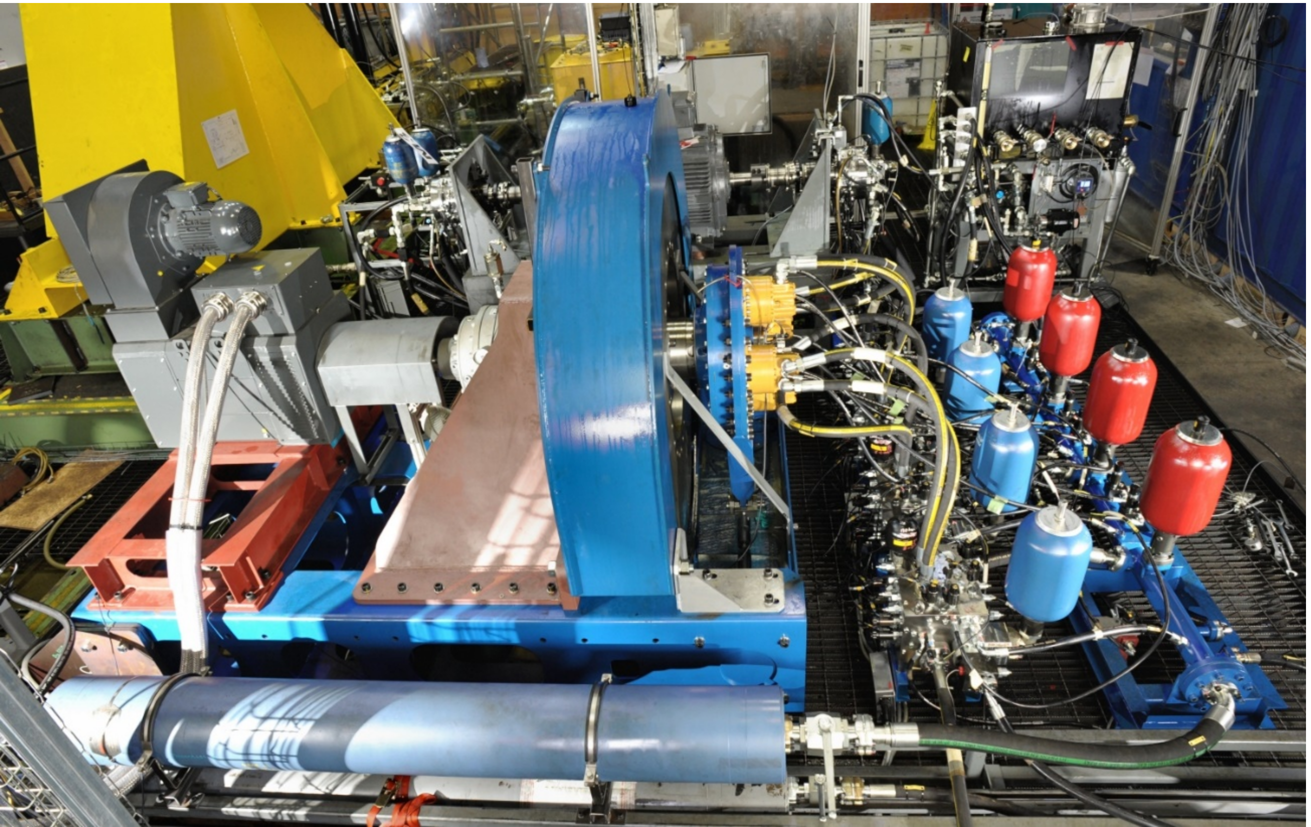
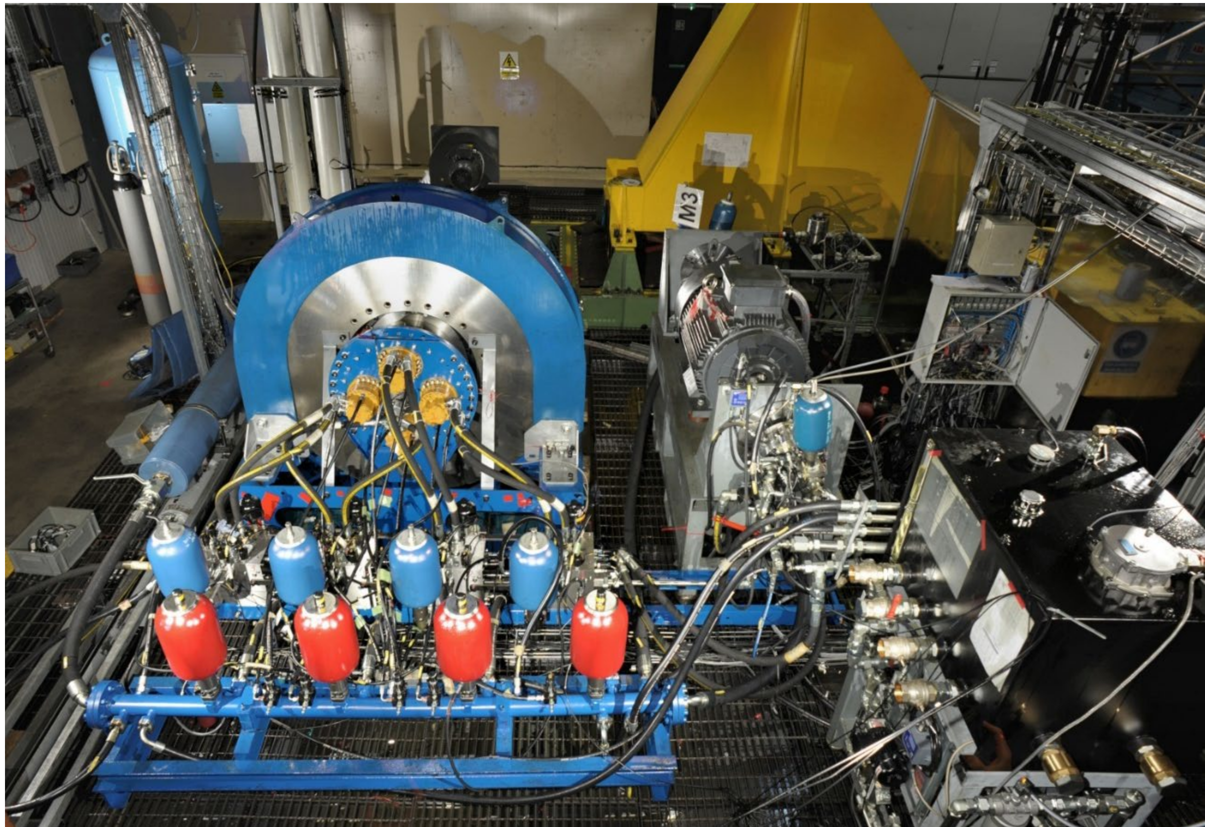
QUANTOR

Hybrid digital hydraulic power-take-off

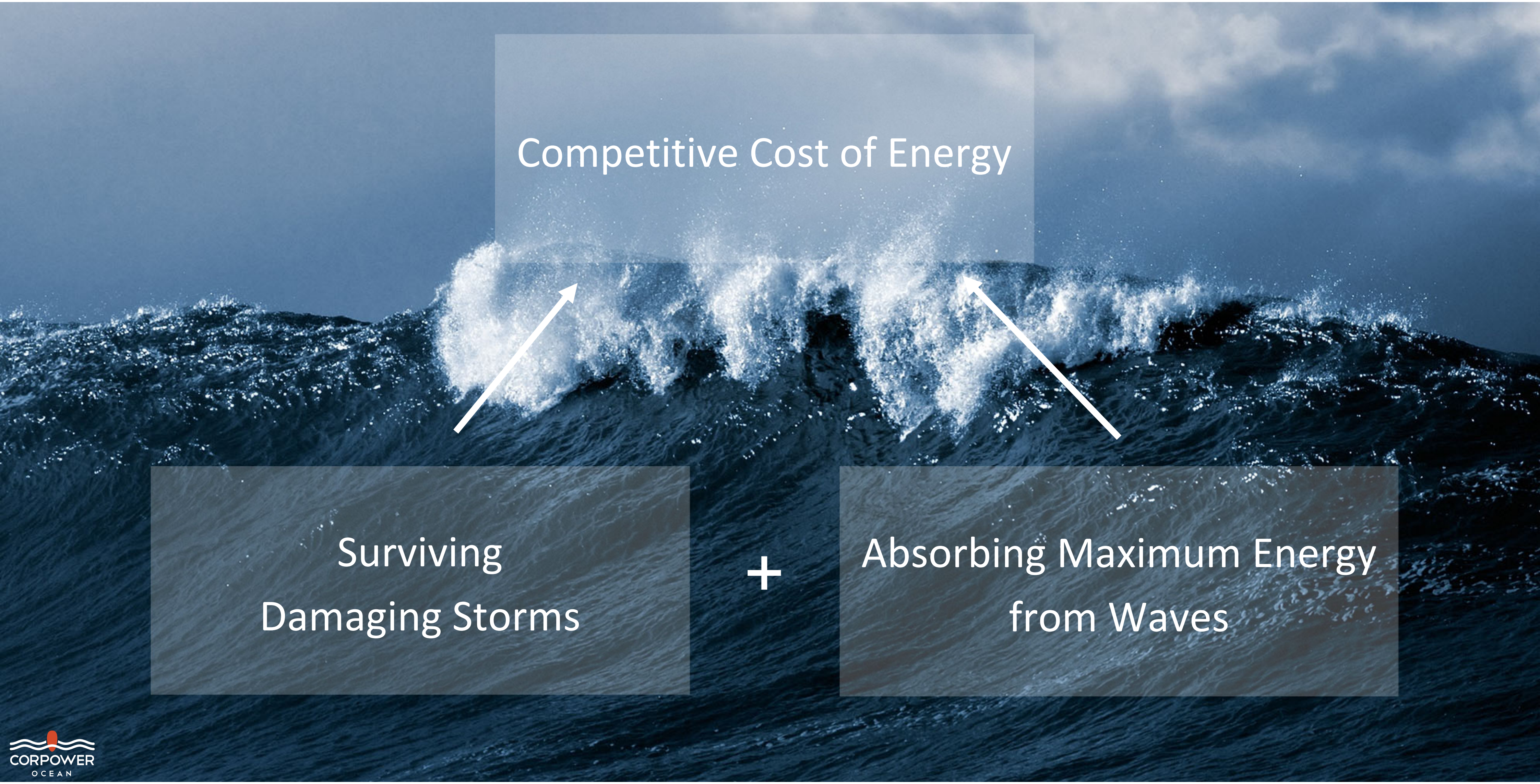
WES annual conference, 5th December 2019



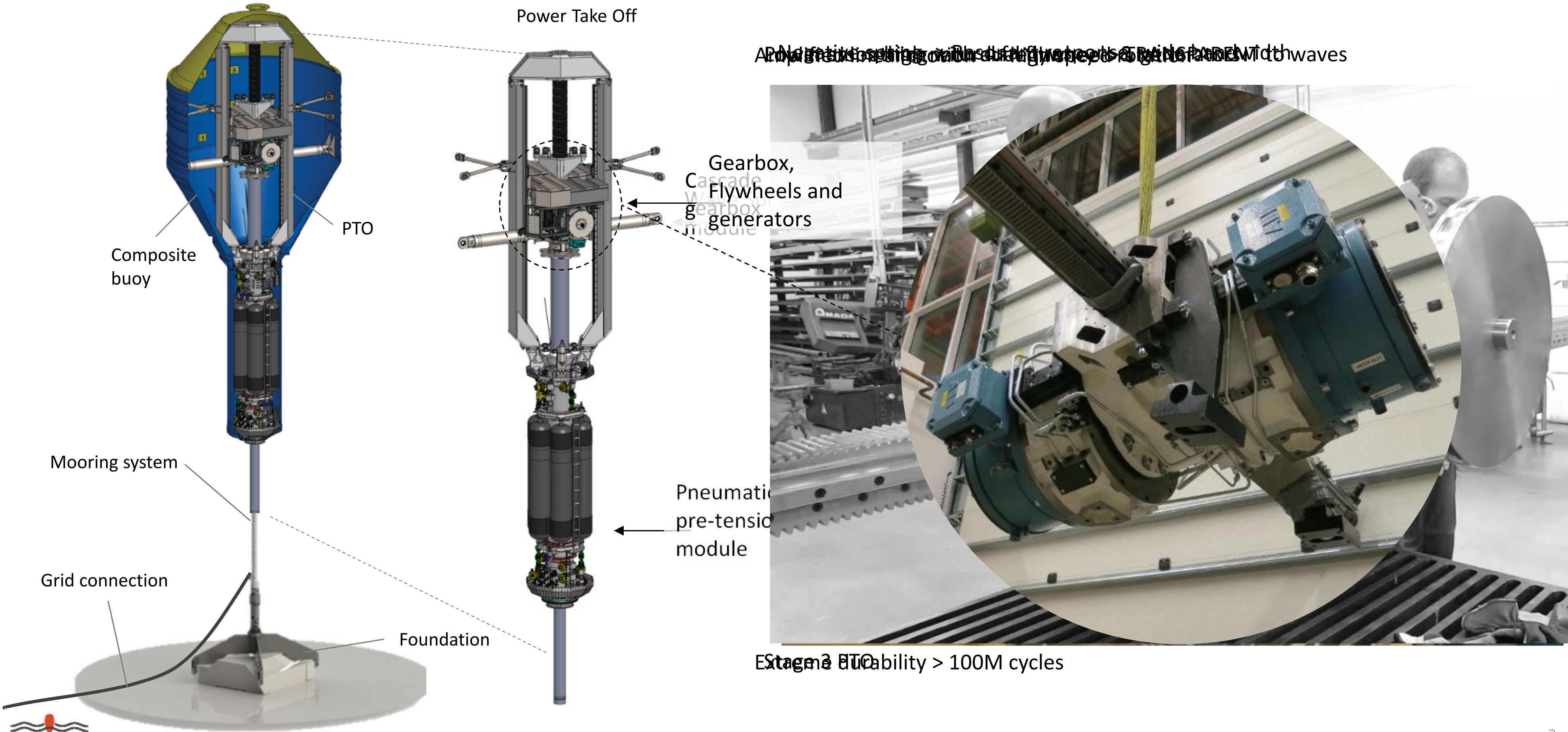


C3 DEPLOYMENT IN ORKNEY
HIDRIVE LESSONS LEARNED

THE CHALLENGES IN WAVE POWER



DETUNED IN STORMS – AMPLIFIED IN NORMAL OPERATION



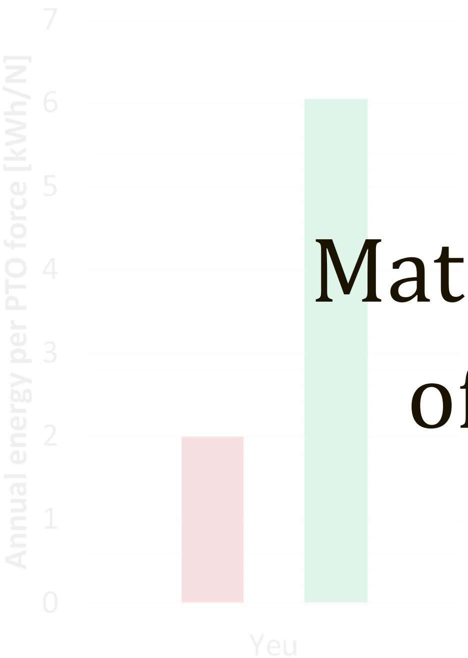
PERFORMANCE METRICS

3 times

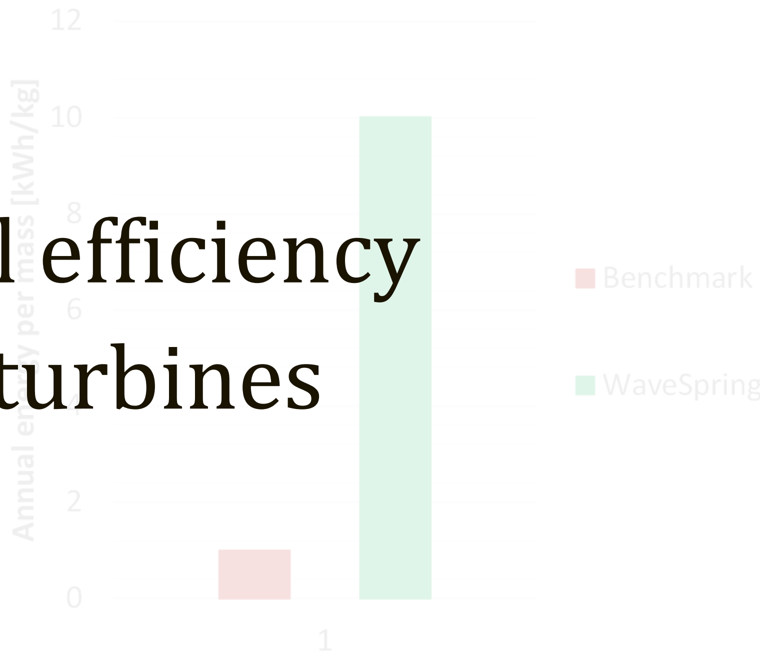
more energy per PTO force

> 5 times

more energy per ton

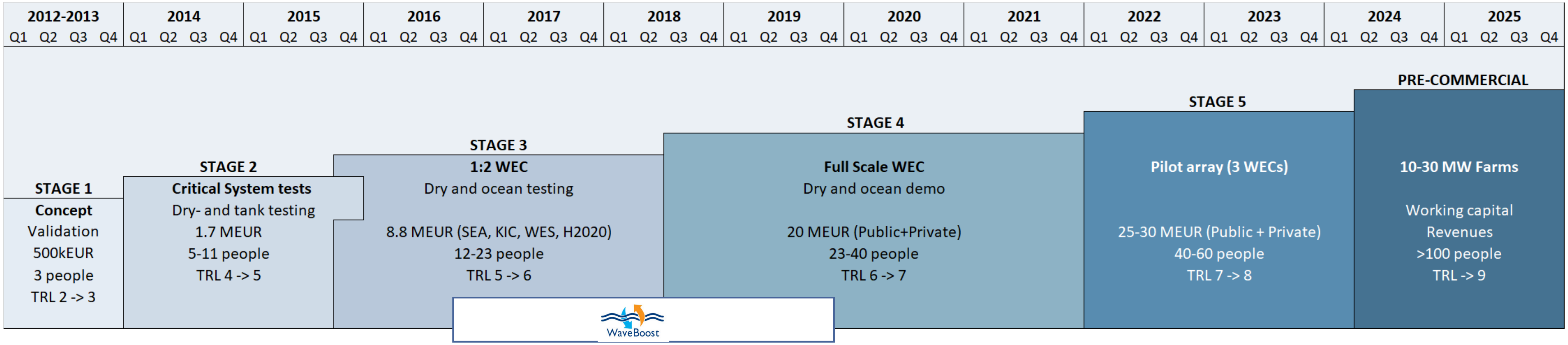


Matching structural efficiency of modern wind turbines

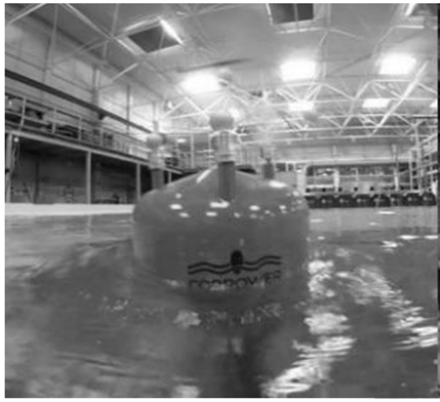


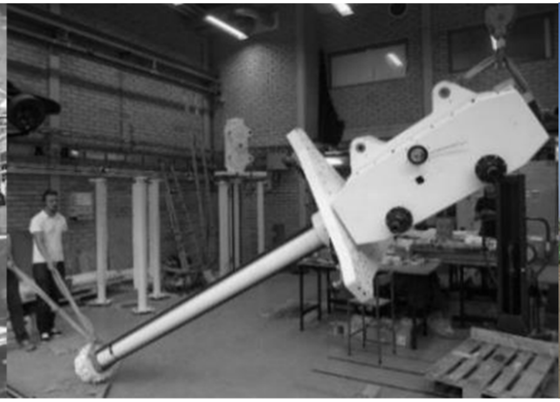
Benchmark: A. Babarit, J. Hals, M.J. Muliawan, A. Kurniawan, T. Moan , J. Krokstad: *Numerical benchmarking study of a selection of wave energy converters*, Renewable Energy 41 (2012) 44-63

STRUCTURED PRODUCT VERIFICATION



Product verification in 5 stages according to IEA-OES / equimar best practice.


Scale 1:30


Scale 1:3


Scale 1:2

Scale 1:2

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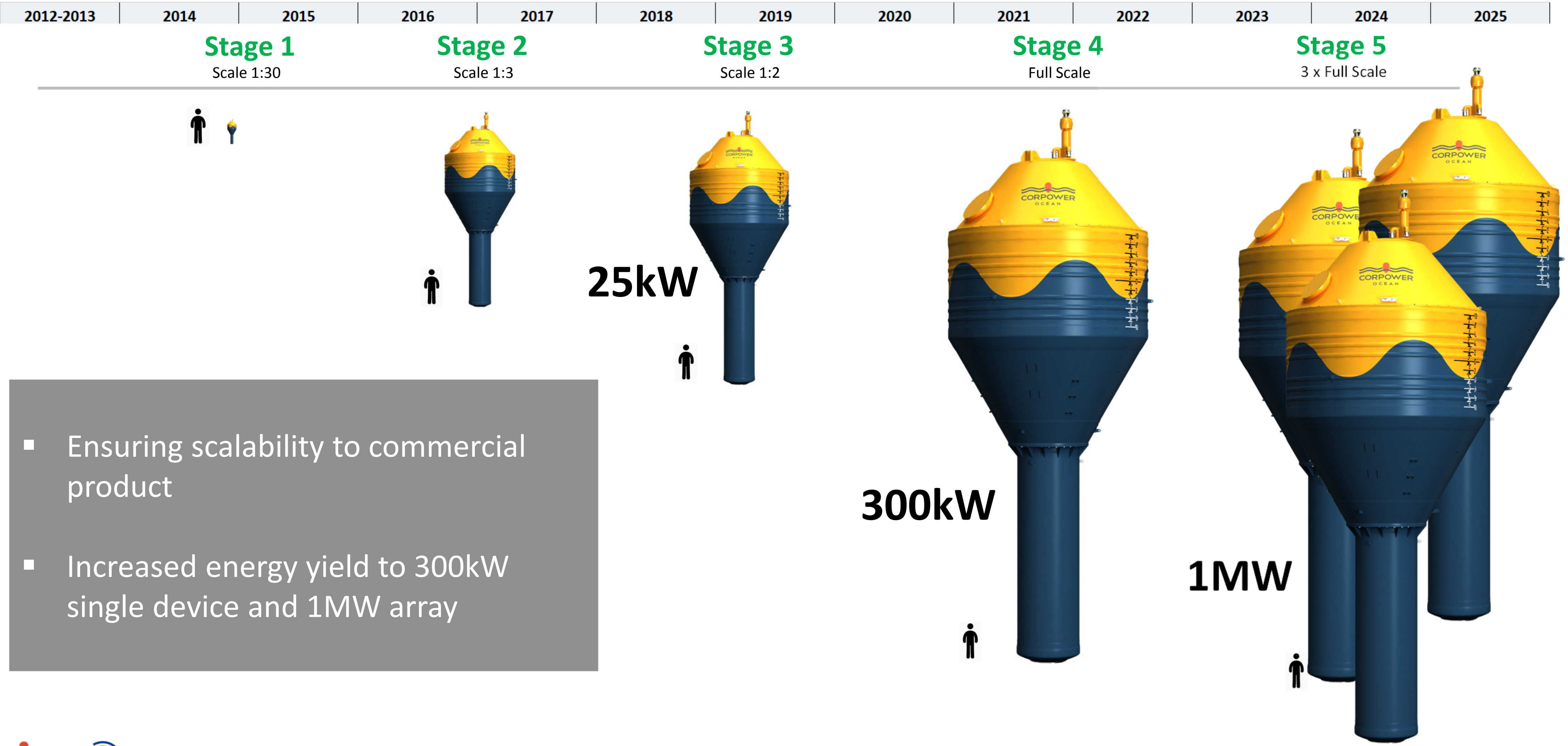
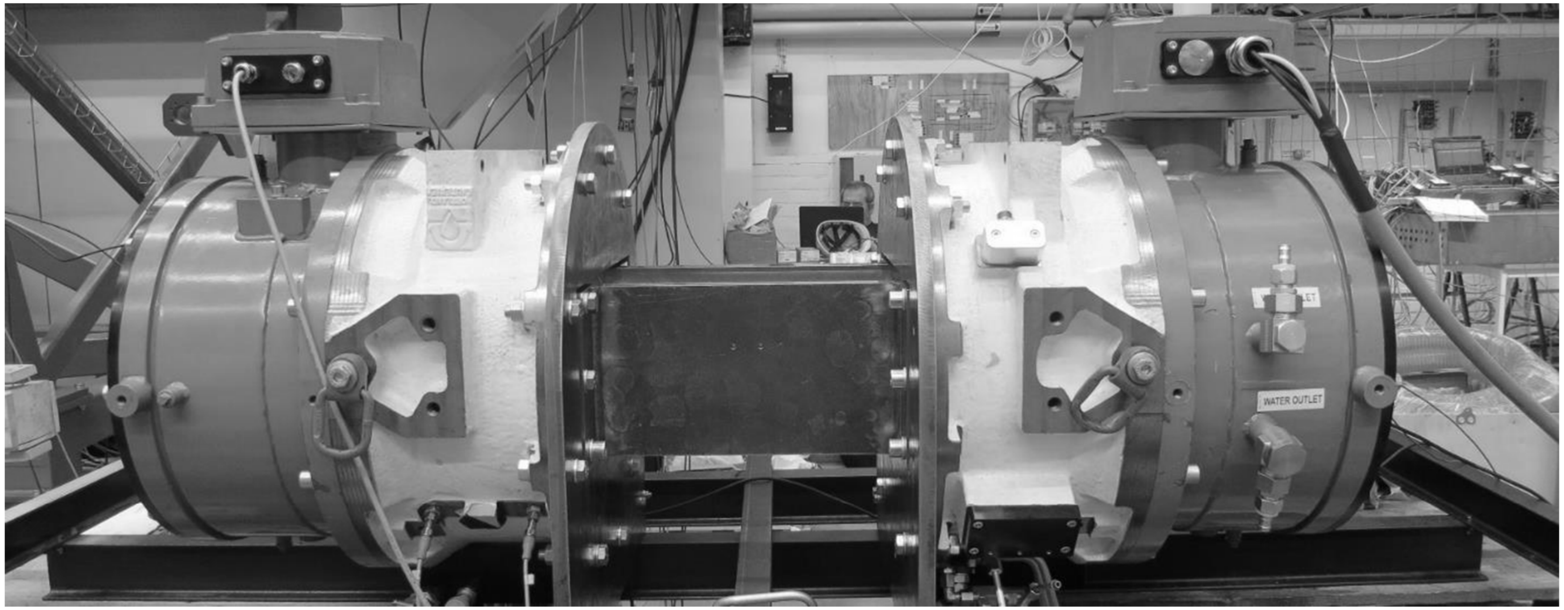
VERIFIED PRODUCT



- Ensuring scalability to commercial product
- Increased energy yield to 300kW single device and 1MW array

CORPOWER OCEAN · eit InnoEnergy Knowledge Innovation Community

MODULE ACCEPTANCE TESTING – FALL 2016

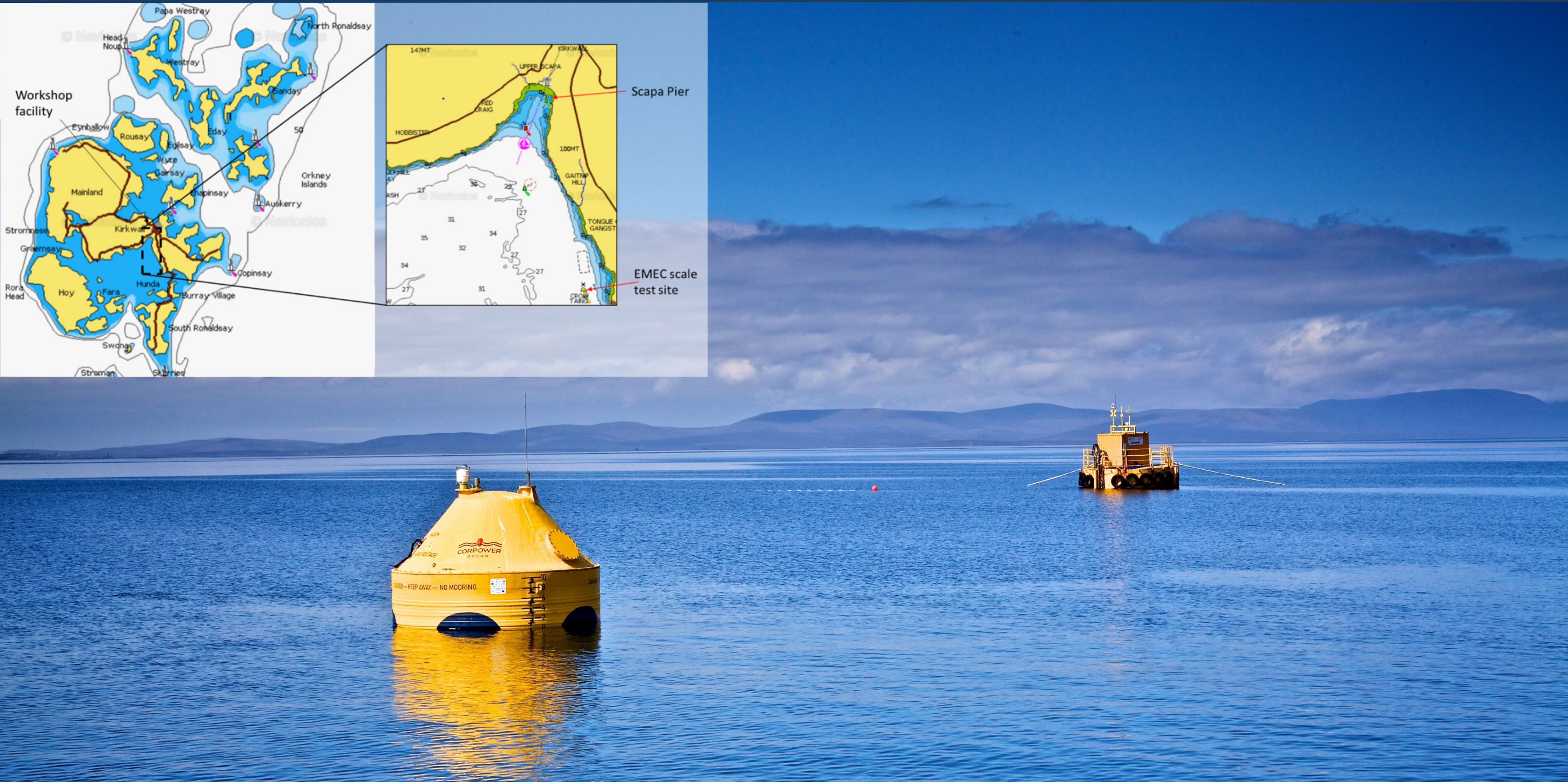


CORPOWER OCEAN

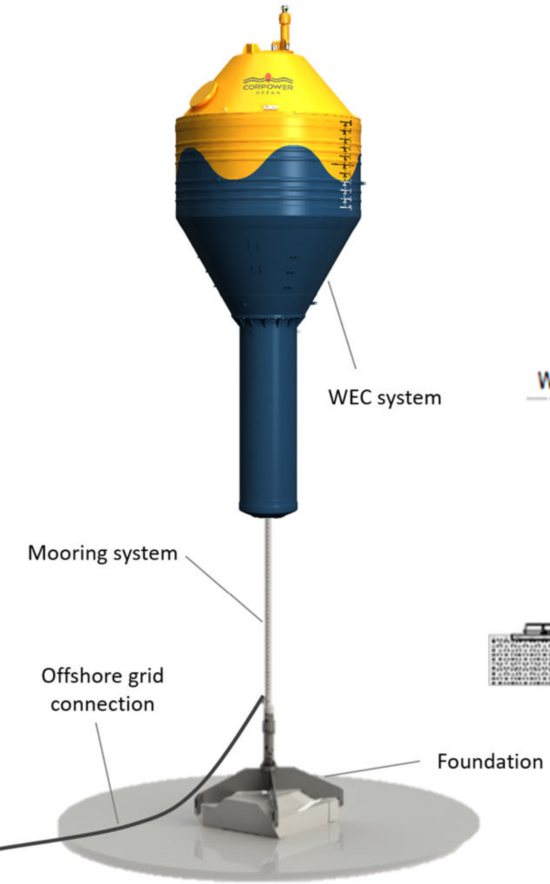
DRY TESTING - HARDWARE-IN-THE-LOOP

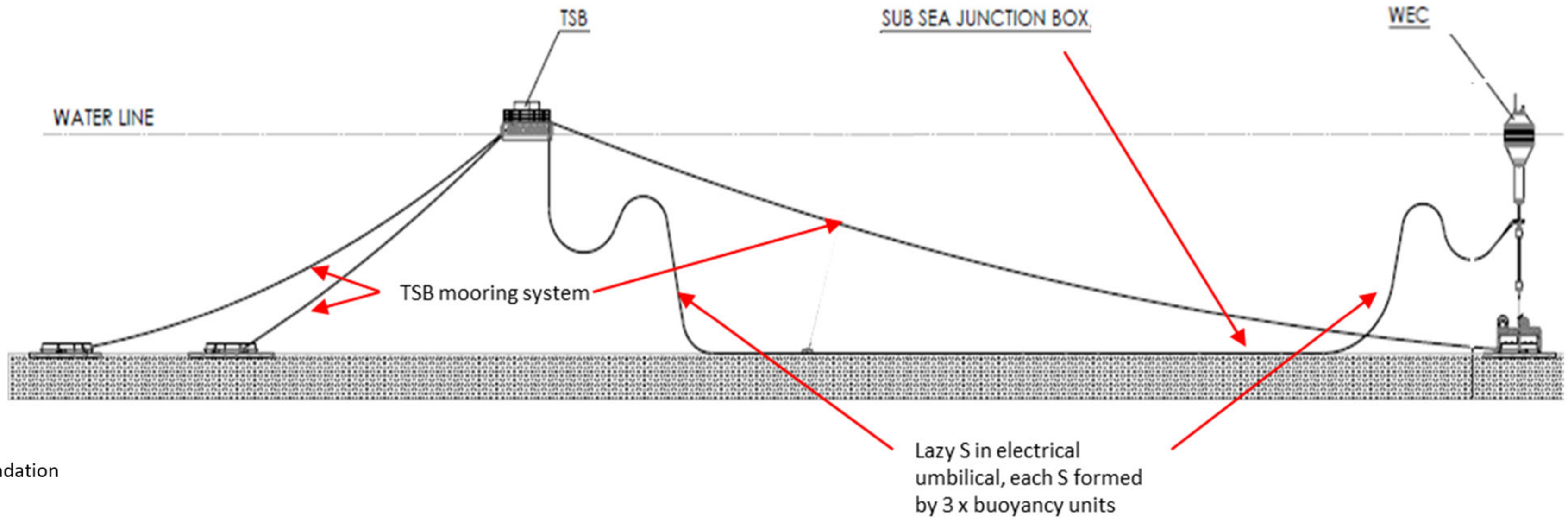
C3 WEC IN ORKNEY

EMEC SCAPA FLOW TEST SITE

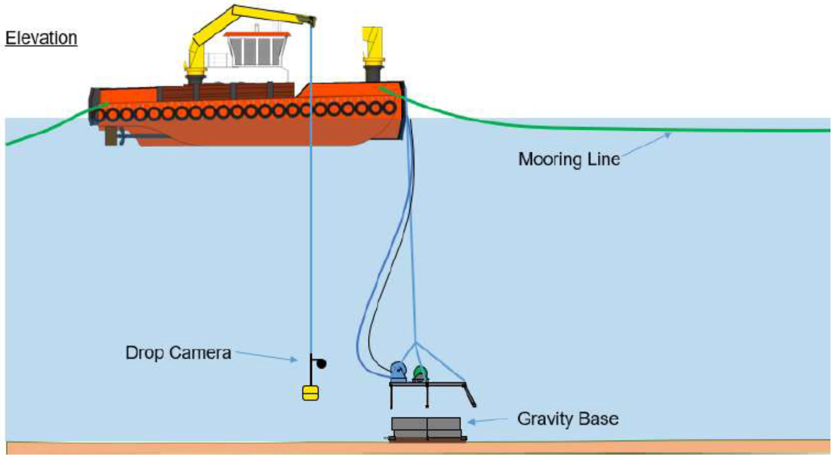


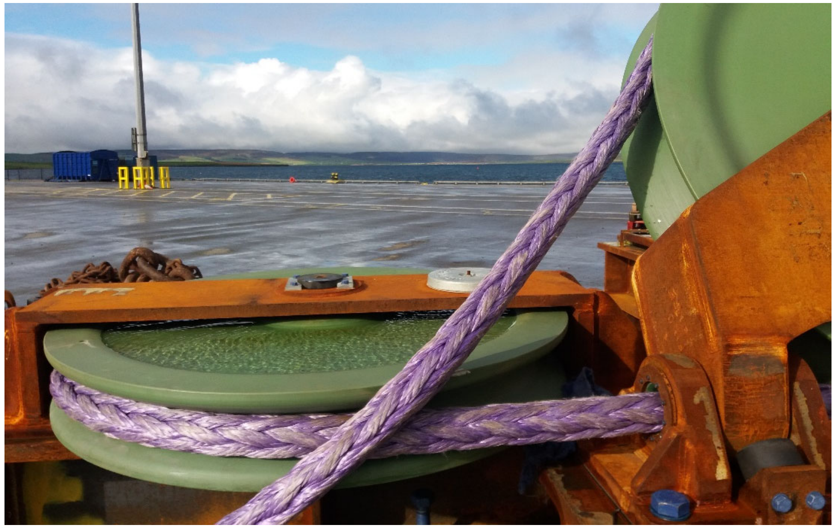
C3 INSTALLATION OVERVIEW



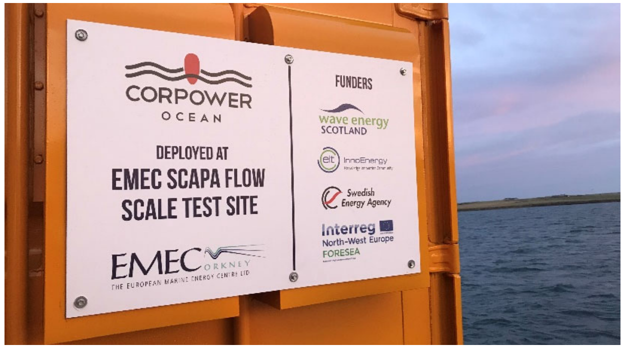


FOUNDATION & MOORING INSTALL – W LEASK MARINE - NOV 2017





MICROGRID & UMBILICAL INSTALL – W GREEN MARINE - DEC 2017



ON-LAND BASE IN HATSTONS INDUSTRIAL AREA

CORPOWER OCEAN

C3 WEC DEPLOYMENT AT EMEC SCAPA FLOW

LOW COST VESSELS AND INSTALLATION METHODS

MICROGRID FOR POWER & COMMUNICATION

Energy storage and active Microgrid function. Redundant radio & 3G comms to shore

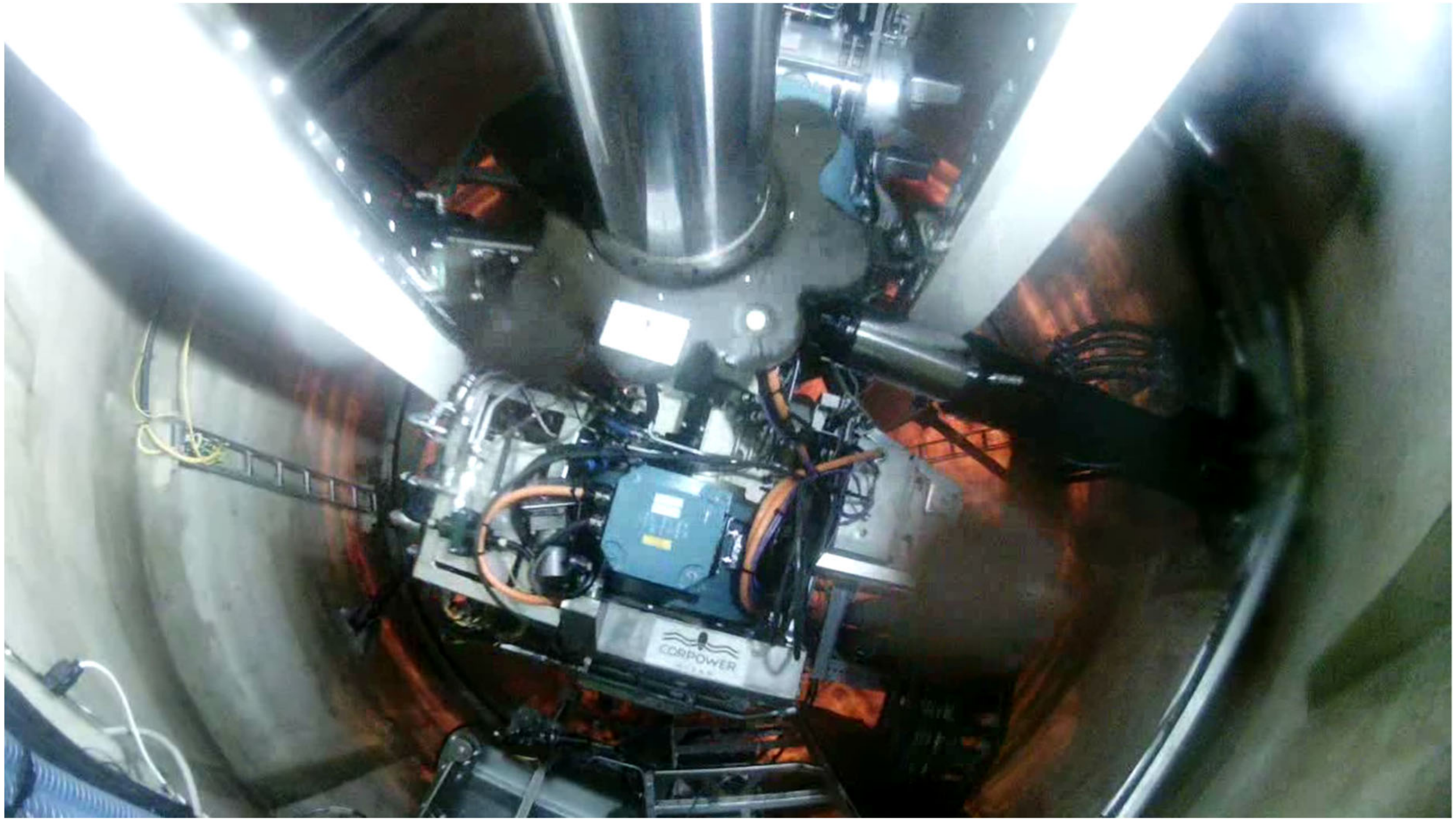
CORPOWER OCEAN

C3 IN TUNED OPERATION – 1.38M HS


C3 Testing in Orkney 2018 – Amplified in 1.38m Hs


C3 Testing in Orkney 2018 - Survival

C3 IN TUNED OPERATION – 1.38M HS



STAGE 3 RESULTS FROM SCAPA FLOW

- Transparent survival mode verified.
- Tuned mode verified. (WaveSpring amplification)
- Power production in ocean was consistent with the prediction by the simulation models.
- Wave spring phase control technology found robust and delivered 99% efficiency.

RESONANT WAVE ENERGY IS NOW A REALITY

Survivability:

TRANSPARENT

Annual Energy Production:

+300%

Required Materials:

-40%

Annual Energy / ton:

+500%

Clear path to competitive LCOE:

→ 100 → 40

EUR / MWh

Certification towards bankability:

Statement of Feasibility

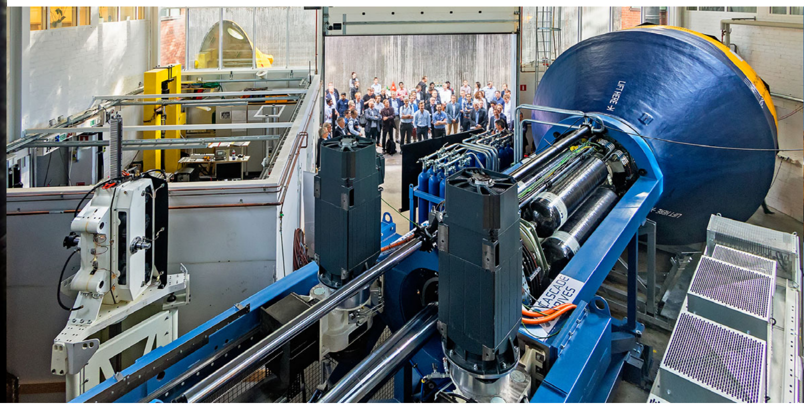
DNV·GL

LESSONS LEARNED FROM STAGE 3

- **Dry testing** with simulated wave loading a is an effective way to debug and stabilize WECs prior to ocean deployment

- The auxiliary systems (anchor-foundation-mooring-tidal-microgrid) need similar levels of **pre-qualification** and stabilization as the WEC itself.

- C3 was a research machine. C4 will be our first iteration of production machine. We aim at significant **reduction of complexity and number of parts**.



WaveBoost

ADVANCED POWER TAKE-OFF SOLUTION
FOR WAVE ENERGY CONVERTER (WEC)

CORPOWER OCEAN

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727598

WAVEBOOST

H2020 LCE07-2016

Status

Ongoing project

Start date	End date
1 November 2016	31 October 2019

Funded under:

H2020-EU.3.3.2.

Overall budget:
€ 3 988 744

EU contribution
€ 3 988 744

Coordinated by:

CORPOWER OCEAN AB

Sweden

Three year programme targeting significant improvements in the reliability and performance of wave energy converters – using direct learning from CPO Stage 3 deployment.

Expected Benefits

- Increased Reliability and Survivability of Wave Energy Converters
- Increased Performance and reduce Cost of Wave Energy Converters
- PTO Size and Cost Reduction
- Increased Energy Production
- Reduce the Lifecycle Environmental Impact

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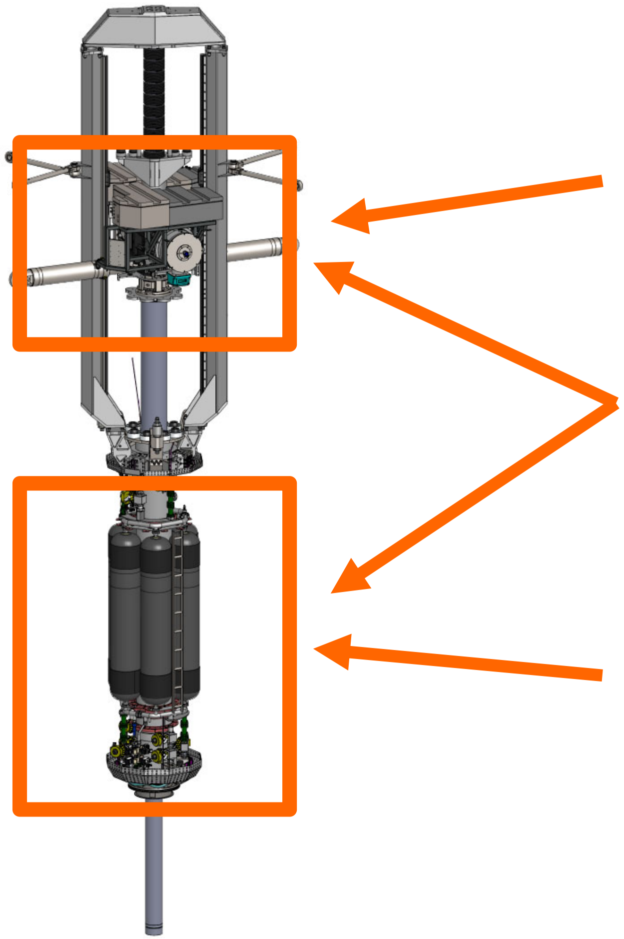
Waveboost Advanced PTO

Improve AEP

Improve LCoE



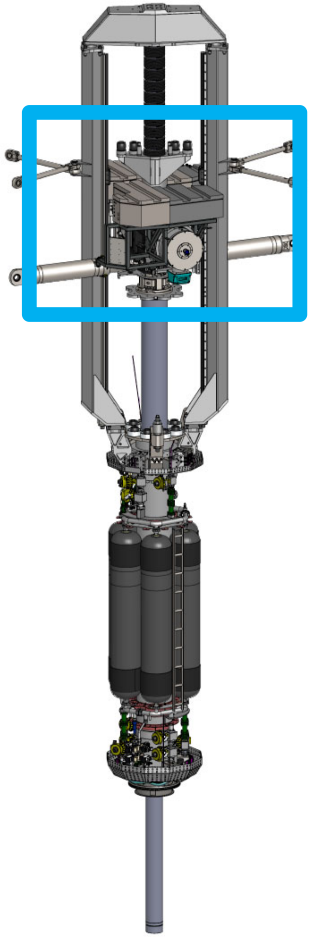
Areas for Improvement in Waveboost

Power Conversion Module
- Improve Peak to mean power ratio
- Simplify System

Dynamic Seals
- Reduce Friction

Pre Tension Cylinder (PTC)
- Reduce Flow Losses
- Improve Breaking Performance
- Improve Control

Waveboost
Advanced PTO



Advanced Power Conversion Module

Two **generators directly coupled** to the gearbox, operating together bidirectionally.

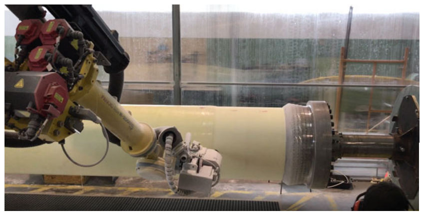
Advanced torque control on the system level, the **peak to mean power ratio of the electrical drivetrain is reduced** without decreasing the energy output.

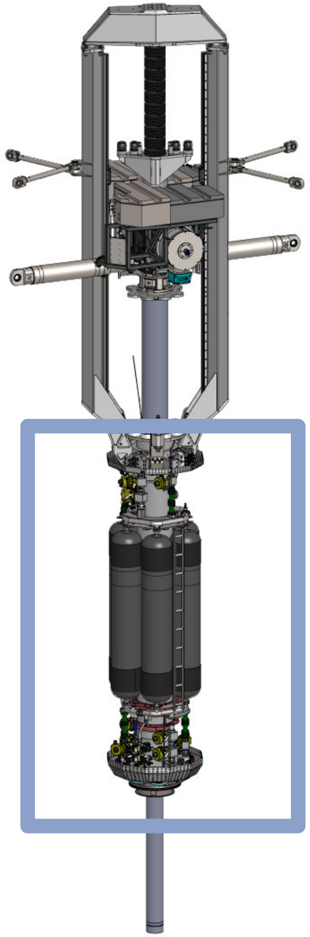
Removes unnecessary complications, risks and the weight of a flywheel storage system between the generator and the gearbox.

High power per weight ratio and efficiency

WAVEBOOST

Waveboost
Advanced PTO





Advanced Pre Tension Cylinder (PTC)

Simplified design using one single cylinder and also using composite PTC manufacturing techniques

Advanced braking system for greater control of movement

98% reduction overall on Flow Losses

Waveboost
Advanced PTO

Dynamic Seals

70% improvement on seal friction

Friction now not as sensitive to speed

State-of-the-art Seal Test Rig

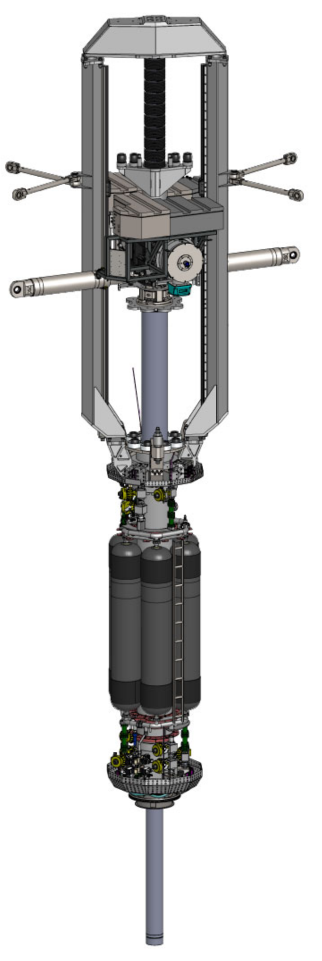
New Seal Product developed

Simplified Design

83% Less Valves

Increased Device Reliability

Waveboost Advanced PTO



System Performance and LCOE

29.3% **reduction in LCOE**

26.9% **increase in AEP**

				Tp																	
				3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5	17,5	18,5	19,5	20,5
				3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
				4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Hs	0,75	0,5	1		9%	8%	10%	13%	17%	21%	26%	32%	37%	40%	47%	55%	61%	67%	72%	76%	80%
	1,25	1	1,5	14%	9%	8%	10%	13%	17%	21%	26%	33%	45%	59%	69%	75%	80%	83%	85%	87%	89%
	1,75	1,5	2	14%	9%	8%	10%	13%	17%	22%	33%	50%	64%	73%	79%	83%	86%	88%	89%	91%	92%
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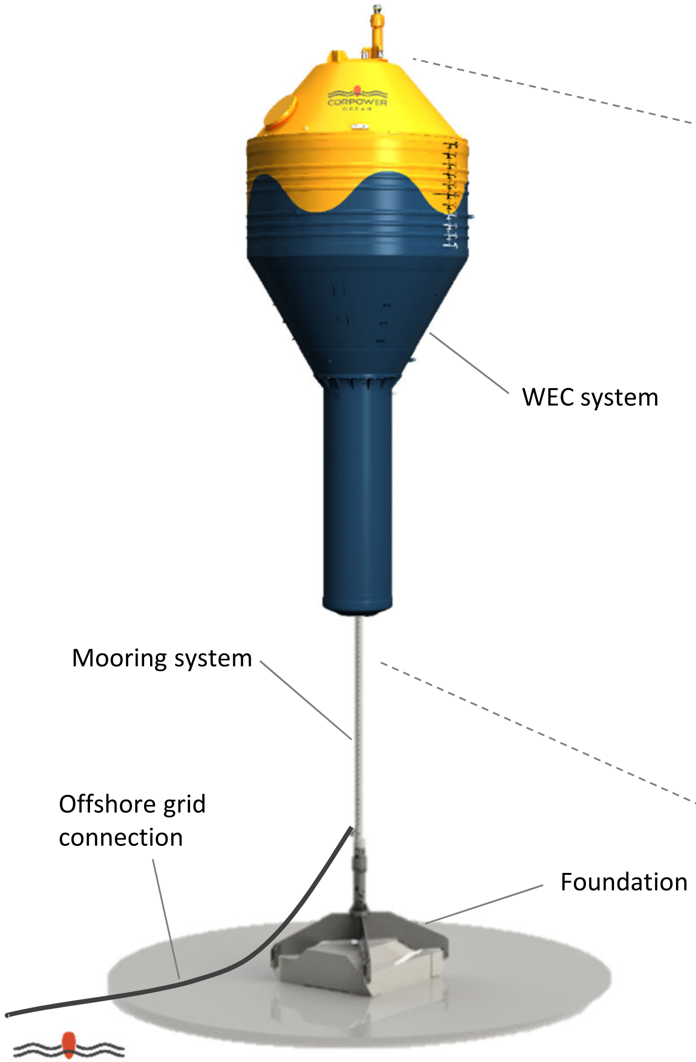
	2,75	2,5	3	14%	9%	8%	10%	13%	22%	42%	60%	70%	72%	72%	77%	79%	81%	89%	93%	94%	94%
	3,25	3	3,5	14%	9%	8%	10%	14%	30%	52%	58%	51%	45%	48%	55%	56%	62%	70%	77%	84%	91%
	3,75	3,5	4	14%	9%	8%	10%	18%	41%	39%	37%	32%	29%	34%	42%	44%	47%	57%	63%	73%	76%
	4,25	4	4,5	14%	9%	8%	10%	24%	24%	23%	24%	20%	19%	27%	31%	35%	39%	46%	54%	63%	64%
	4,75	4,5	5	14%	9%	8%	11%	19%	11%	10%	14%	12%	15%	22%	26%	28%	32%	42%	49%	57%	59%
	5,25	5	5,5		9%	8%	14%	8%	1%	3%	4%	6%	10%	17%	20%	24%	29%	38%	42%	48%	54%
	5,75	5,5	6		9%	8%	3%	0%	-5%	-4%	-1%	3%	5%	11%	15%	21%	27%	33%	42%	44%	

2023 TARGET: BANKABLE ARRAY OFFERING TO CUSTOMERS

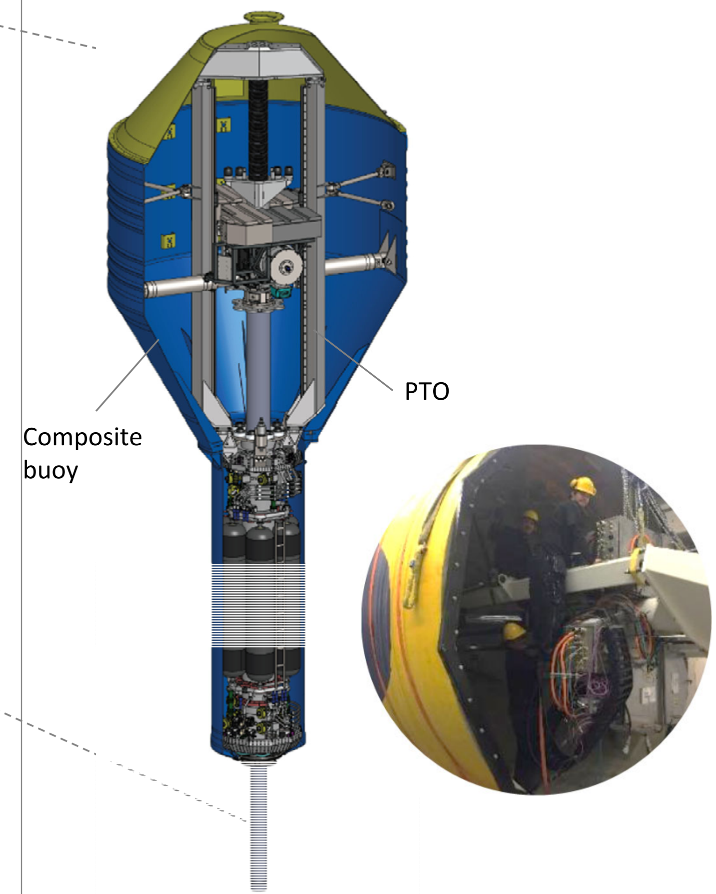
Vision:

By 2023 have an array with three devices delivering electricity to the grid, certified through Stage 5, achieving bankable accreditation

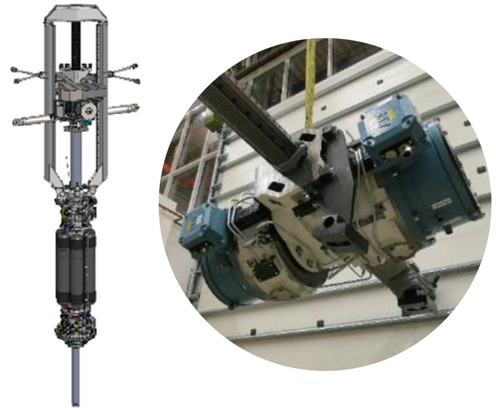
WEC SUPPLY CHAIN IN SCOTLAND



WEC system assembly – On-land base, close to farm sites



PTO supply – CPO AB, Sweden



Composite buoy supply – CPO Ltd / Balmoral

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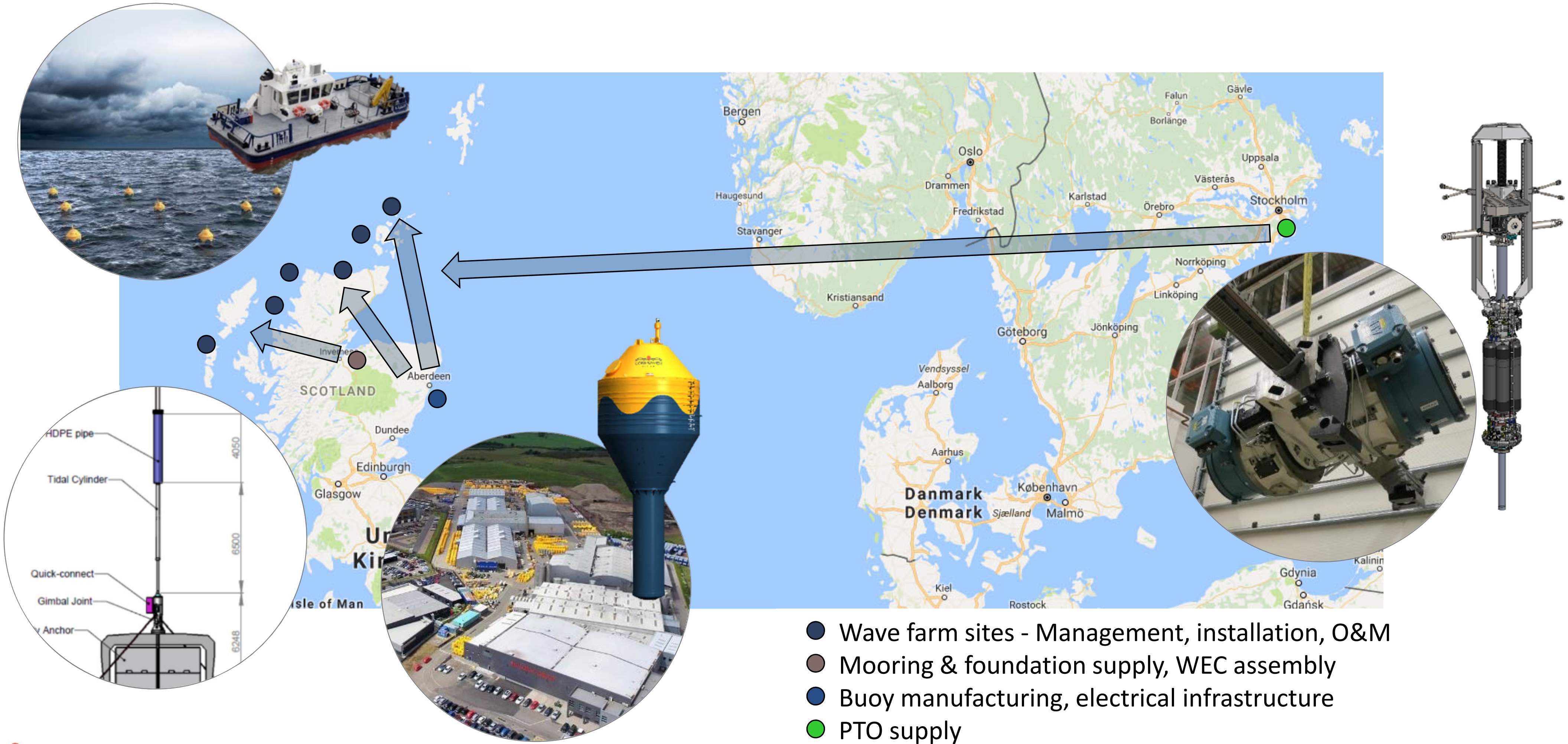
SUPPLY CHAIN FOR SCOTTISH WAVE FARMS



- Wave farm sites - Management, installation, O&M
- Mooring & foundation supply, WEC assembly
- Buoy manufacturing, electrical infrastructure
- PTO supply

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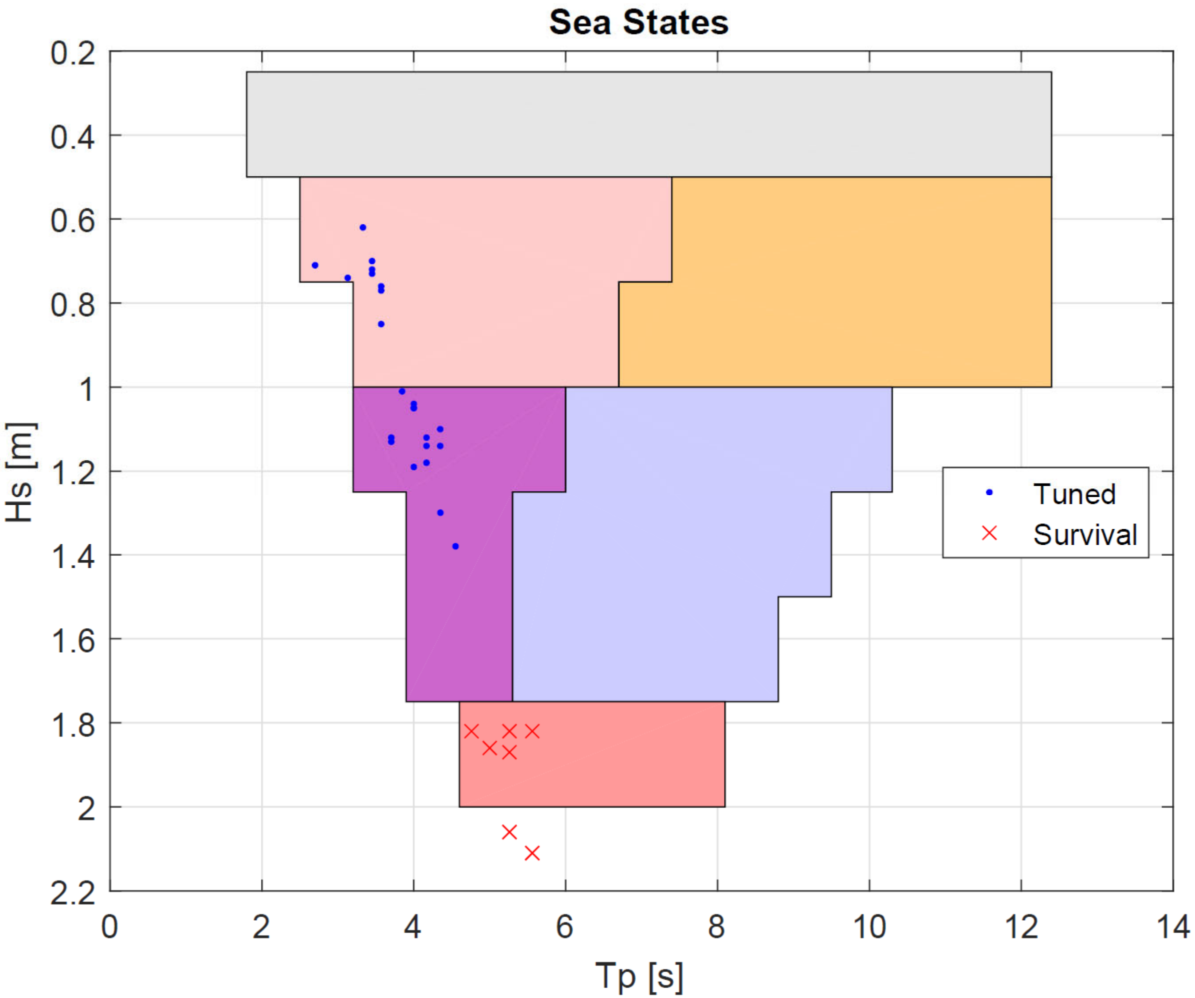
SEA STATE VERIFIED IN SCAPA



CORPOWER OCEAN

THANK YOU

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Skype: Matt.Dickson

www.corpowerocean.com

OCEANEERING®

Stage 3 PTO: PECMAG

WES 4th Annual Conference, Edinburgh, 5th December 2019

Mark Brown, Oceaneering
Craig Britton, Supply Design

BEDL Bathwick Electrical Design Ltd | SUPPLYDESIGN BESPOKE ELECTRONICS | Pure Marine

PECMAG

|POWER ELECTRONIC CONTROLLED MAGNETIC GEAR|

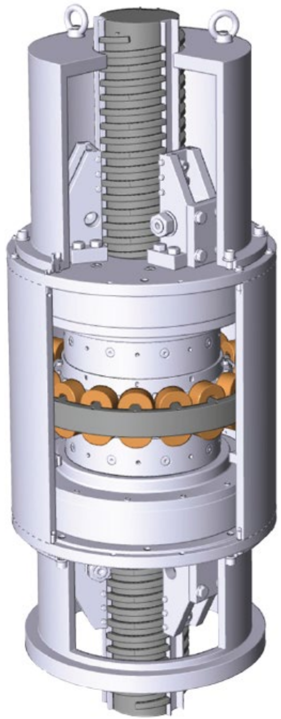
Highly efficient all-electric PTO; magnetic gear and generator controlled by custom power electronics.

|SURVIVABILITY| Low friction non-contact design allows damage free overload, modular redundant power electronics for high availability.

|COMPACT| At least 10 x smaller than equivalent direct drive systems. High gearing achieved in a single stage.

|INTEGRATED| Highly scalable mechanical and electrical solutions.

|COMPATIBILITY| Straightforward integration with a variety of WEC types and control strategies. No stroke length limit.



Stage 3 Project

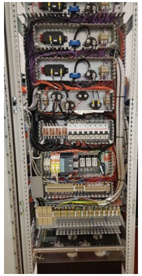
|SCOPE|

- Develop 10kW rated linear to rotary system
- Design and manufacture; gear & generator, power & control system, onshore and offshore test systems
- Onshore performance bench testing
- Offshore sea trials
- Techno-economic analysis and commercialisation strategy

|KEY OBJECTIVES|

- Bring PECMAG to a readiness level for deployment on pre-commercial demonstrators
- Deliver a PTO that can successfully integrate into a WEC system
- Demonstrate key power capture and system protection features
- Allow reliability and availability metrics to be quantified

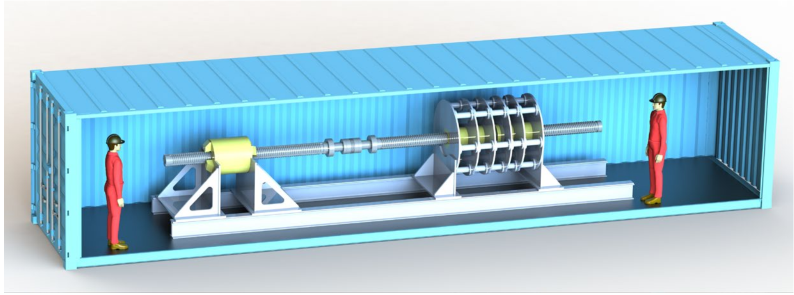






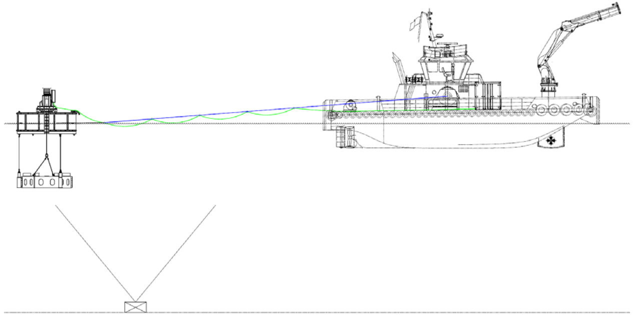
Current Status

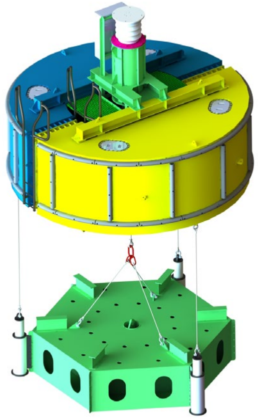
|ONSHORE BENCH TESTING|



- Rosyth, Q4 2019
- PECMAG3 driven by 2No. PECMAG2 machines
- Exercise PTO through full performance range
- Determine key performance metrics
- Demonstrate overload and survival characteristics

|OFFSHORE SEA TRIALS|



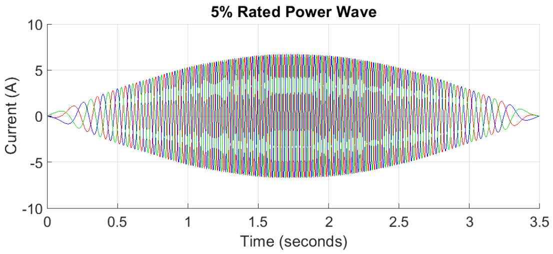


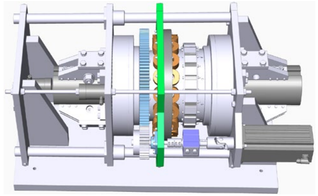
- Firth of Clyde, Q1 2020
- 5-10 days vessel operations
- Integration with WEC type structure
- Confirm seagoing operability of PTO
- Assess suitability of marinisation measures

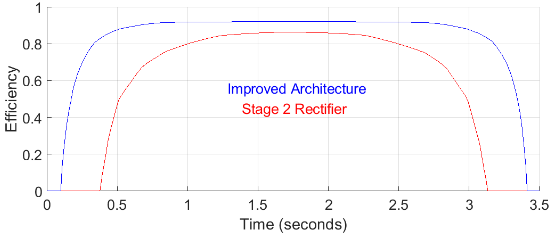
Stage 3 - Advanced R&D

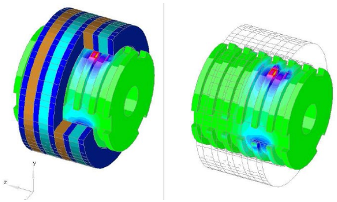
|TECHNOLOGY ADVANCEMENTS|

- Improved speed, acceleration and force capabilities
- Reduced size, weight, cost and inertia
- Modular machine design for simplified assembly and maintenance
- Magnetic thrust bearings reduce rotating losses
- Improved capture efficiency for lower speed & prevailing waves
- No-skip overspeed control strategy
- N+1 redundant, high availability power electronics







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UMBRAGROUP

EMERGE

Electro–**ME**chanical **R**eciprocating **GE**nerator

emerge (/ɪˈmɜːdʒ/): to appear, or to become recognized

Luca Castellini
Energy R&D and BD Manager

umbragroup.com

EMERGE project n. UMB PTO32

*(**E**lectro-**ME**chanical **R**eciprocating **G**enerator)*

Wave Energy Scotland call for innovative PTOs – stage 3

The EMERGE project purpose was to study and assess technology level of an Electro-Mechanical PTO for marine wave energy converters.

A linear EMG (Electro-Mechanical Generator) based on recirculating ballscrew architecture has been developed. During EMERGE project, UMBRA EMG has been assessed both in laboratory bench and in marine environment, successfully managing to achieve TRL-7 (Technology Readiness Level)

TIMELINE

TRL advancement

TRL 5

TRL evolution for a 100 kW PTO

TRL 6

TRL 7

May 2017
Project kick-off

July 2017
MS2: System Specification Control Document

December 2017
MS3: Finalization of Design

June 2018
MS4: Finalization of **EMG** fabrication

December 2018
MS5: Laboratory Tests Completed

May 2019
MS7: Techno-economical Evaluation

Aug 2019
MS6: Sea Tests Completed

Oct. 2019
MS8: Technology and Test Qualification

Dec 2019
End of project

UMBRAGROUP innovation

Technology transfer

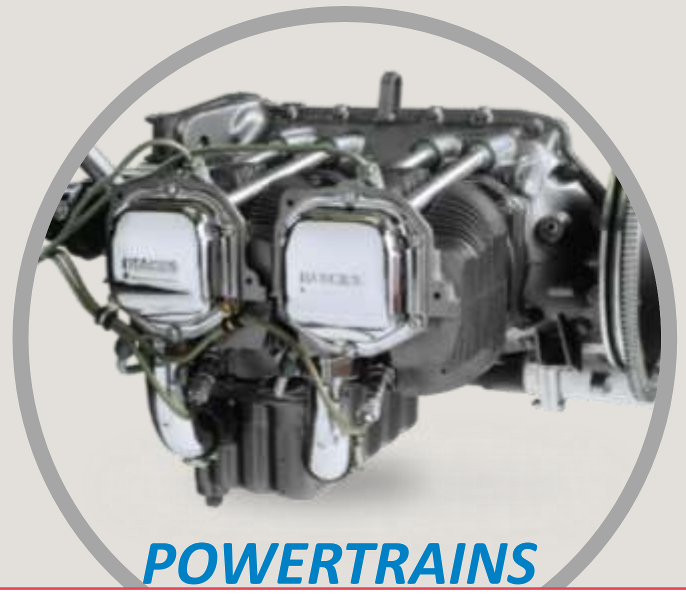
Technology transfer from other sectors to OCEAN REN. ENERGY

1972

FAG and GEPI found UMBRA to produce high-precison bearings

1978

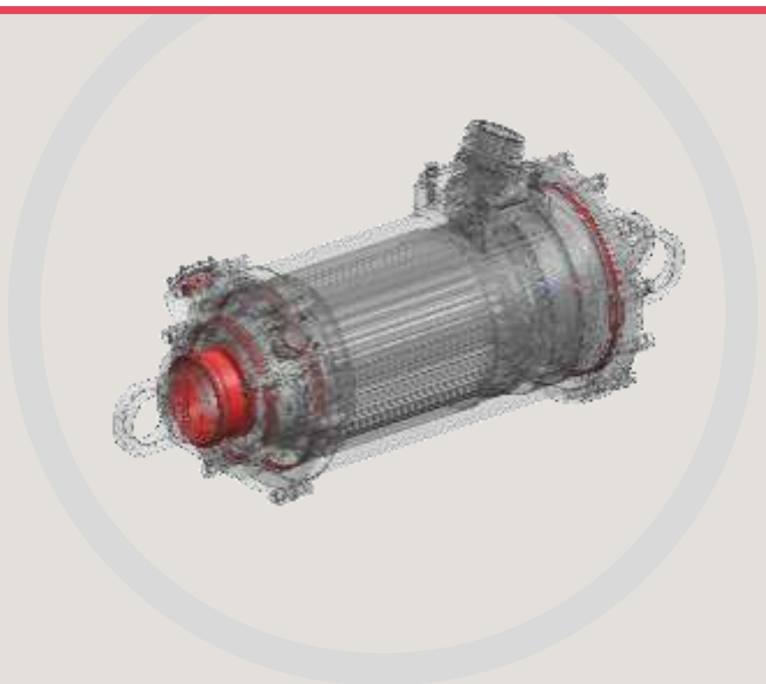
The company starts producing ballscrews for aviation industries



UMBRAGROUP innovation

ROADMAP

ANALYSIS & SIMULATIONS



2015

2016

2017

2018

2019

DRY TESTS

TANK TESTS

SEA TRIALS

EMERGE project team

EMERGE

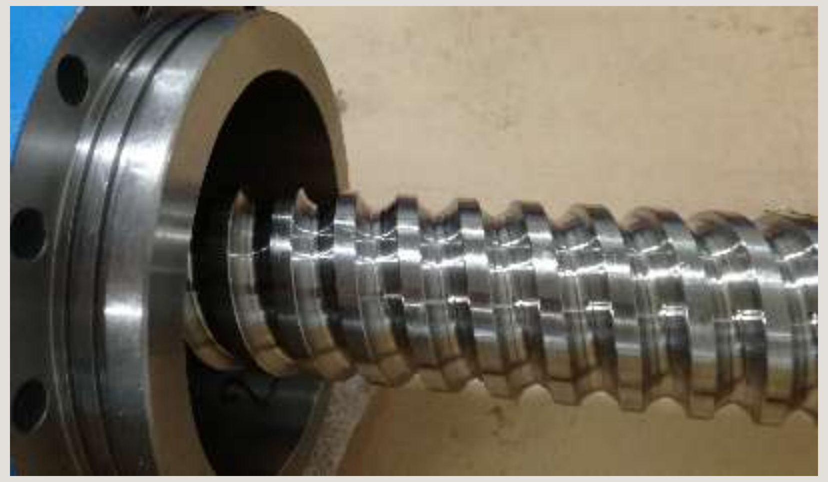
Electro-MEchanical Reciprocating GEnerator

emerge (/ɪˈməːdʒ/): to appear, or to become recognized

EMERGE project represented thousands of work hours, involving the collaboration of several teams from different project contractors.

EMERGE project objective

EMG prototype
- Design for marine environment
- Manufacturing at Umbra's facilities



TRL 5

Bench tests
- Submerged in synthetic sea water
- Hardware-in-the-loop configuration

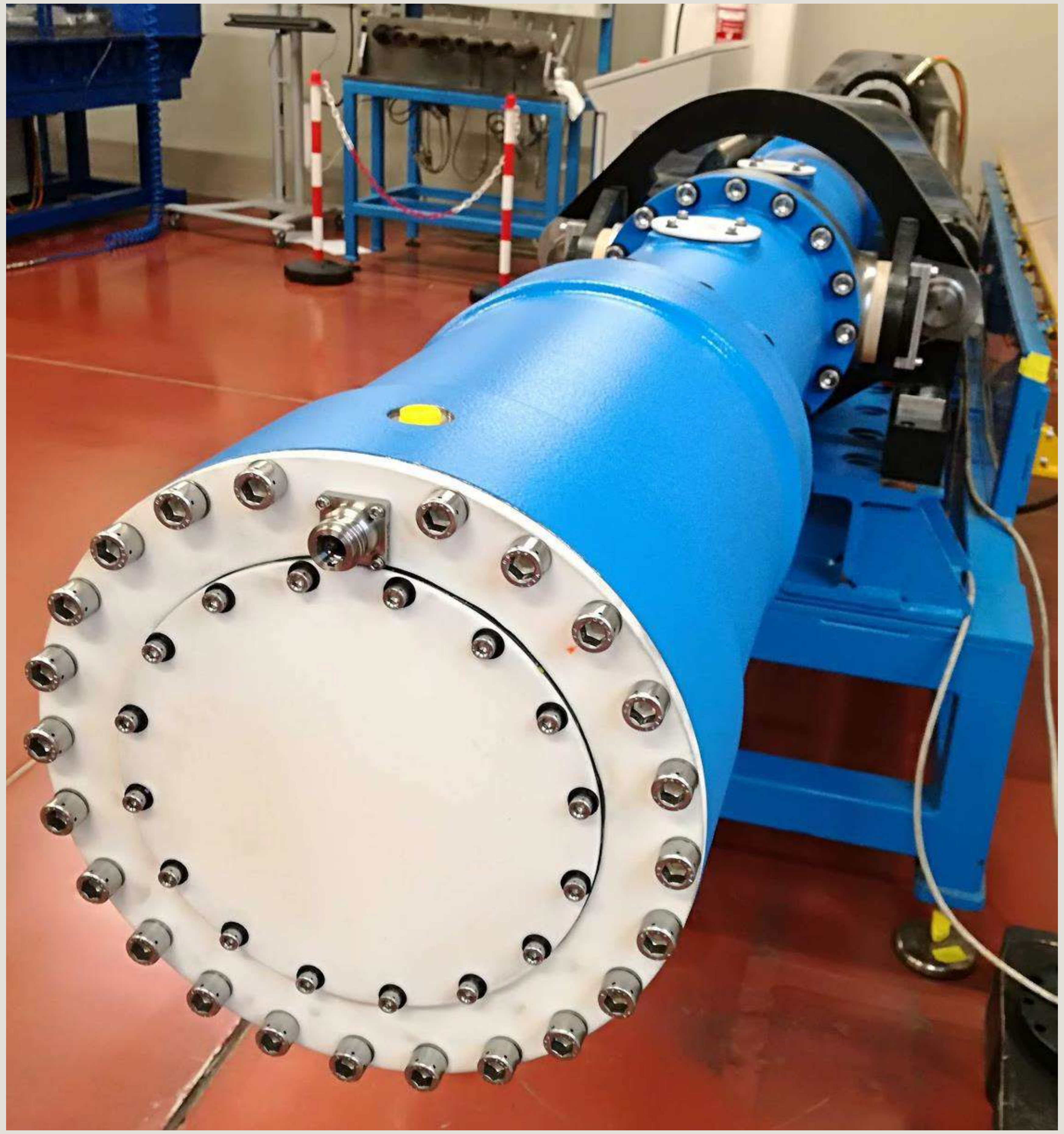
TRL 6

Sea trials
- Installation on point-pivoted buoy
- Use of gantry barge for ease of access

TRL 7

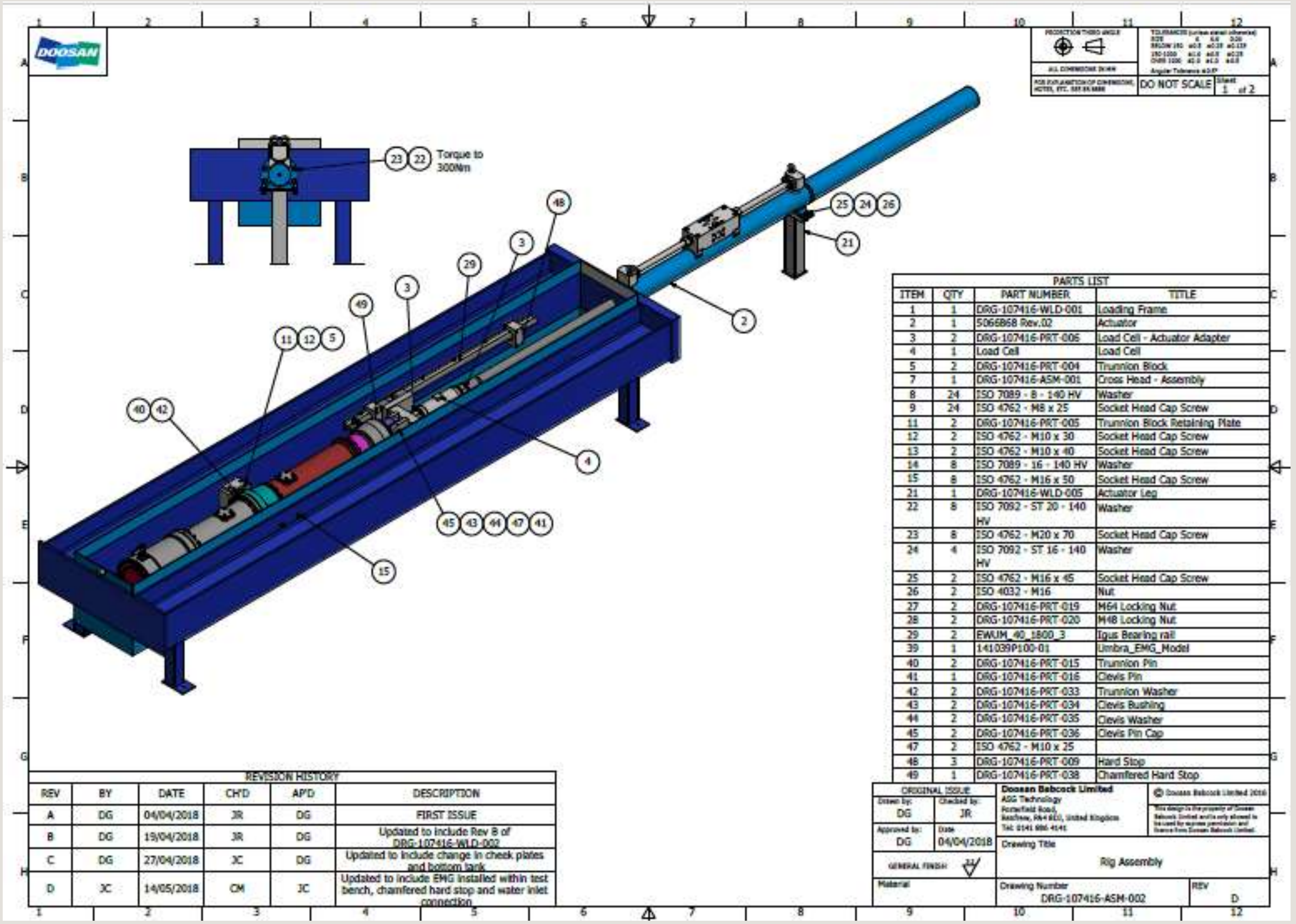
EMERGE – WP06

Procurement



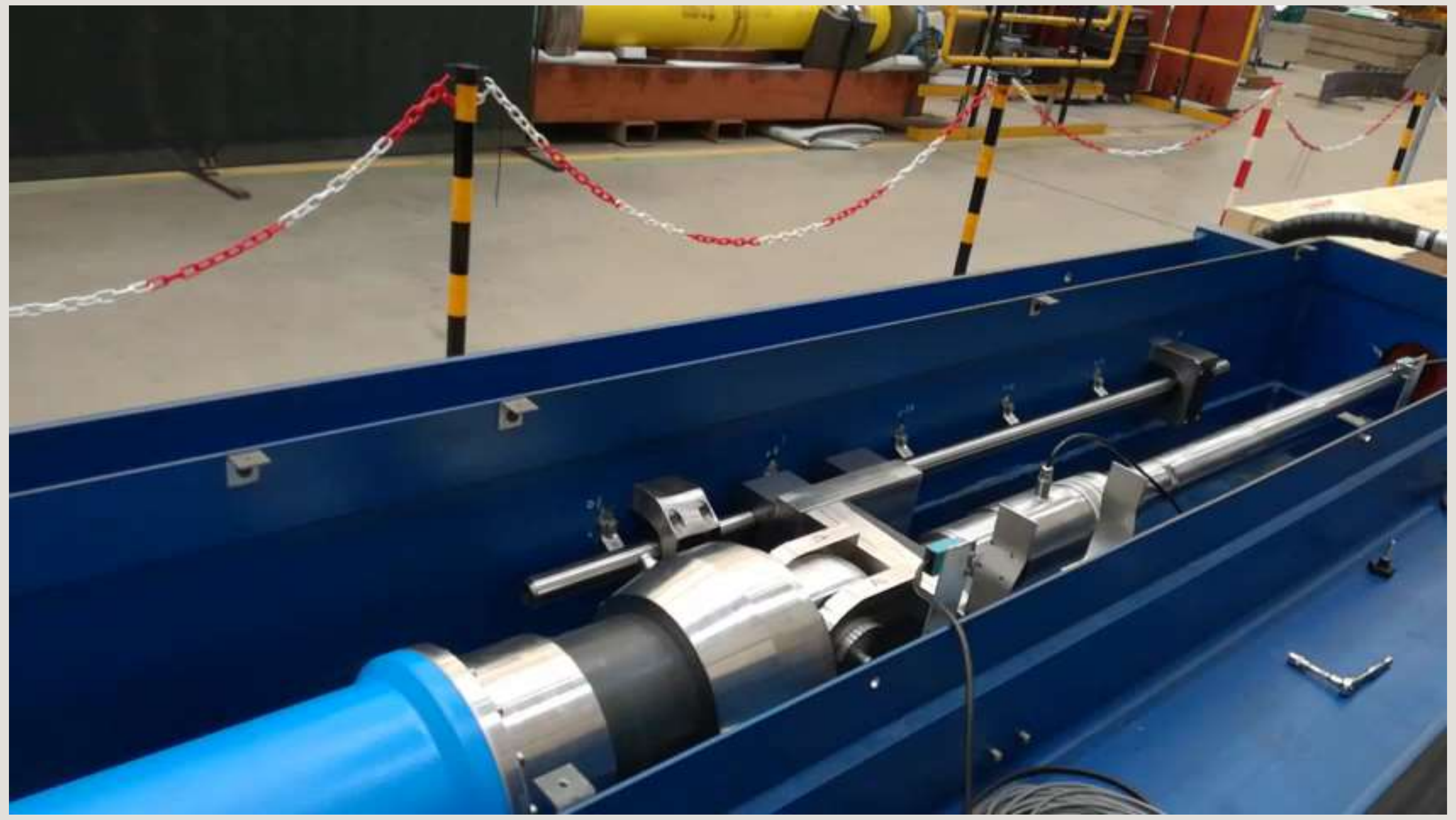
EMERGE – WP07

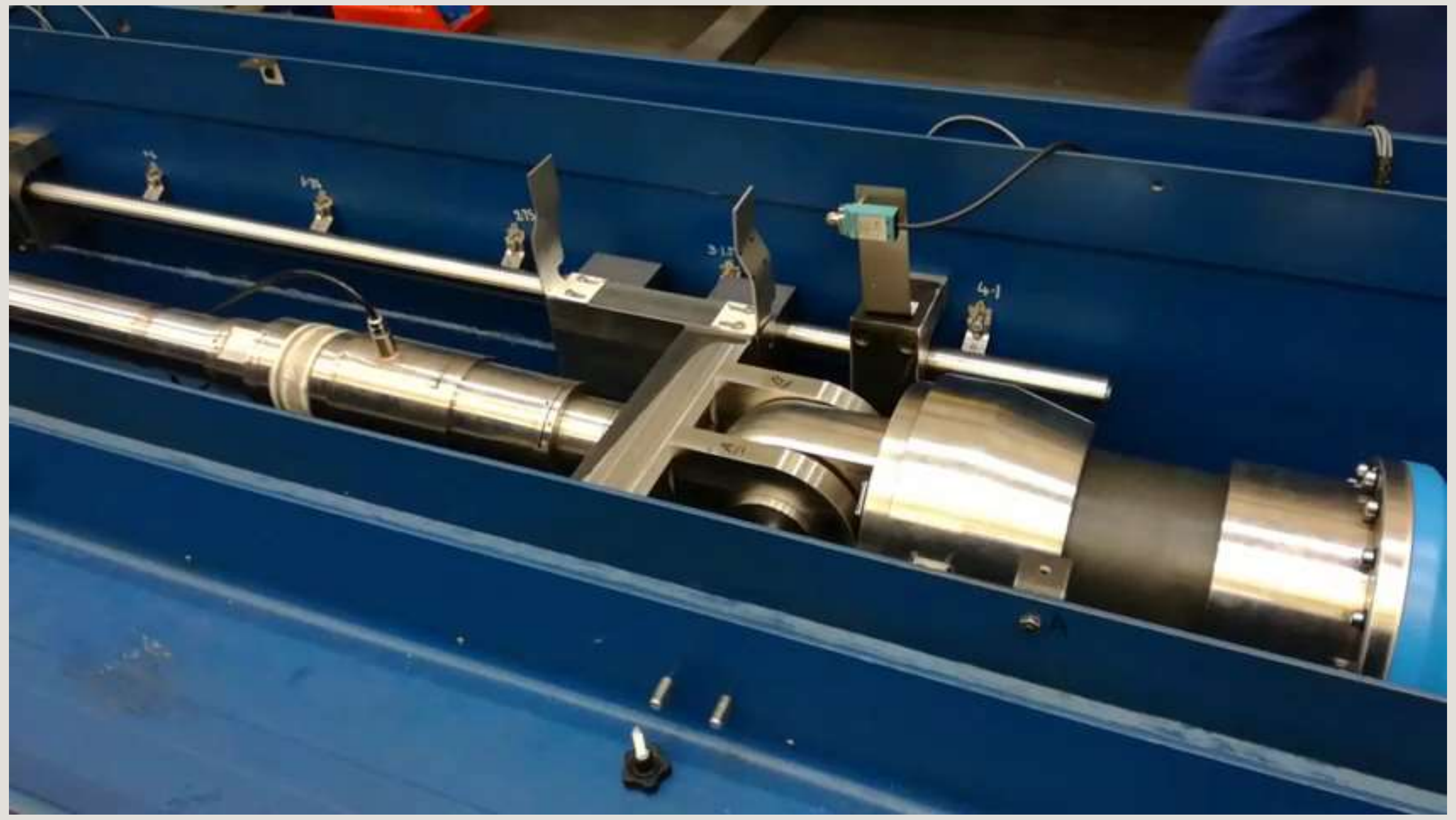
Power Take-Off Laboratory Tests

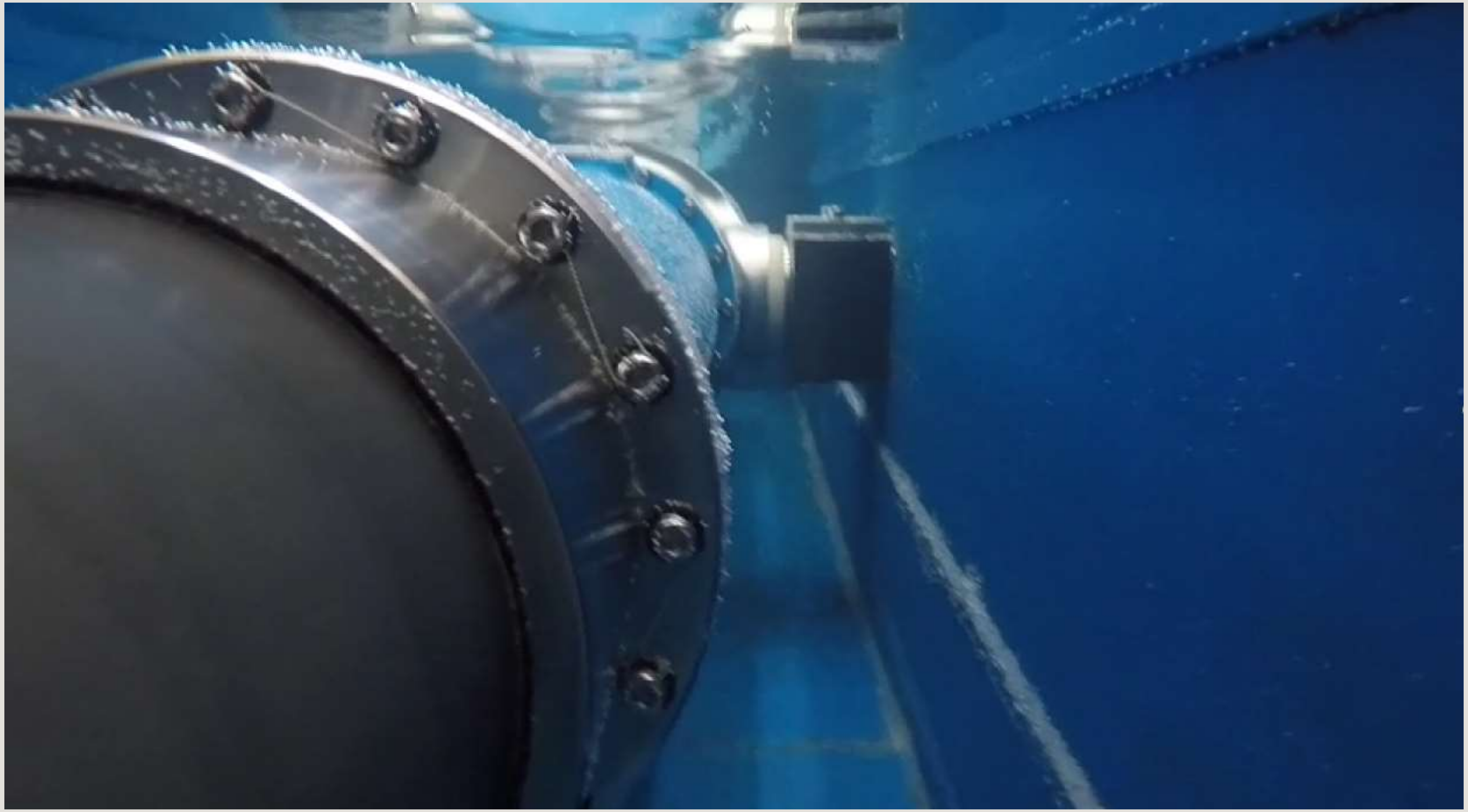


EMERGE – WP07

Power Take-Off Laboratory Tests





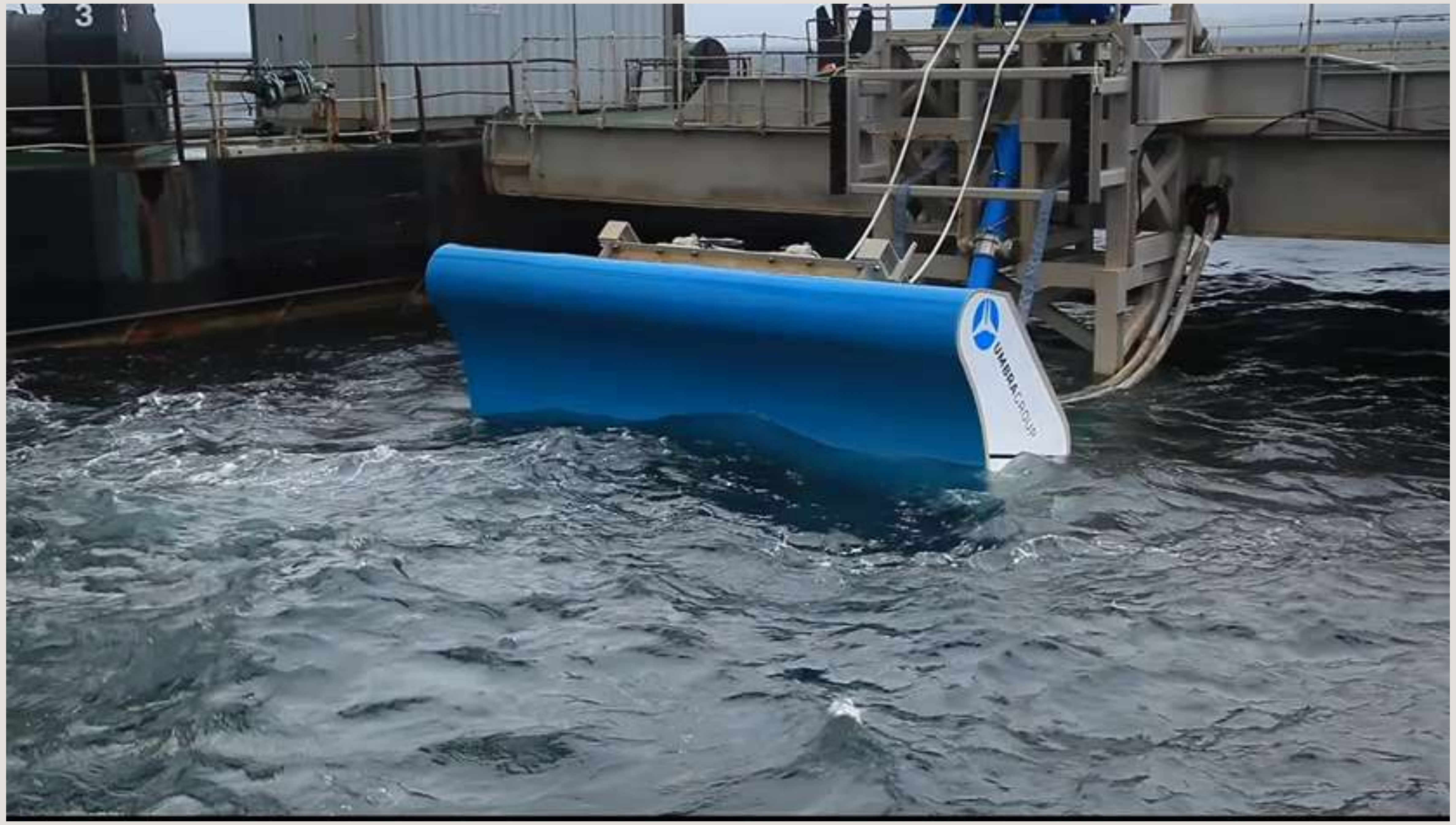


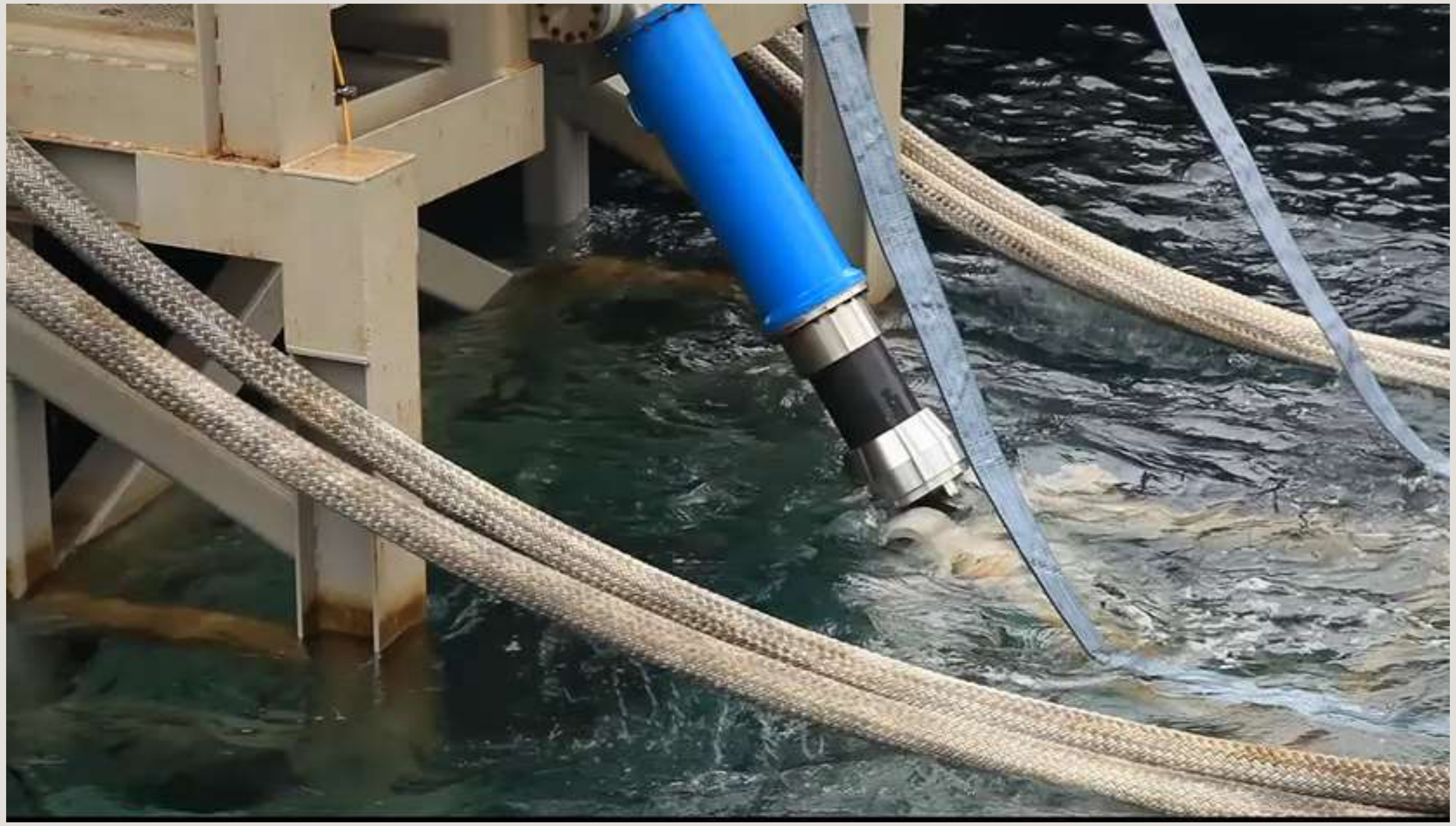
EMERGE – WP08

Power Take-Off Sea Trials

EMERGE – WP08

Power Take-Off Sea Trials





Check on LINKEDIN for more video

EMERGE – WP 10

Power Take-Off Technology Qualification

WP 10 lead by BV aimed at providing a third-party evaluation of EMG viability

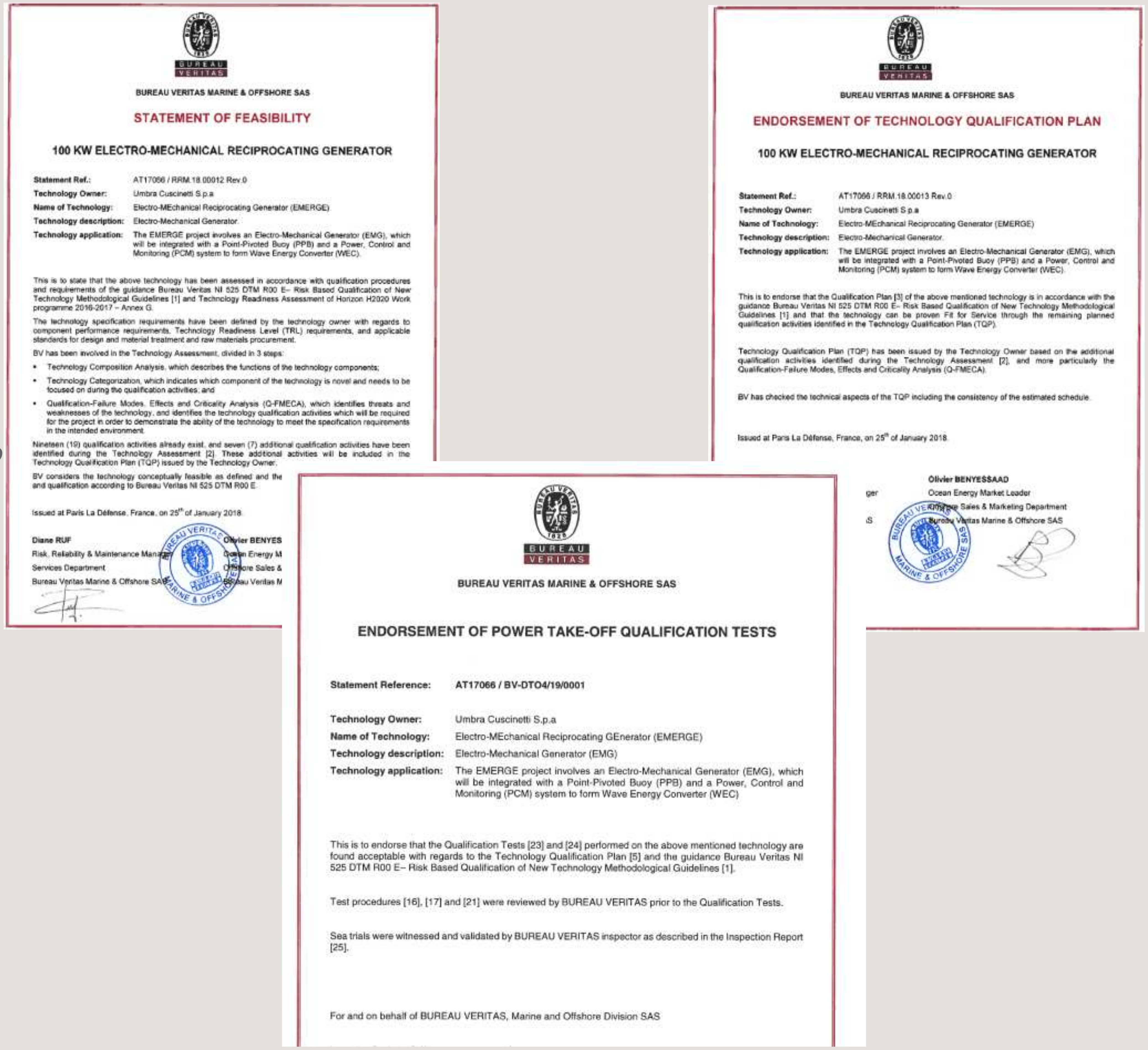
- *Task 10.1 Technology Assessment*
- *Task 10.2 Review of Qualification Plan*
- *Task 10.3 Review of Qualification Tests*

***Results**:*

- *FMECA workshop has been performed*
- *Both Laboratory tests and Sea trials have been validated and they are compliant to TQP*
- *TRL 7 has been achieved*

Presented Technical reports:

- *D14 – "Power Take-Off Statement of Feasibility"*
- *D15 – "Endorsement of Power Take-Off Qualification Plan"*
- *D16 – "Endorsement of Power Take-Off Qualification Tests"*



EMERGE project objectives

EMG has undergone testing both in relevant and operational environments to reach a Technology Readiness Level (TRL) of 7. It has been first tested in a bench with a Hardware-In-the-Loop (HWIL) configuration while submerged in synthetic salt water. Then, it has been integrated with a point-pivoted Wave Energy Converter (WEC) and underwent sea trials in Scapa Flow. This project allowed to develop engineering solutions for survivability in open marine environment and gave valuable information concerning EMG performance in real sea conditions.

Metric		TO expected (qualitative)	TO expected (quantitative)	Industrial TO expected (quantitative)	Project TO	Industrial TO
Affordability	CAPEX	*During the implementation of WP07 and WP08, the EMG will work in relevant and operational environments, respectively. Inspection of the generator after the tests will ensure no damages occurred on any component.*	*Considering this context (FOAK device), the project CAPEX is in the range 800-1000£/kW of peak electrical power (IEC 60034-1 S6 duty 15%).*	Cost of PTO 650 £/kW for a 100 kW (peak electrical, IEC 60034-1 S6 duty 15%) power generator.	Confirmed	Confirmed
	OPEX	*The maintenance targets are mainly related to the PTO itself and only partially deal with the working conditions of a specific application.*	*OPEX (PTO only) £500/yr*	OPEX is expected to reach values as low as 400-450£/year per EMG by slightly reducing the maintenance frequency based on a maintenance contract agreement.	*Confirmed*	*Confirmed*

EMERGE project objectives

Metric		TO expected (qualitative)	TO expected (quantitative)	Industrial TO expected (quantitative)	Project TO	Industrial TO
Availability	**Reliability**	*Within the Stage 2 project, the reliability was already assessed by tests, and calculations of FMEA and MTBF.*	*Confirm the maintainability capabilities of the generator by achieving zero failures indications after the tests in relevant and operational environments.*	Expected life of 20 years (continuous operation).	Confirmed	Confirmed
	Maintainability	*Failure Modes results are intended to be confirmed and in addition a FMECA study will be provided.*	*Zero failures*	Maintenance intervals every 4 years	Confirmed	Confirmed
Survivability	**Load ratio**	*The EMG is declared to survive load ratios up to 5.*	*The EMG is declared to survive load ratios up to 5.*	The EMG is declared to survive load ratios up to 10.	Confirmed	Confirmed
	Fatigue loading	*The EMG is declared to survive load ratio, while being not affected by fatigue issues for the total period of testing.*	*not fatigue issues.*	-	Confirmed	Confirmed
	Corrosion resistance	*EMG will have an appropriate protection (painting or coating) against marine environment (anti-corrosion, anti-fouling).*	*Marine protection solution is expected to survive without problems for the whole period of testing.*	Marine protection solution will be most likely aligned with market standards.	Confirmed	Confirmed

EMERGE project objectives

Metric		TO expected (qualitative)	TO expected (quantitative)	Industrial TO expected (quantitative)	Project TO	Industrial TO
Other	Manufacturability	*Stage 3 prototype is expected to be entirely manufactured in Umbra plant in Foligno using existing equipment, tools and processes. No other novel equipment tools or processes were required.*	*Production lead time will be 6 months*	Production lead time will be 4 months	Confirmed	Confirmed
	Installability	*EMG installation on the WEC with a pin-to-pin connection performed through simple operations.*	*Installation time: 8 hours.*	Installation procedure will not require extensive equipment	Confirmed	Confirmed
	Integrability	*The Integration of the device is extremely easy and possible in a wider range of systems.*	*2 mechanical interfaces (hinges) and 2 electrical connectors*	pin-to-pin architecture of the EMG	Confirmed.	Confirmed.
	Scalability	*The generator is easily scalable up to 300 kW of peak power, with the possibility of parallel arrangement or arrays.*	*Two or three device cases will be evaluated during the execution of this project.*	A feasibility study for at least two full scale WEC will be provided.	Confirmed	Confirmed
	Controllability	*Demonstrate that the EMG easily works with variable damping*	*Test at least 3 damping factors*	Commercial product will be controllable with a complete range of damping values reacting immediately to input and informing the same system on its status. Ability to be controlled can maximize the efficiency with respect to the working conditions.	Confirmed	Confirmed

EMERGE project

Conclusions

- Technology transfer from other sectors to OCEAN REN. ENERGY
- Highly reliable and efficient solution (proved by robust methodology)
- Third-party technology validation
- High TRL and established manufacturing capabilities
- Clear ROADMAP to commercialization

THANK YOU FOR THE ATTENTION

Luca Castellini
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Wave Energy Scotland Annual Conference 2019: #WESAC19

Project Neptune: A 75 kW Linear Generator for Wave Energy Conversion

Dr Joseph Burchell

University of Edinburgh

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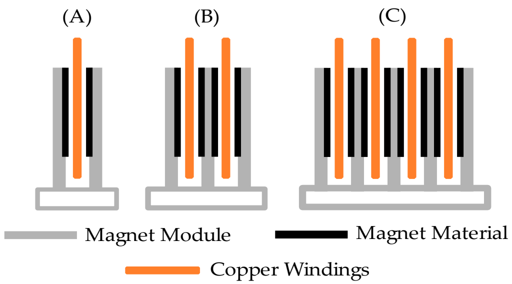
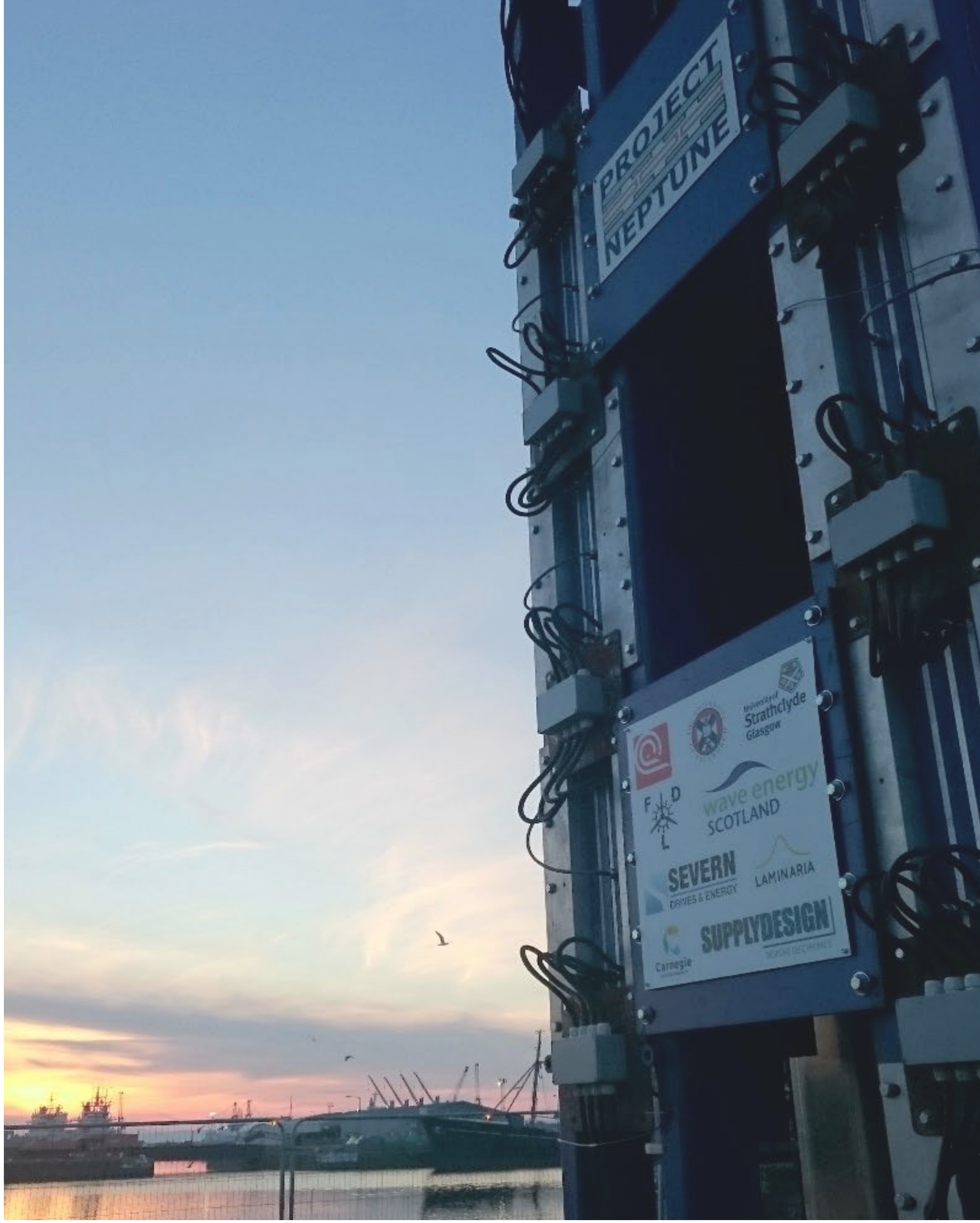
Dr Ignacio Barajas-Solano, Mike Galbraith, Dr Nisaar Ahmed, Okechukwu Ubani & Prof. Markus Mueller

Contents

- C-Gen PTO Background
- Project Neptune Stage 3 Outcomes
- Project Neptune Test Rig
    - Design
    - Manufacture
    - Build
- Dry Commissioning & Wet Testing
- Component Replacement on site
- Summary of Achieved Outcomes



(A) Single stage C-GEN
(B) Double stage C-GEN
(C) Four stage C-GEN



C-Gen PTO Concept

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C-GEN is an advanced multi-stage air-cored direct drive permanent magnet generator technology providing high reliability and availability in renewable energy converters.




C-GEN PMG Technology has the Following USPs over existing Generator Technologies used for Direct Drive PTO

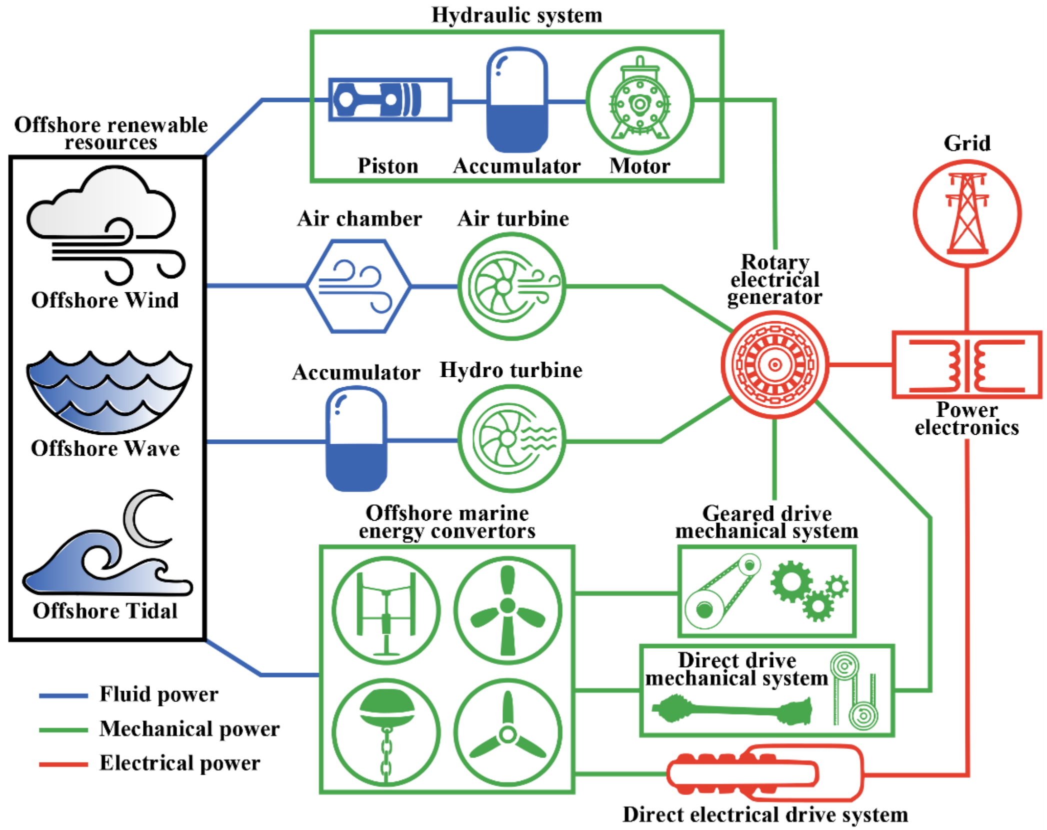
- No Magnetic Attraction Forces within Airgap
- No Cogging Torque
- High Degree of Modularity
- Affordable with low CAPEX
- Easy Integrated into various Renewable Energy Device Types
- High efficiency across full operating range

Current C-GEN Technology Status

- TRL level 5 for Rotary
- TRL level 3 for Flooded Linear
- Patent Granted in USA, China, Japan, Canada, Australia & Europe
- Numerous C-Gen Machines built from 10kW to 1MW
- Marinised C-Gen components have been tested for Submerged Offshore Operation

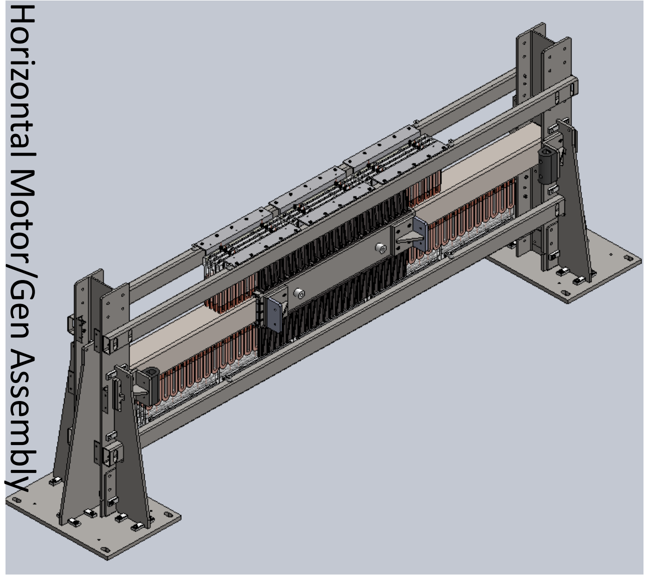
WES Stage 3 PTO Project

- C-Gen Machine capable of running in a fully flooded marine environment
- Demonstrate C-Gen in a real environment, at a relevant scale and under realistic load profiles
- Industrialise the design and manufacture of C-Gen for Marine Renewable applications
- Obtain qualification from an independent body
- Demonstrate O&M Capabilities
- Align the commercial strategy with device developers for a full-scale demonstrator

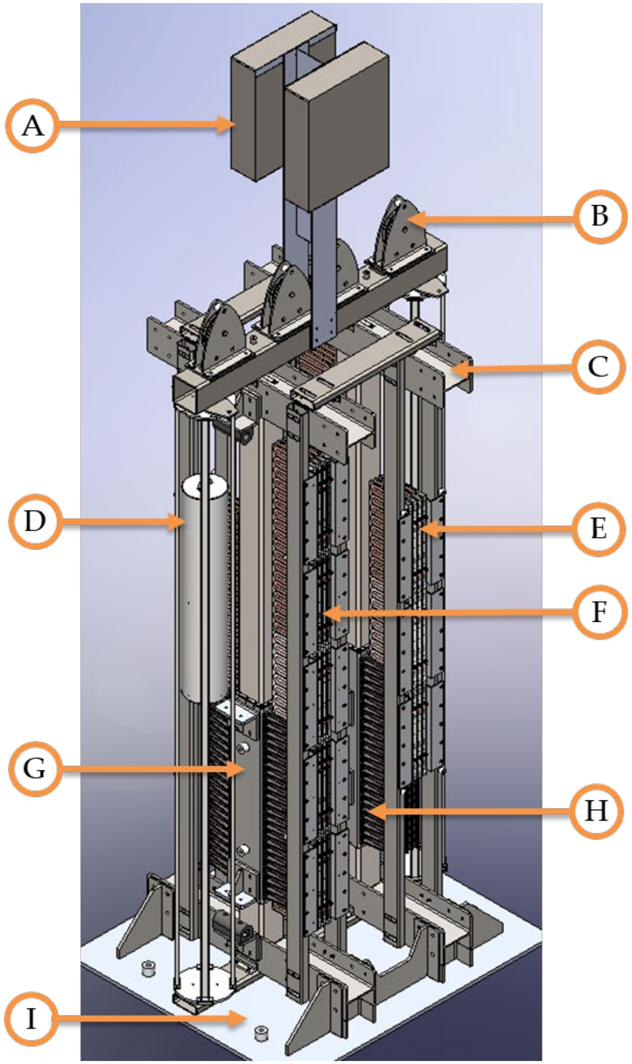


Project Neptune – PTO Test Rig Spec

- Sinusoidal motion with a peak velocity range of 1-1.5ms^{-1}
- Voltage = 415 V (peak), and 339V (rms), per phase
- Current density: nominal 4-5 Amm^{-2}, but with > 20 Amm^{-2} overload capability
- Efficiency >60-80% for the peak velocity range of 1-1.5ms^{-1}
- Overload = 200% continuous, 500% short term rated
- Back to back linear double motor-generator test rig*



Notation	Component Description
A	Data acquisition and power boards
B	Translator/counterweight pulley system
C	Test rig support structure
D	Counter weight 1, counter weight 2 opposite
E	Generator coil modules
F	Motor coil modules
G	Translator 1
H	Translator 2
I	Test rig base plate



Industrialisation of Manufacture

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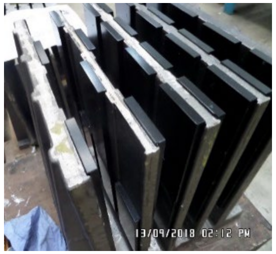
Project Neptune – Test Rig Build

Component Manufacture


Stator module


Cast iron PM module


Bearing Pad module

Assembly Process


Stator Supports


Translator Installation

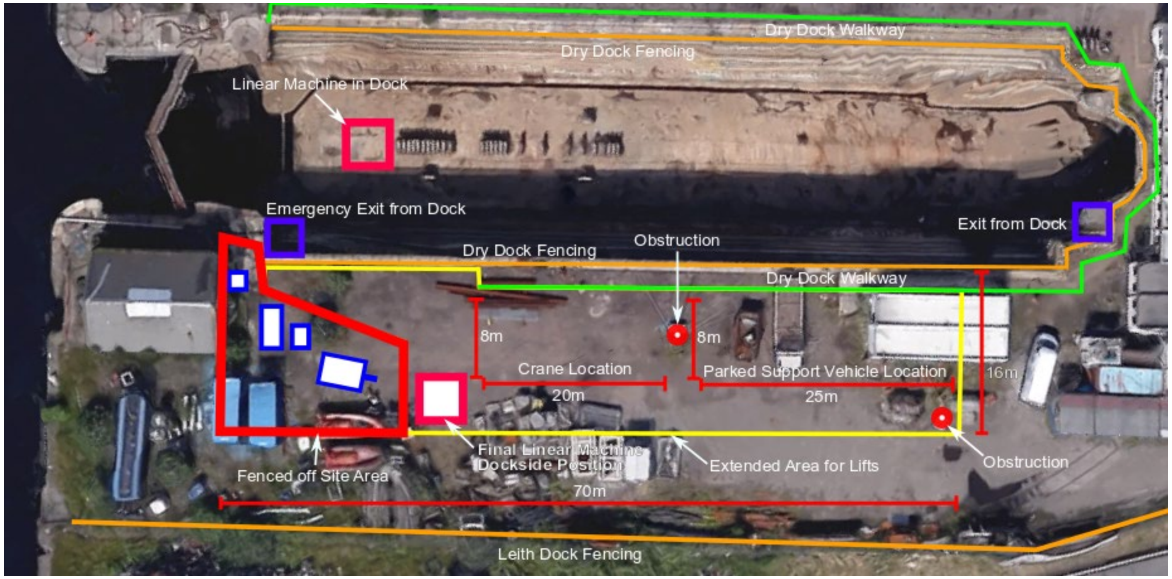

Single Machine Horizontal



Horizontal Installation

Testing at Leith Docks

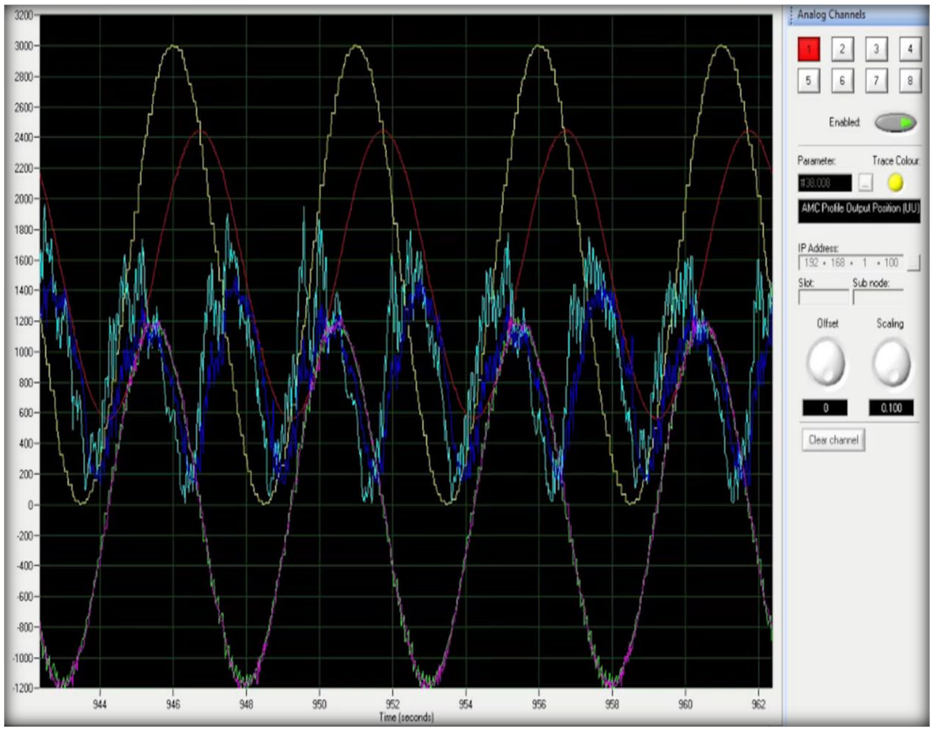
- Diesel Gen Set – Motor Drive – Output to Grid Convertor
- Dry Commissioning – 1 month
- Dry run testing – 2 months
- Wet run testing – 3 months
- Component replacement
- Component and rig inspections

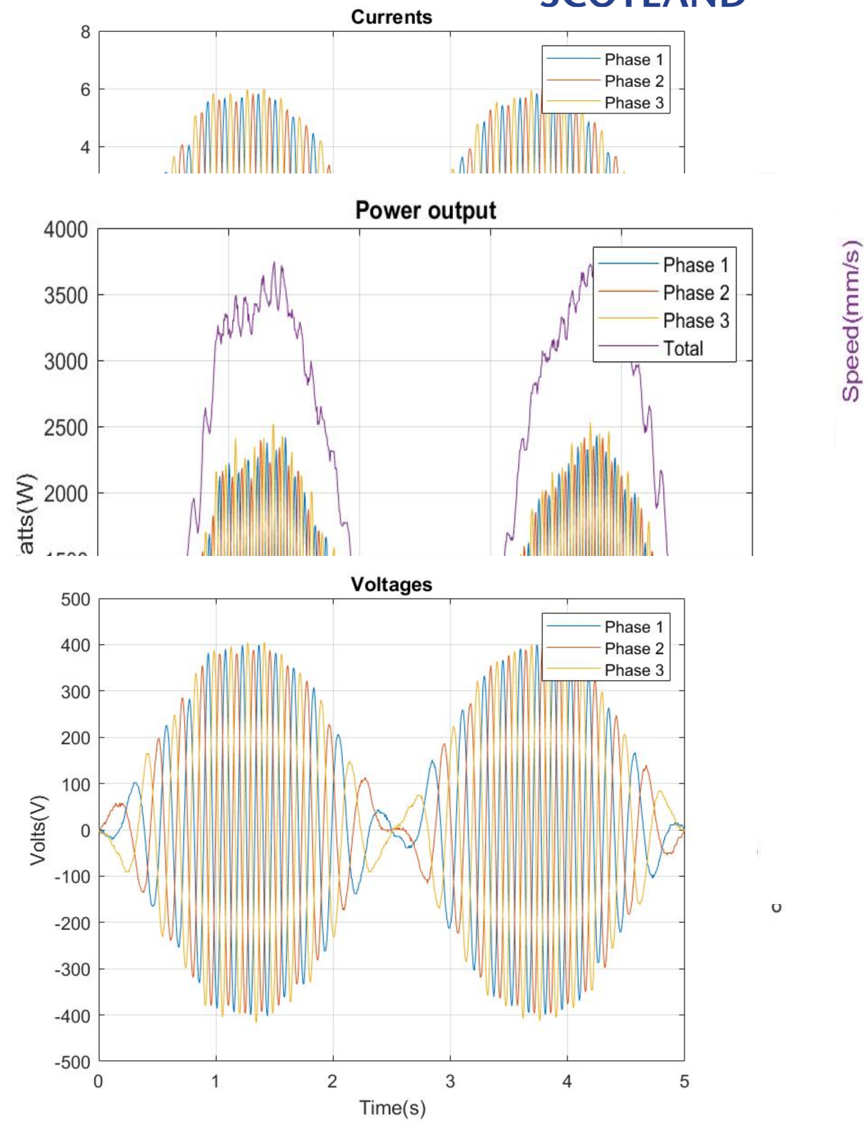


Data from Leith Docks

- Monitoring & recording
  - Translator position
  - Translator speed profiles
  - Motor drive characteristics
  - Generator drive characteristics
  - Search coil voltages
  - 3 phase voltages & currents per stage
  - Coil temperatures
  - Bearing temperatures
  - Airgap deflection
  - Test rig vibration
  - Bearing wear

Test Results Snapshot





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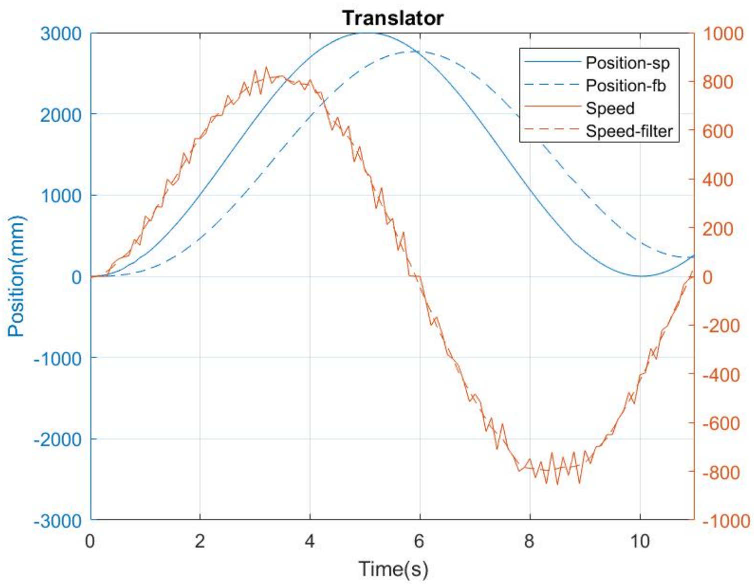

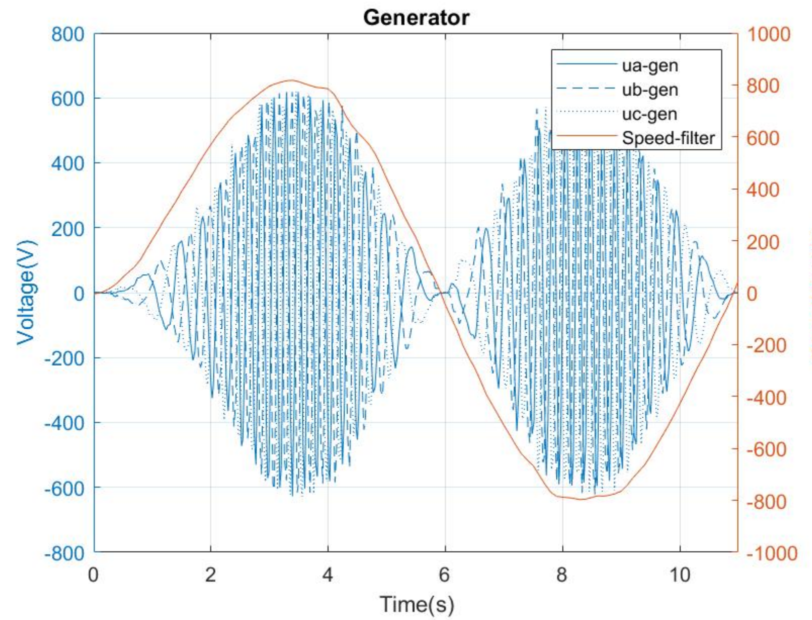

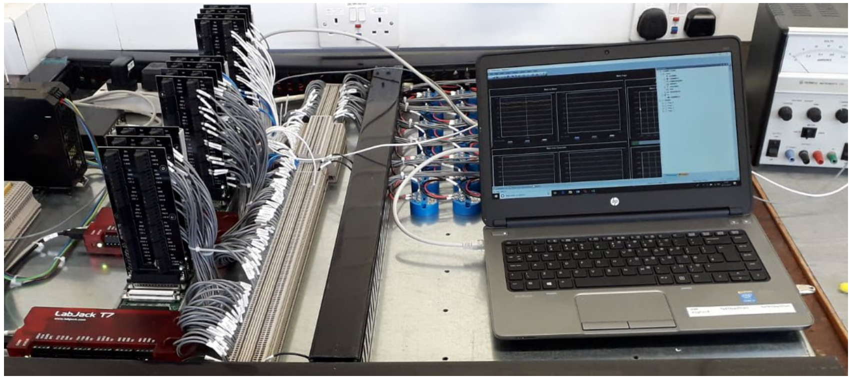

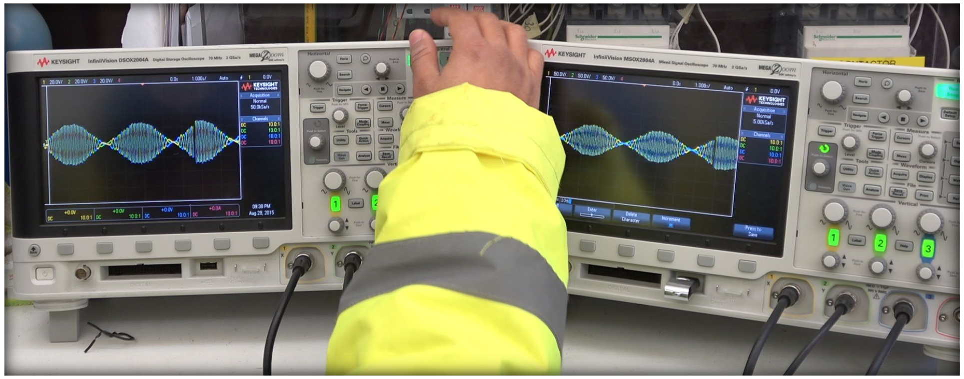

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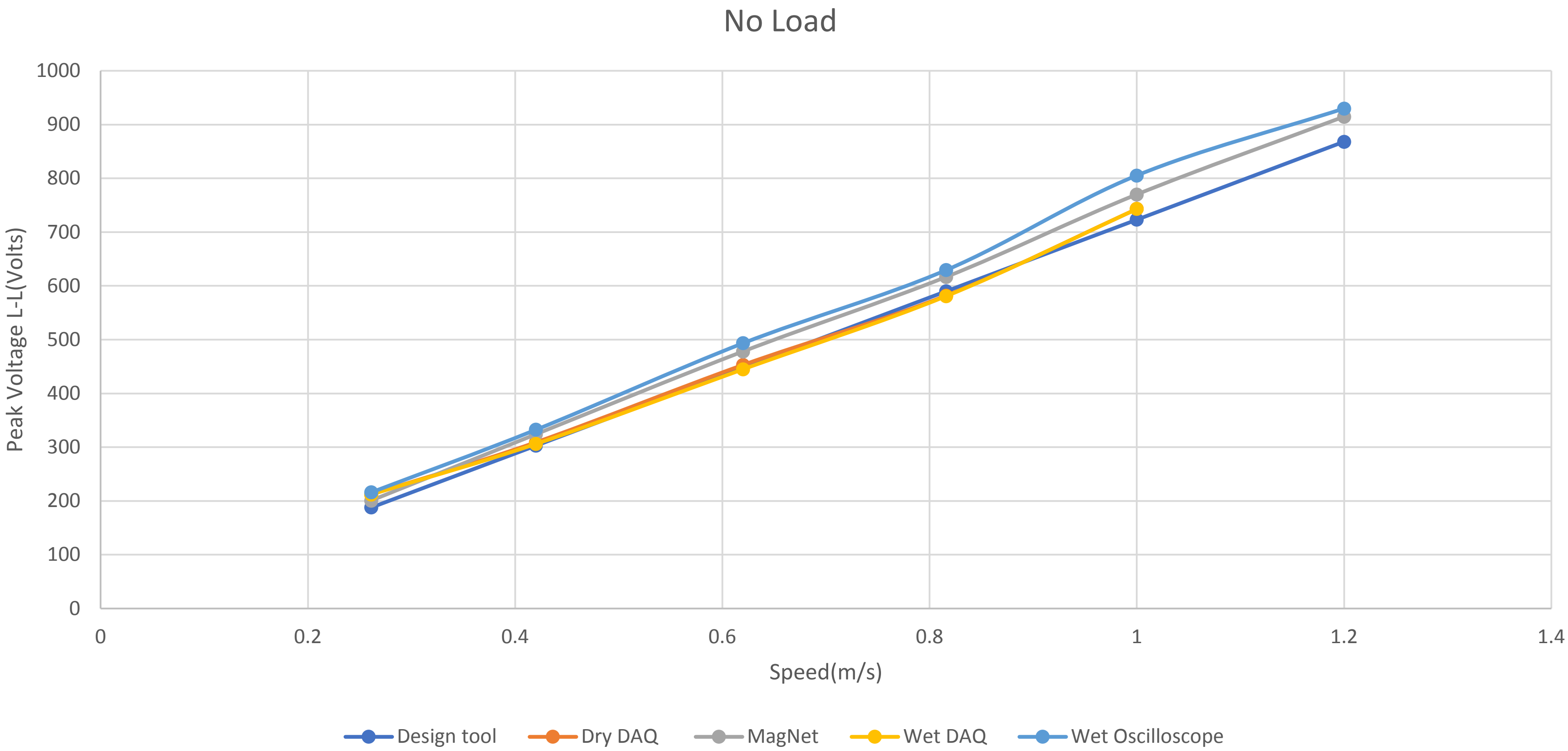

Test Results Snapshot

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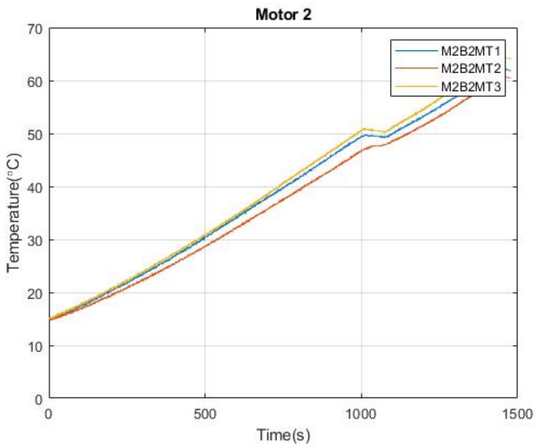

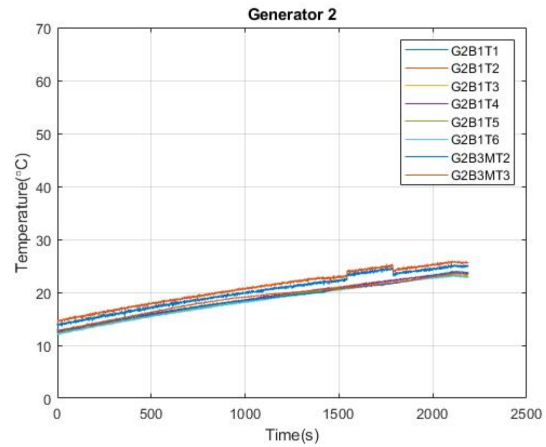

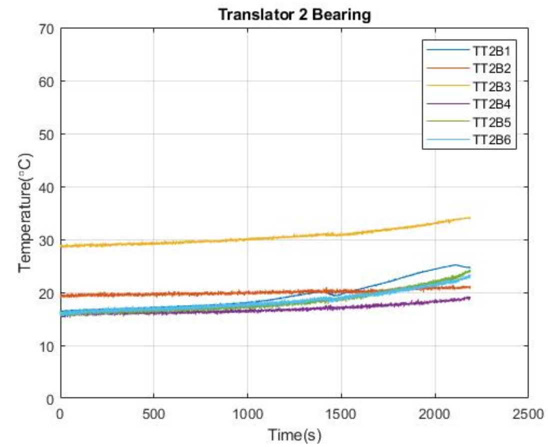

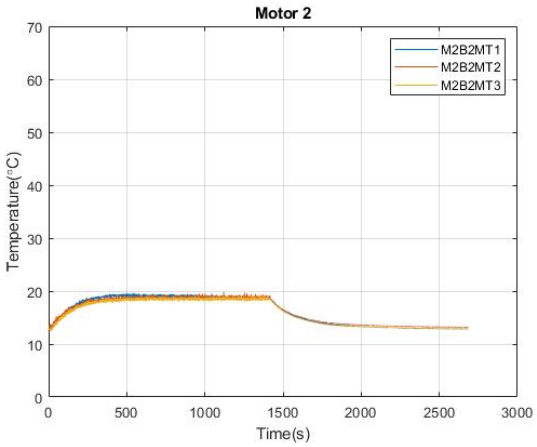

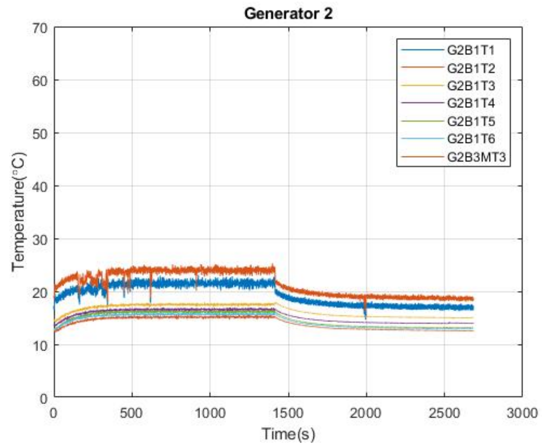

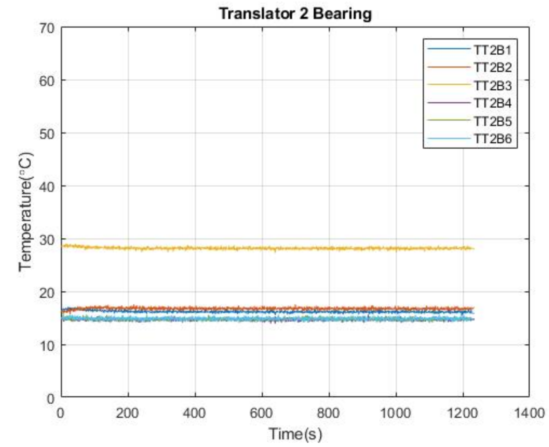

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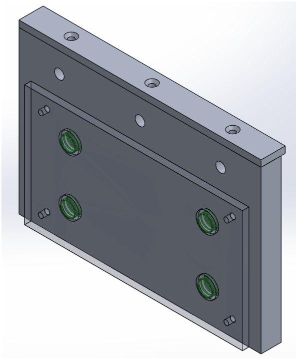
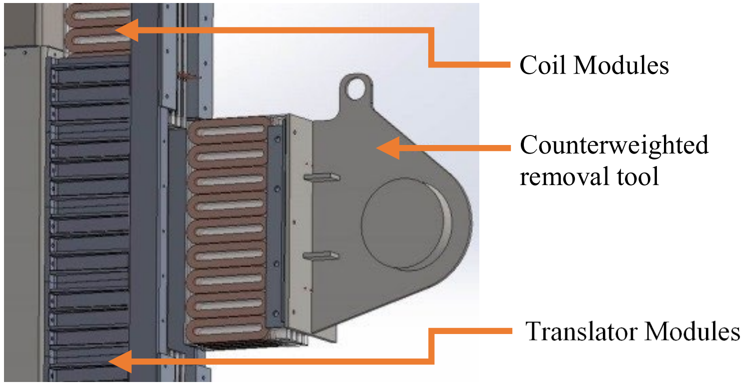
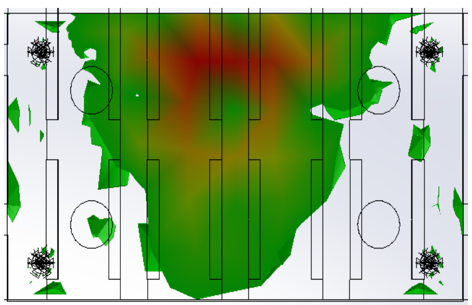
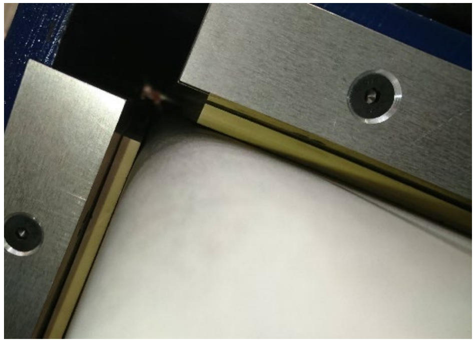
Demonstrate O&M



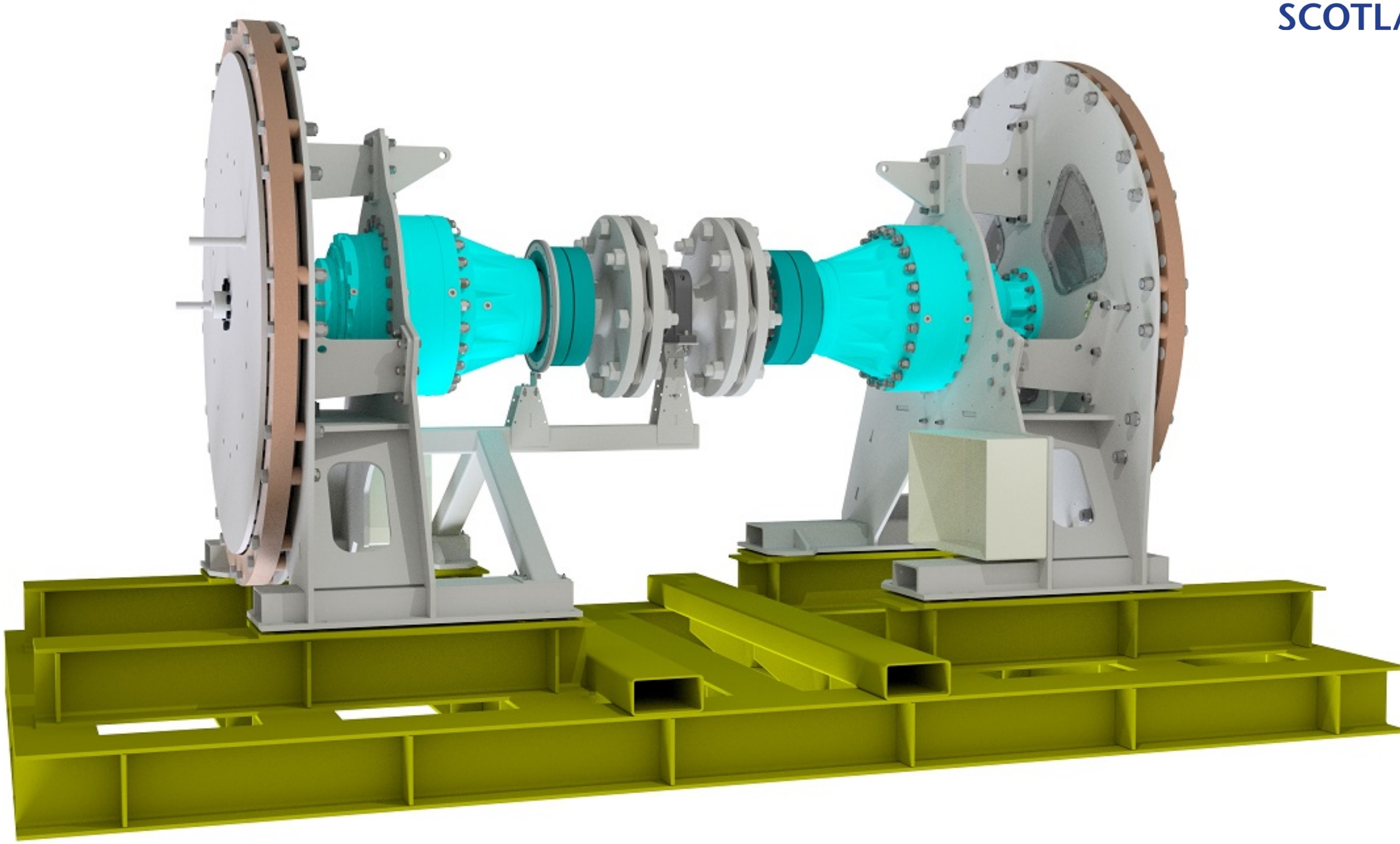






Summary

- C-Gen Machine capable of running in a fully flooded marine environment
- Demonstrate C-Gen in a real environment, at a relevant scale and under realistic load profiles
- Industrialise the design and manufacture of C-Gen for Marine Renewable applications
- Started the route to obtain qualification from an independent body, demonstrate O&M Capabilities and apply a standardised testing process
- Align the commercial strategy with device developers for a full-scale demonstrator



“Wave energy developer Mocean Energy has selected the University of Edinburgh’s C-GEN technology to provide the power take-off (PTO) for its first half-scale wave energy prototype.”

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Many thanks for your attention

Place your orders now!

THE UNIVERSITY *of* EDINBURGH
School of Engineering

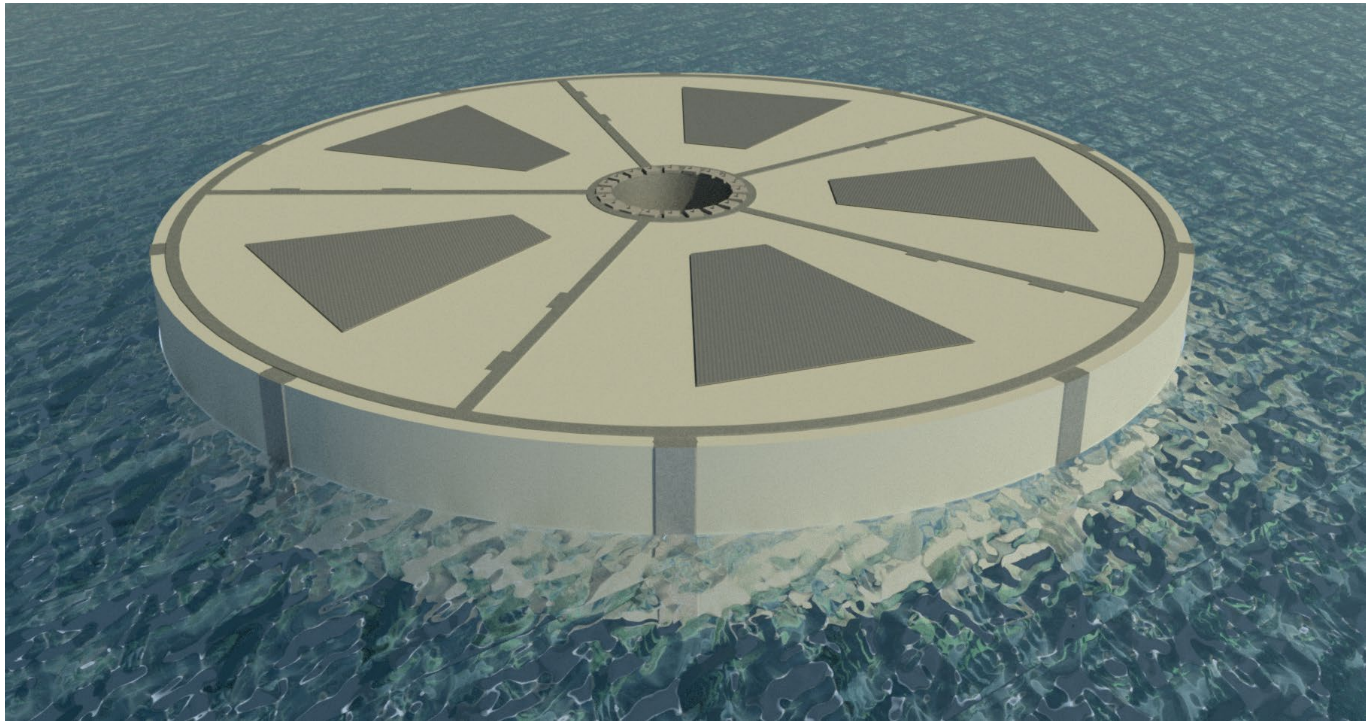
Institute for Energy Systems

ARUP

WES Annual Conference 2019

CREATE Stage 2

Concrete as a Technology Enabler



Karoline Lende | Arup

5th December 2019

Carnegie wave energy

mpa The Concrete Centre British Precast

cruz atcheson CONSULTING ENGINEERS

mocean energy

DOOSAN

bam Infrastructure Advisory

Aim

Demonstrate that **concrete** can make a step-change in the **Levelised Cost of Energy** (LCoE) for **Wave Energy Converters** (WECs)

Stage 1: 2017-2018

Stage 2: 2018-2019

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bam Infrastructure Advisory

mpa The Concrete Centre British Precast

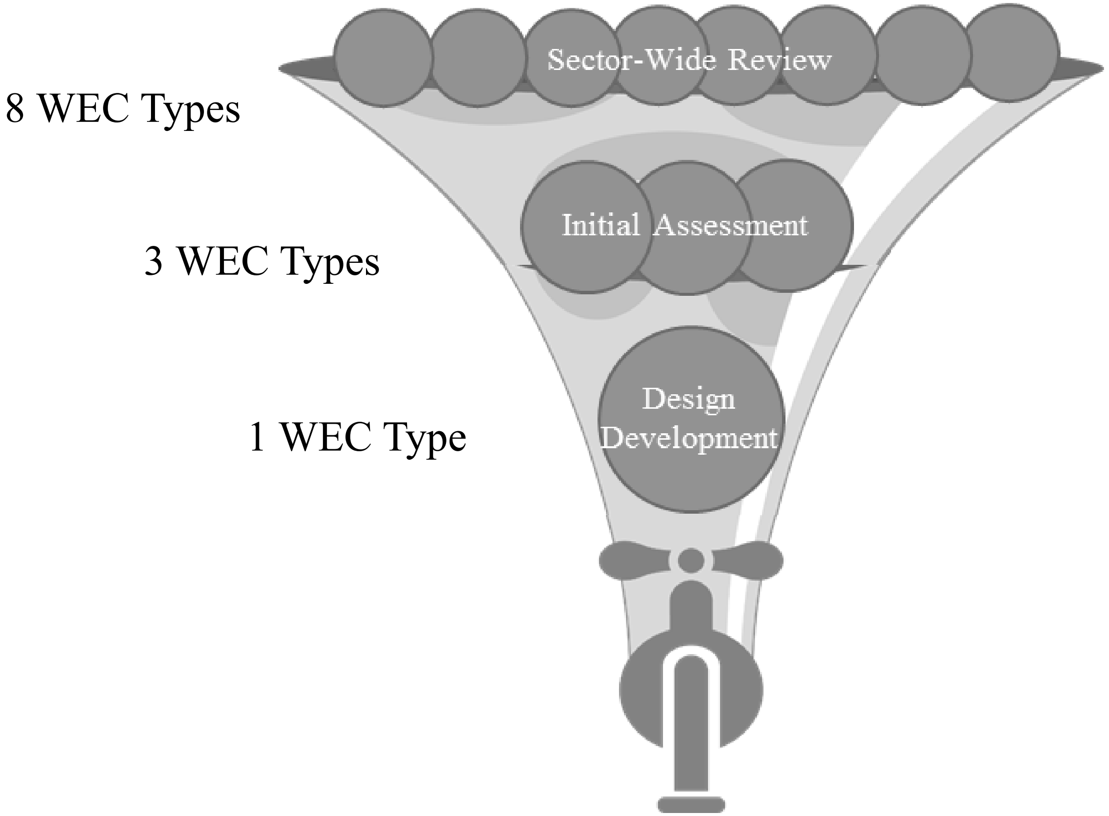
Carnegie wave energy

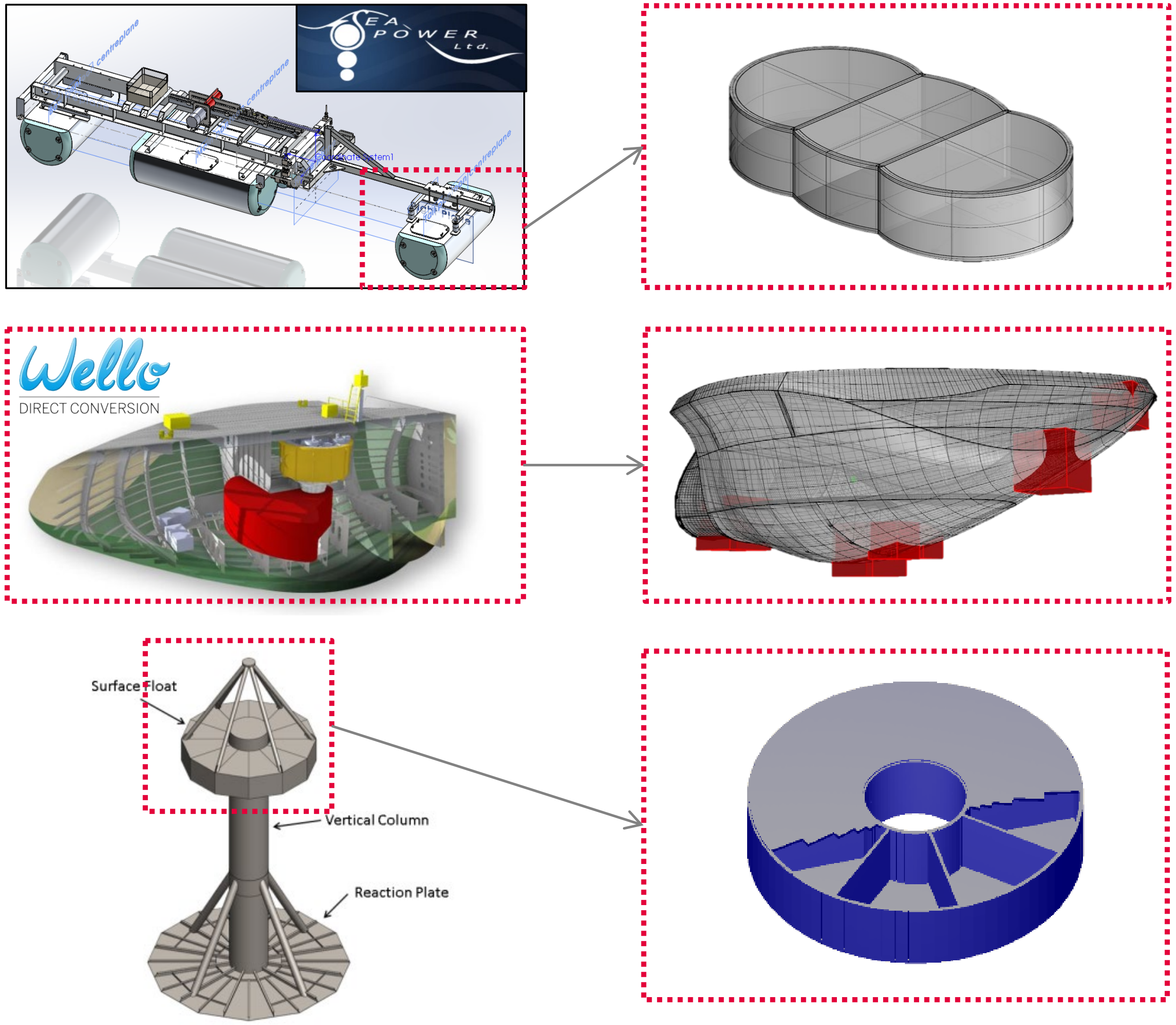
cruz atcheson CONSULTING ENGINEERS

mocean energy

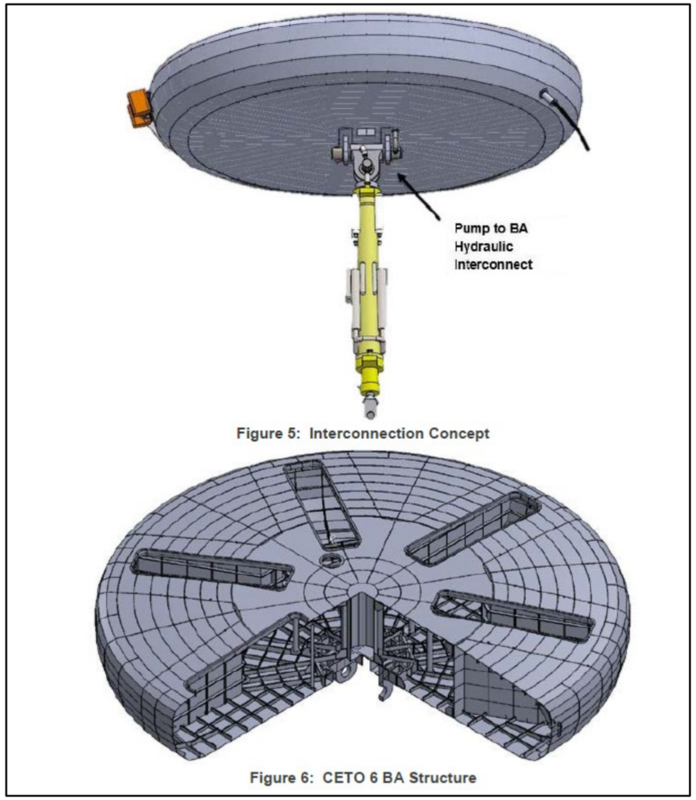
DOOSAN

Stage 1: 2017-2018

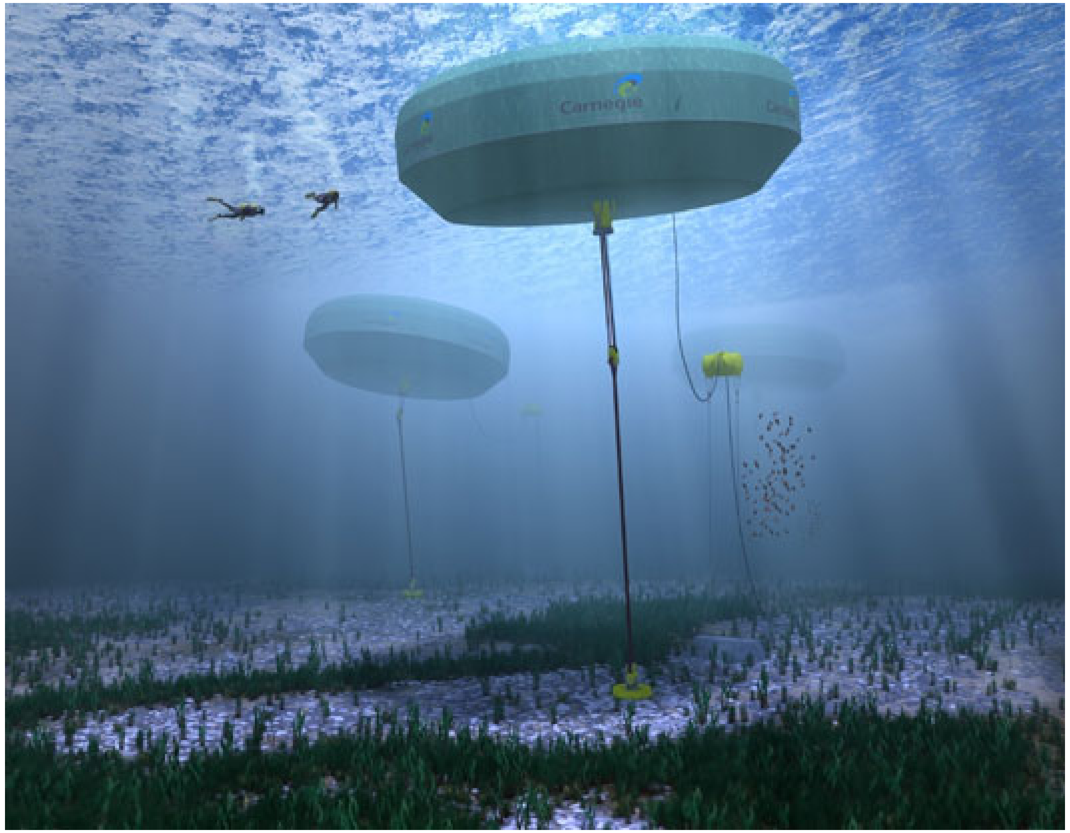




Submerged Pressure Differential



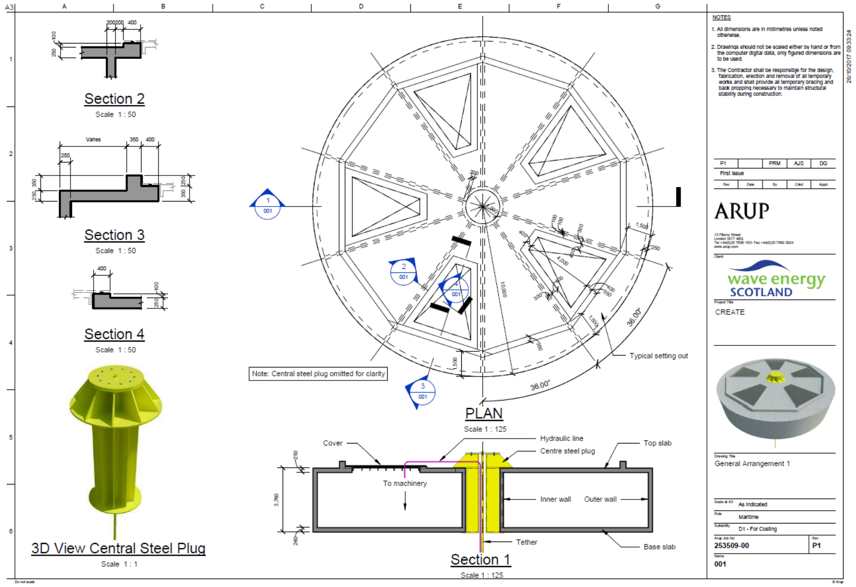
Carnegie "CETO 6"

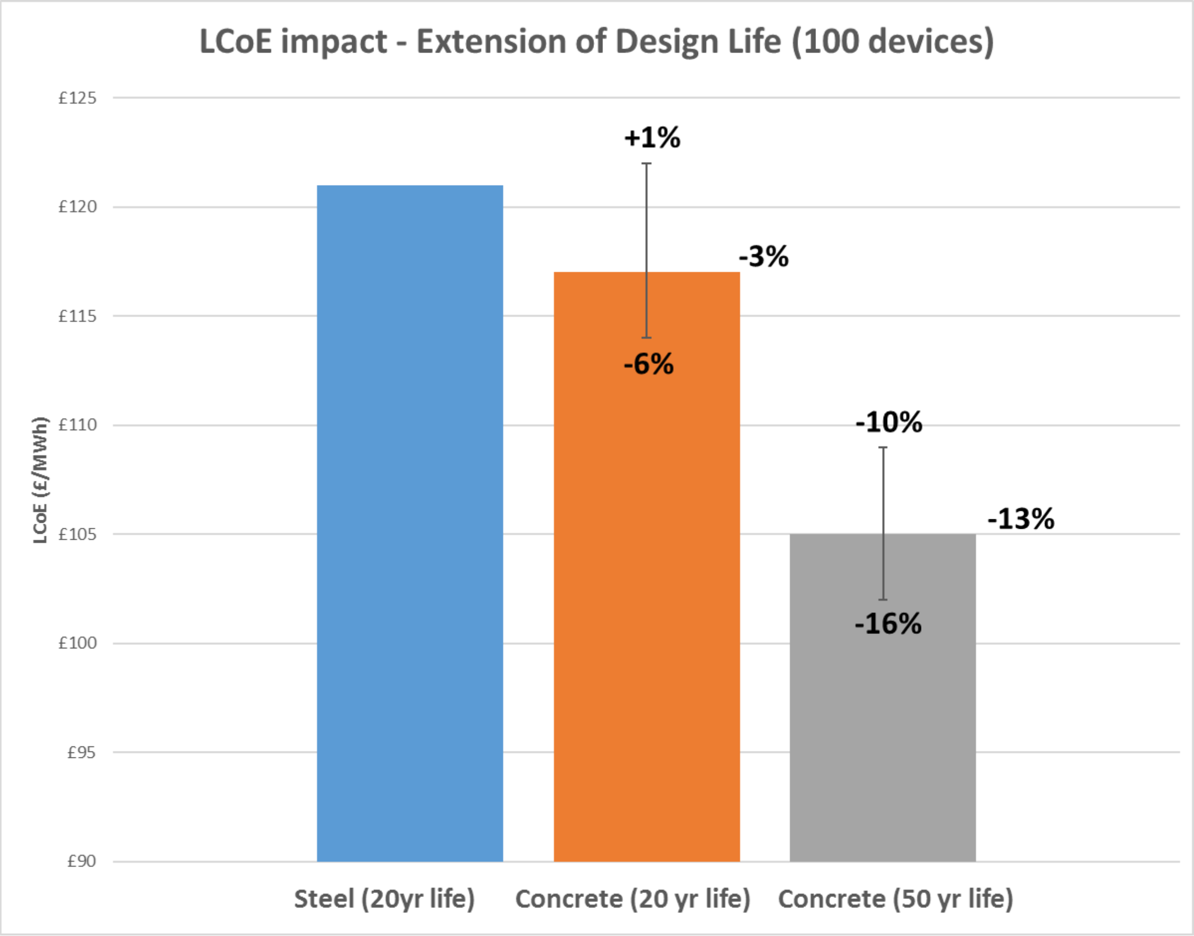


Carnegie wave energy

Stage 1 Conclusions

- Structural design to pre-FEED level
- Demonstrated opportunity for cost reduction

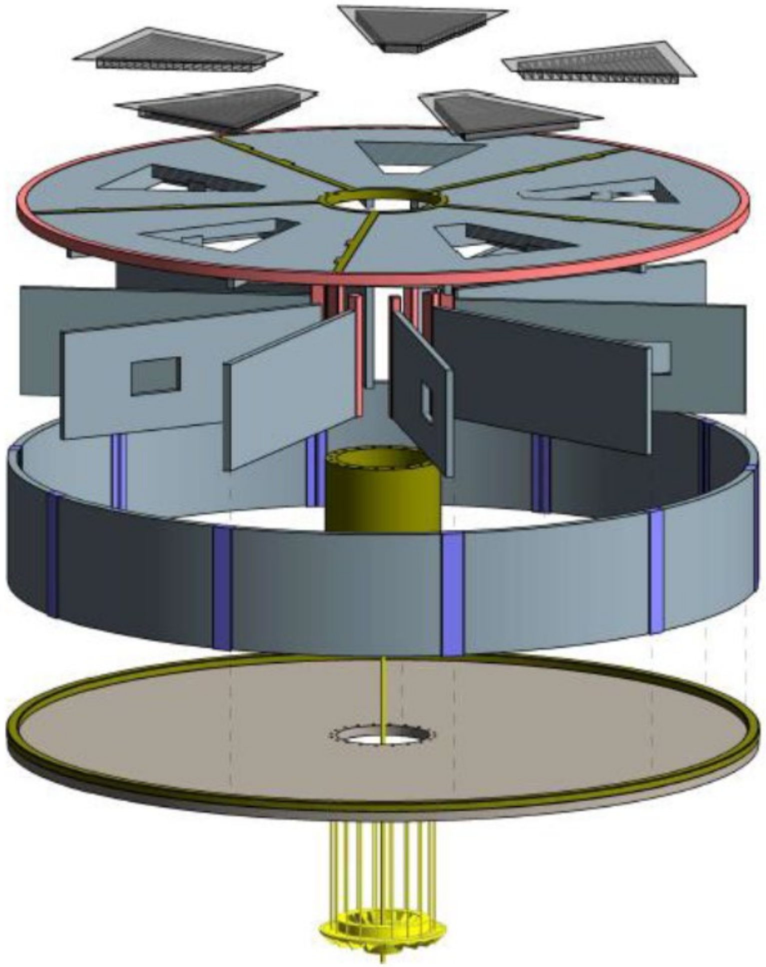




Stage 2 Aims

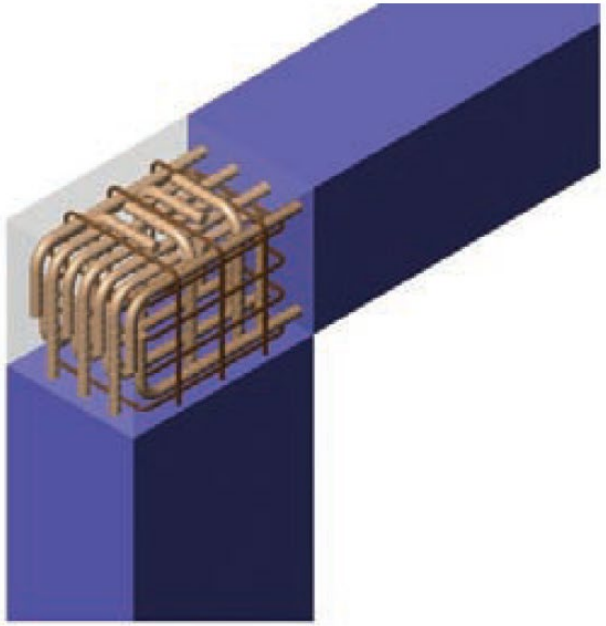
Justify that concrete is a **feasible, cost effective** material with a **focus on high risk structural details**:

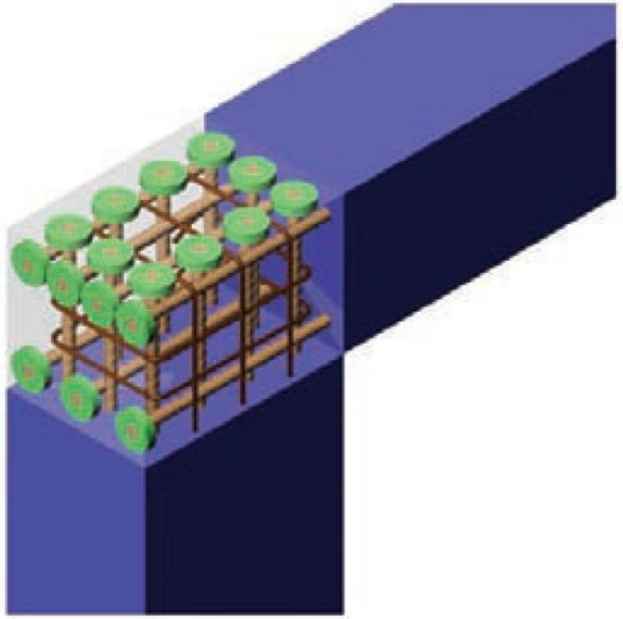
- Precast connections
- Point loading, e.g. tether connections

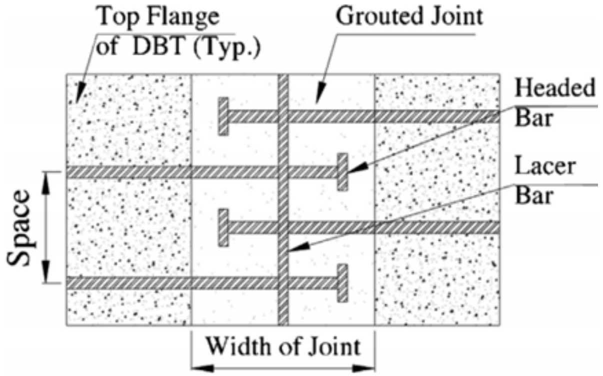


Stage 2 Innovation

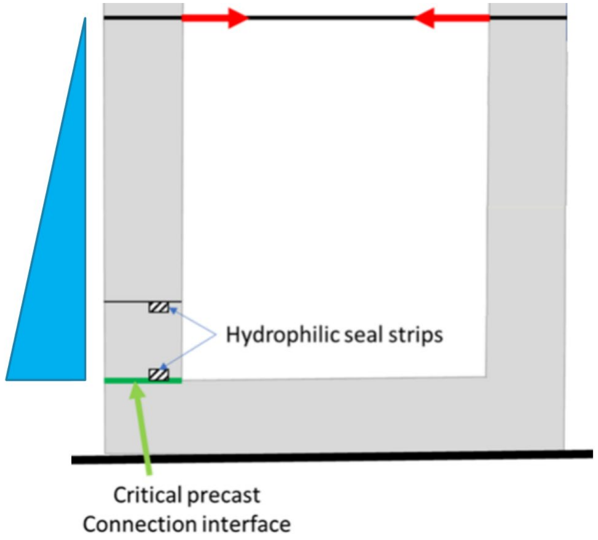
Interleaved T-headed bar precast connection

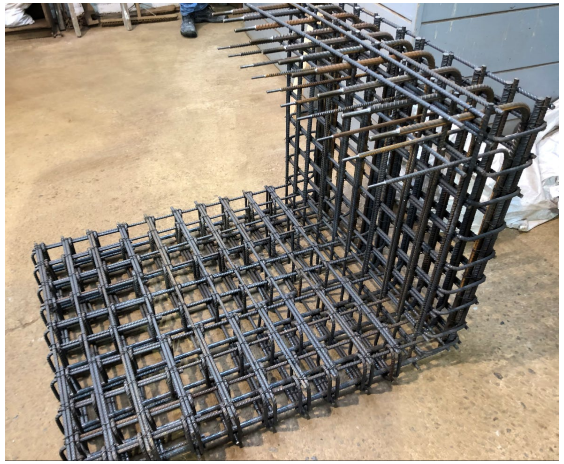


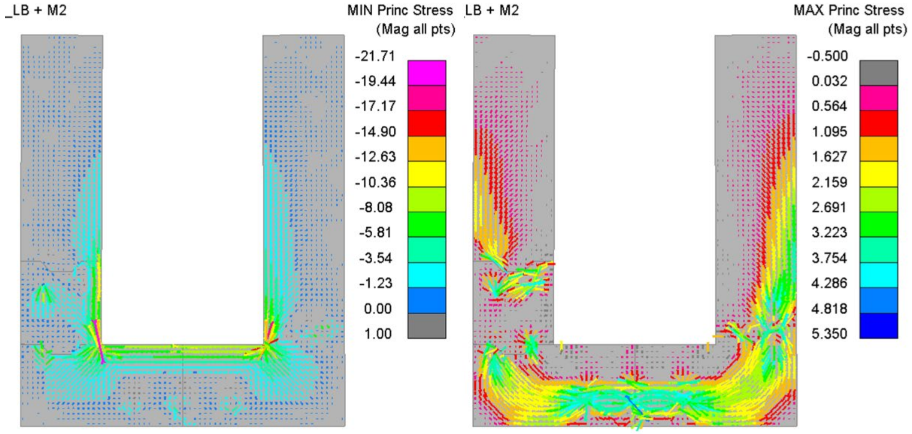




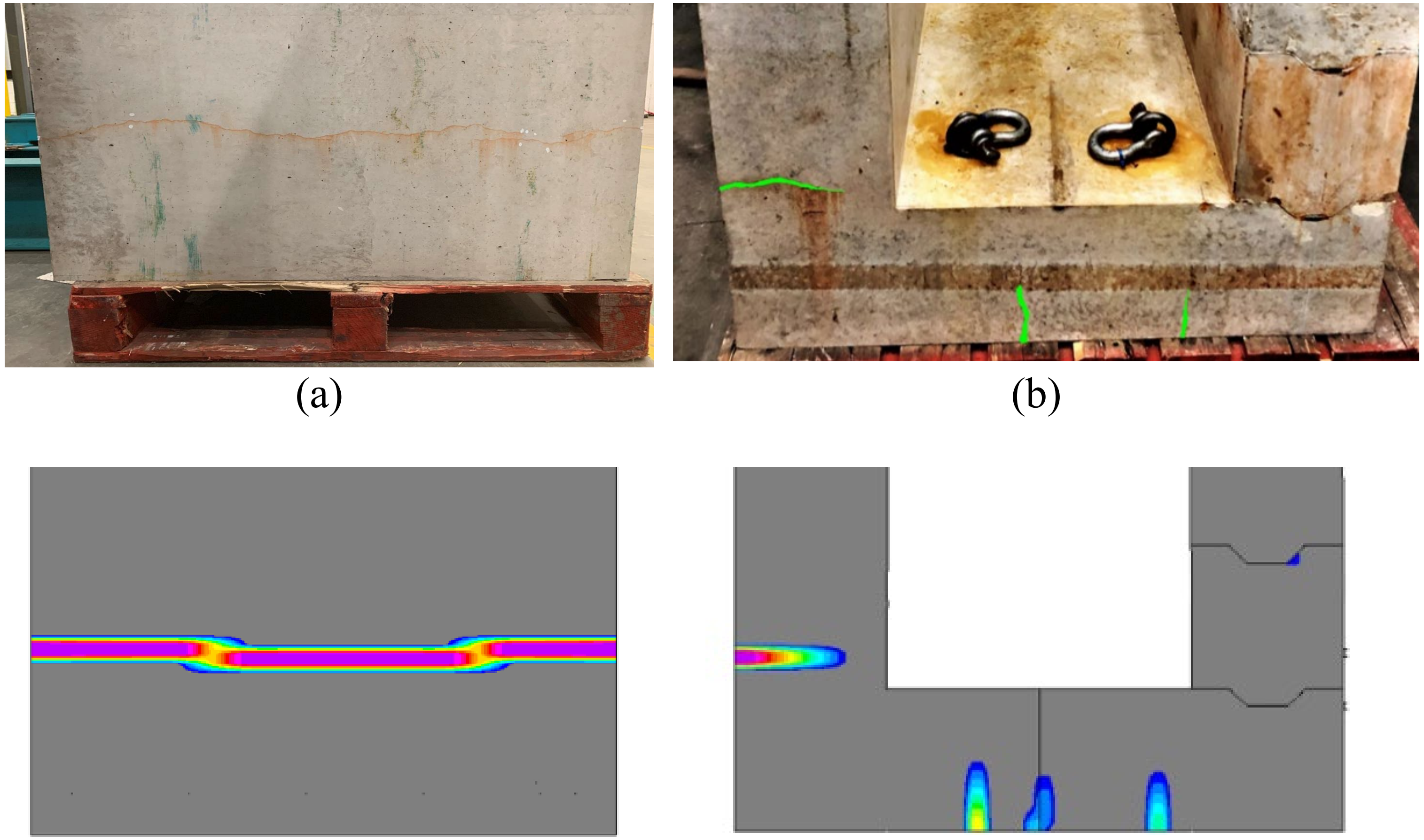
Risk Reduction Testing





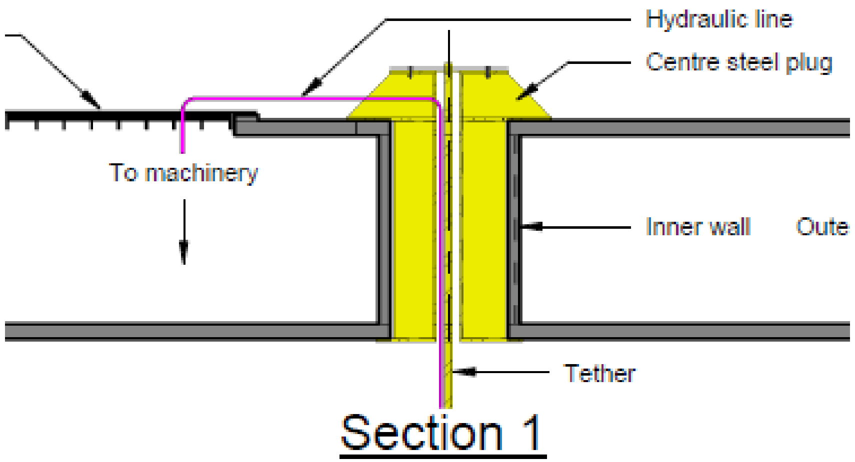


Risk Reduction Testing

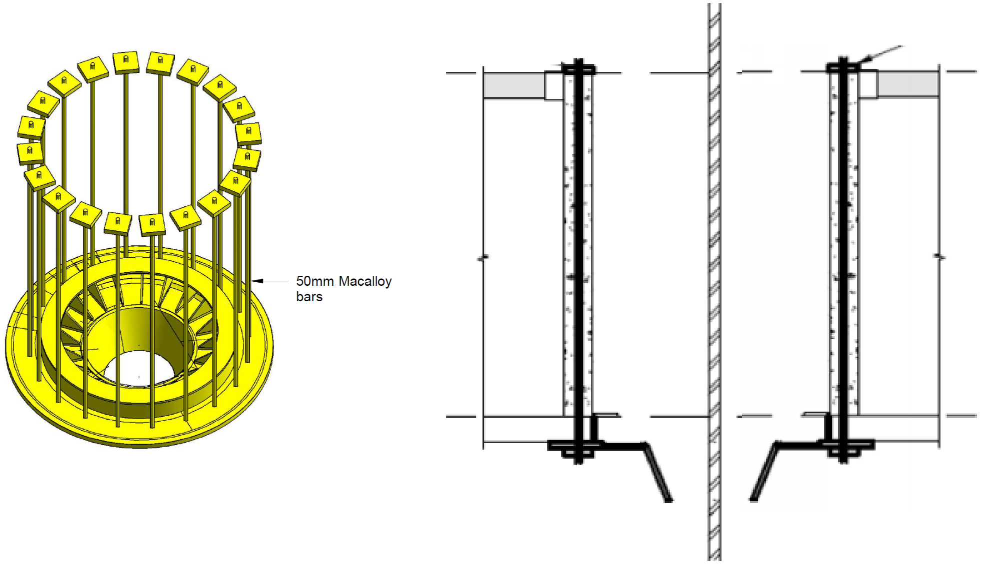


Central Connection Design

Stage 1

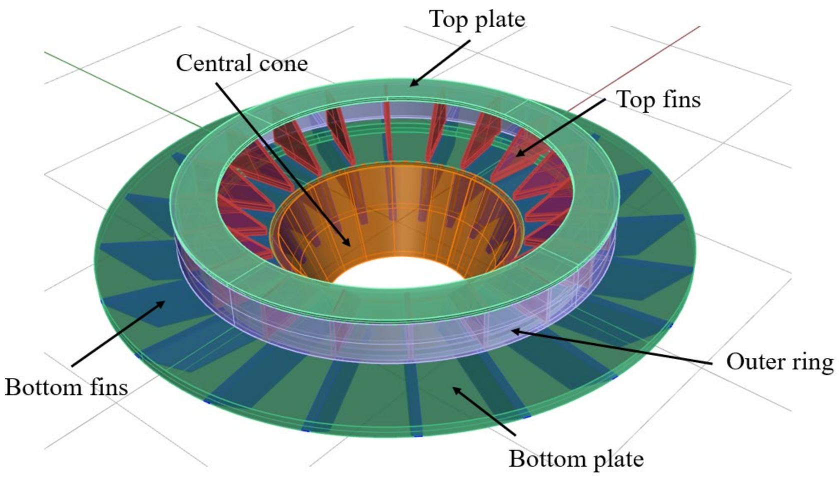


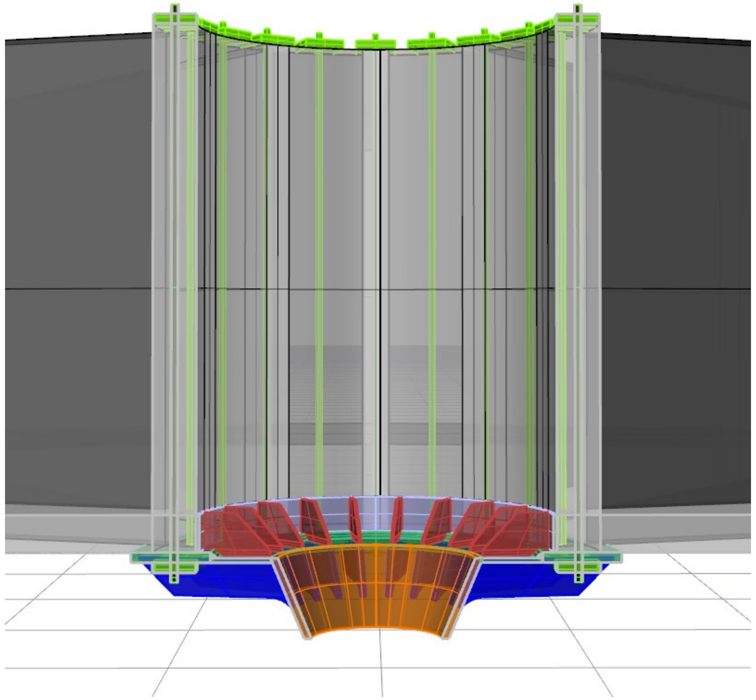
Stage 2

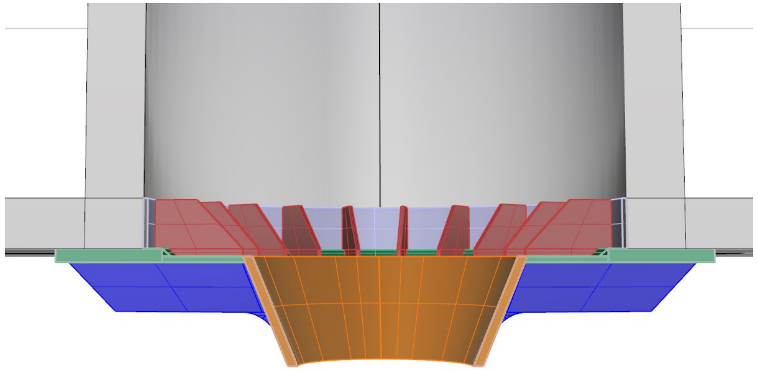


Central Connection Design

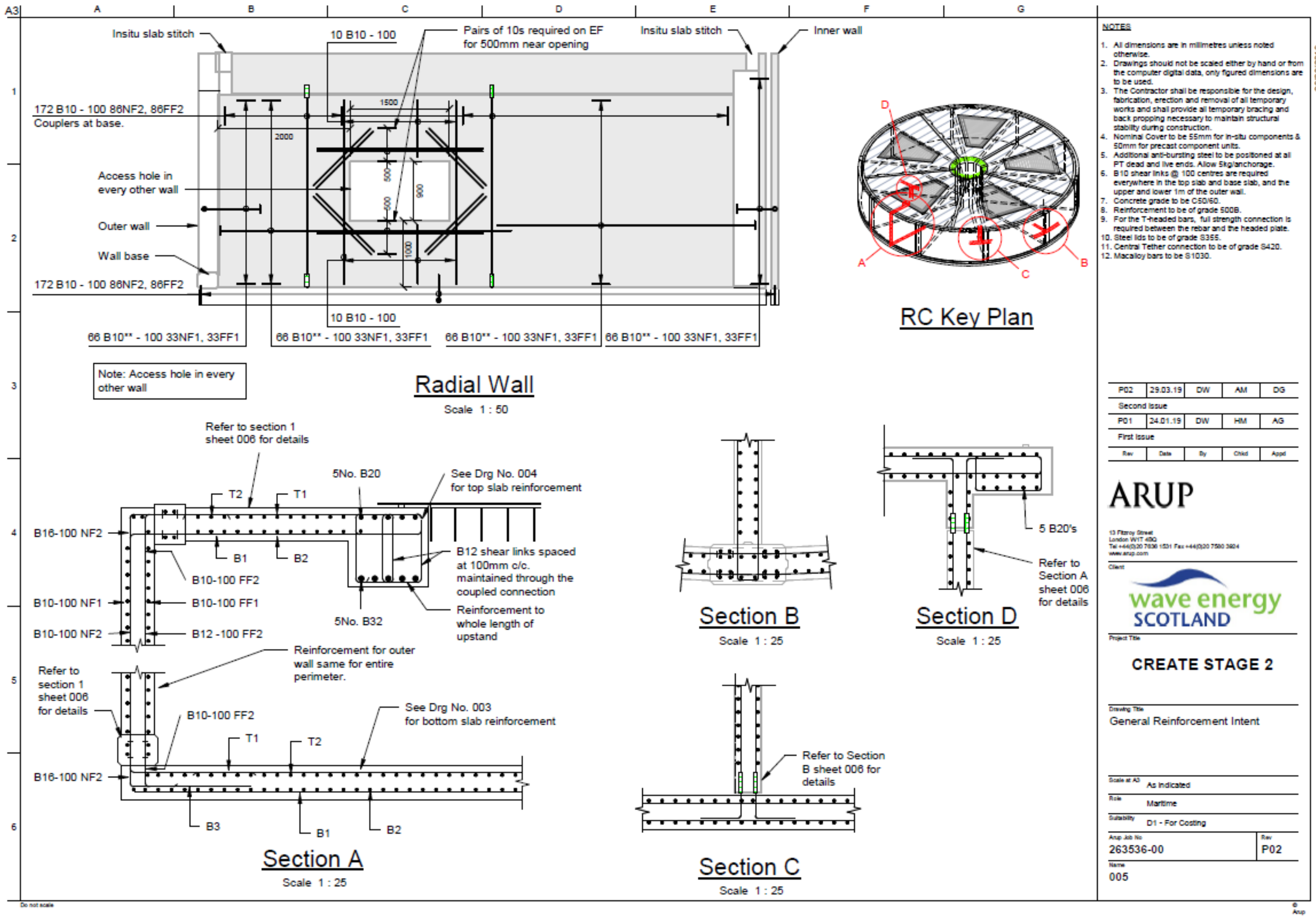
Component	Thickness
Base Plate	70mm / 30mm
Top fins	20mm
Top ring	50mm
Bottom fins	40mm
Central cone	50mm

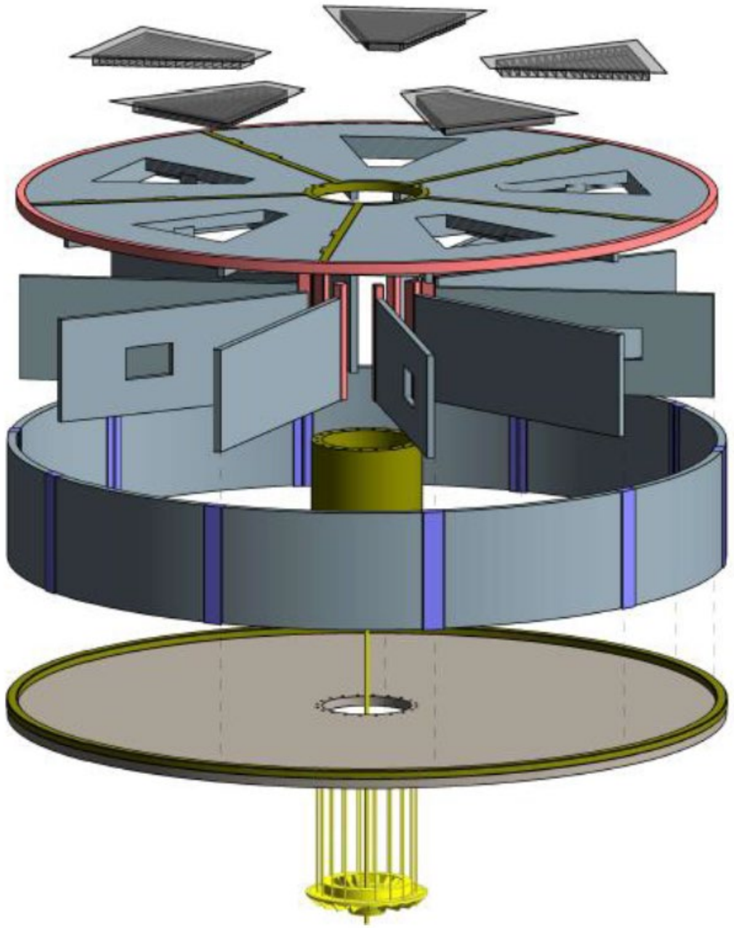




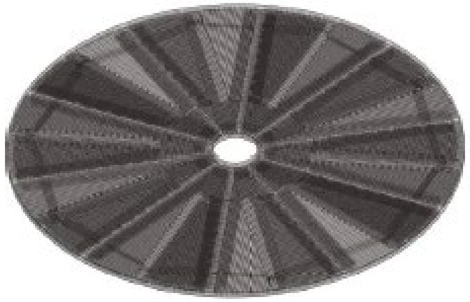


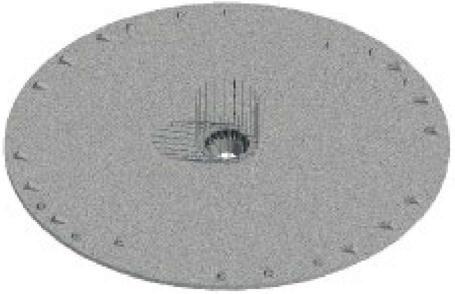
FEED Design Drawings

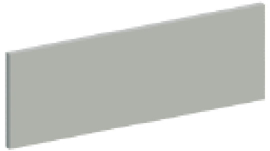




Fabrication Methodology

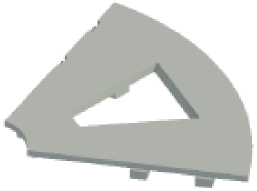




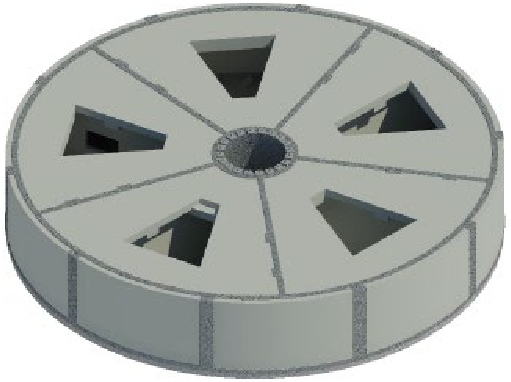


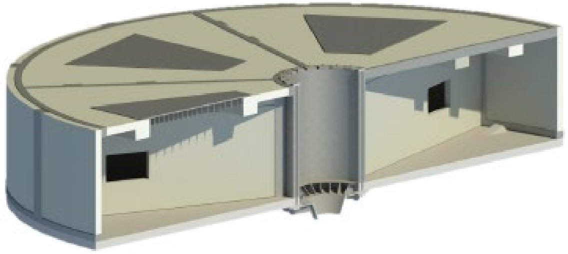
10 no. flat panel

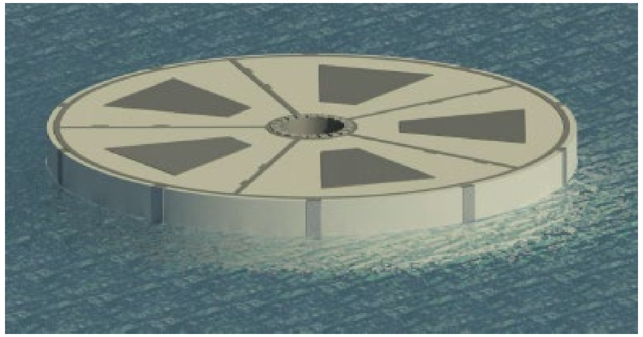
10 no. curved panel



5 no. roof panel





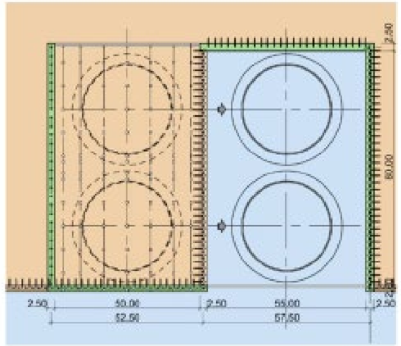


bam Infrastructure Advisory

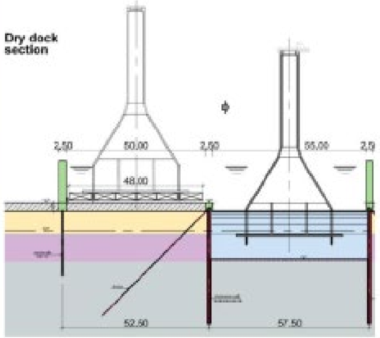
mpa The Concrete Centre

Launch Methodology and Possible Construction Sites

Site	Dry dock	Heavy lift crane	Ship lift
Rosyth Dockyard	✓	✓	~
Port of Rosyth		✓	
Port of Leith	✓	~	
Fife Energy Park		✓	
Nigg Energy Park	✓	✓	
Kishorn Port	✓	✓	
Inchgreen, Glasgow	✓		
Hunterston Port	~	✓	

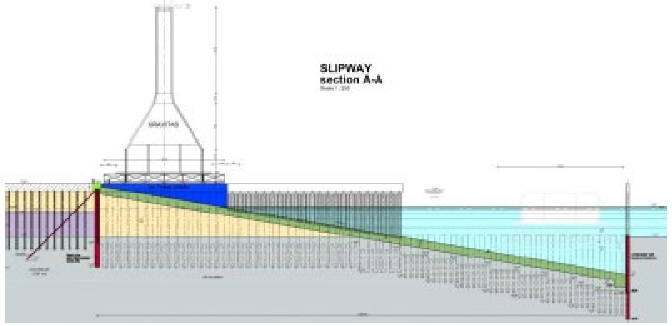


Top view of dry dock



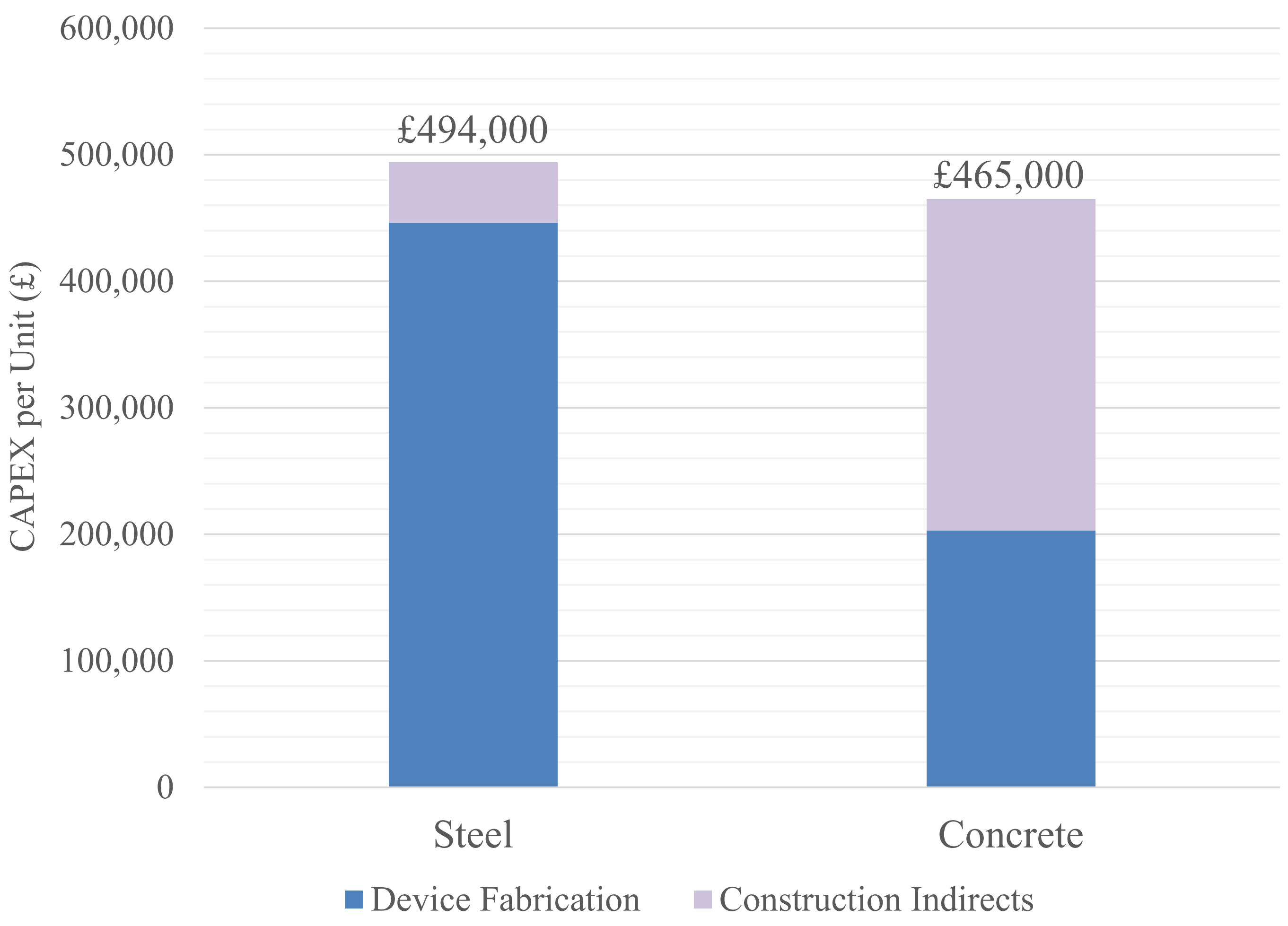
Side view of dry dock

Dry dock construction and launch was identified as the most suitable method for low volume construction at demonstrator scale.



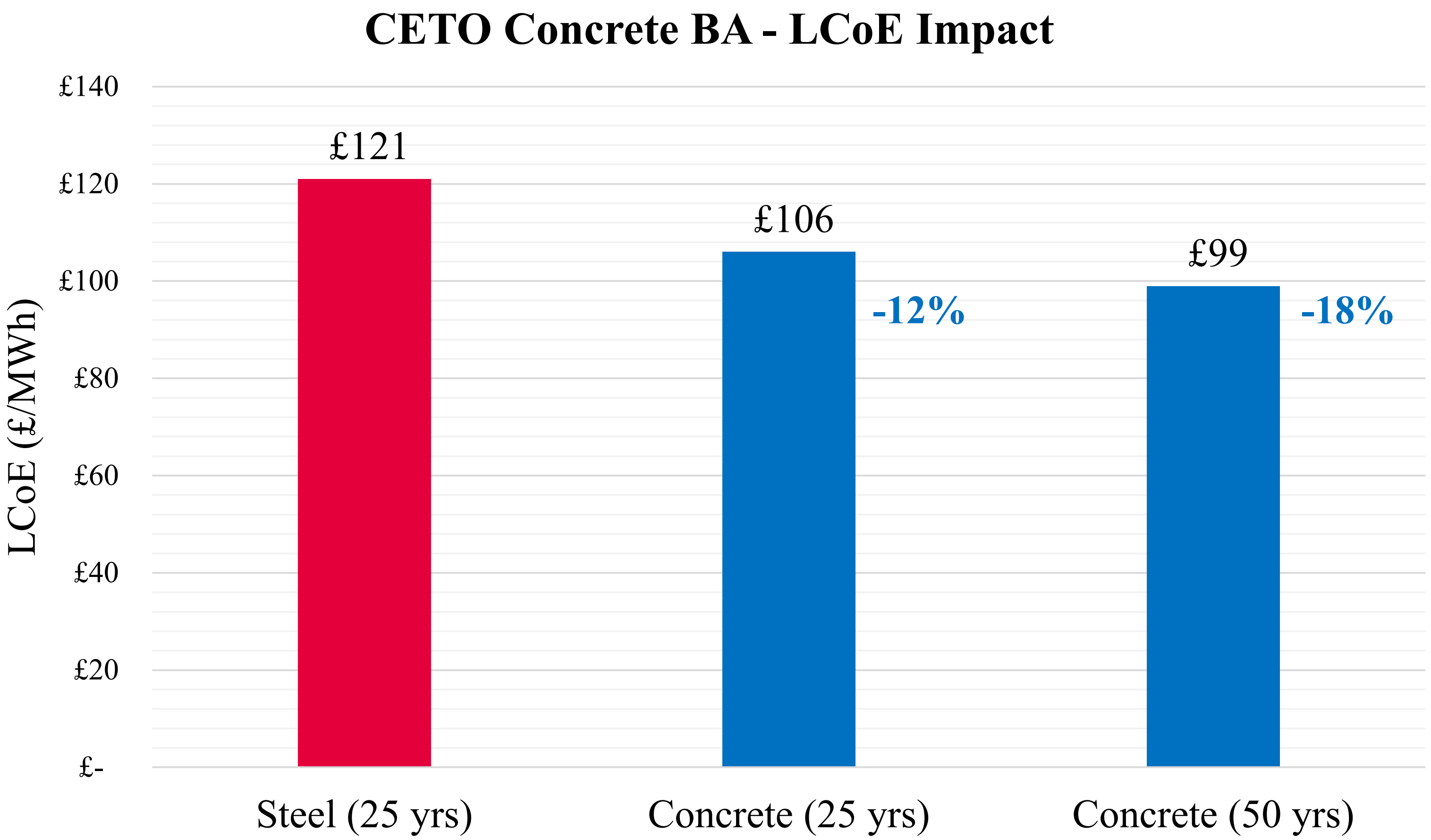
For larger production volumes, limited dry dock space would inhibit production rates. Therefore quayside construction and launch using a heavy lift crane, slipway or skidding onto a submersible barge represent more effective options for serial production.

LCoE Inputs



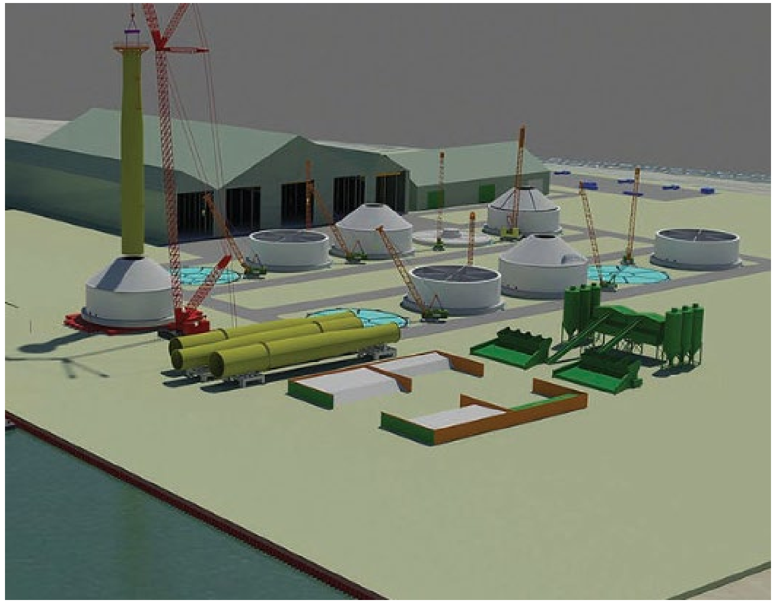
	Availability	OPEX /WEC/yr
Steel BA	89.6%	90,300
Concrete BA	95.8%	72,700

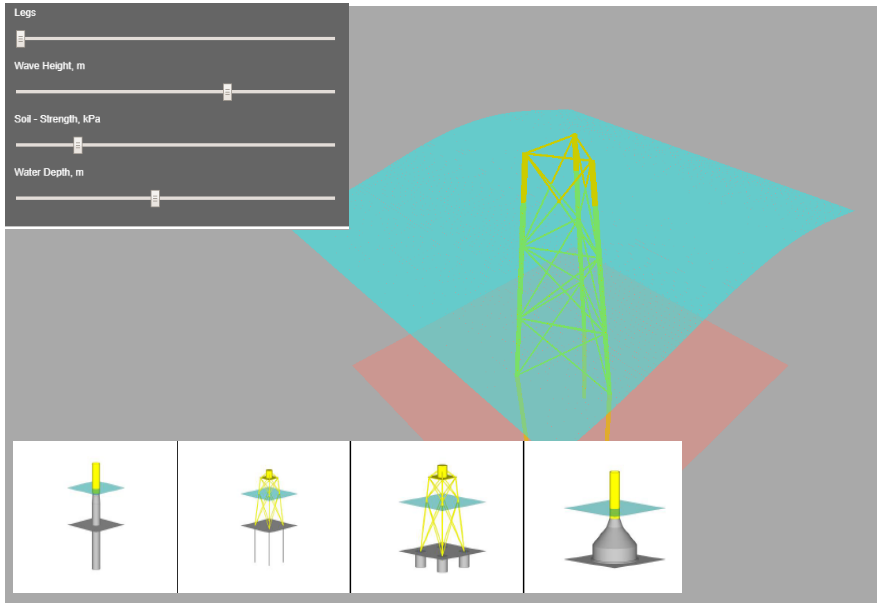
LCoE Results

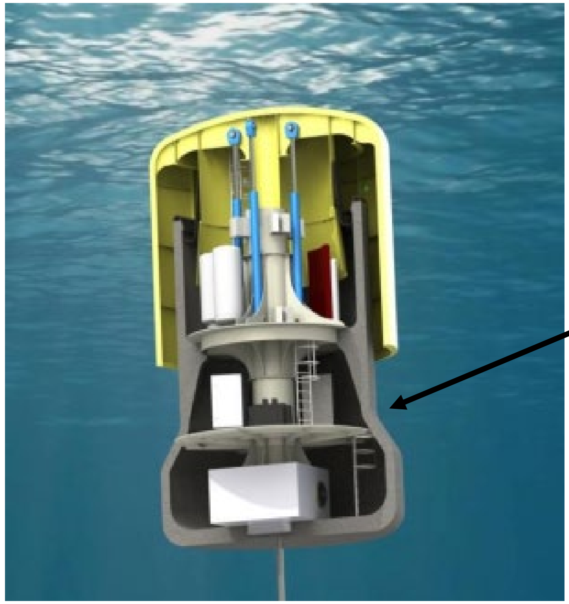


CREATE Project Further Work

- The CREATE project has demonstrated a high TRL for concrete in a WEC context.
- Recommended further work includes **priming the supply chain for serial production** of floating concrete WEC structures, and **equipping developers with design tools to exploit it.**







Concrete silo component

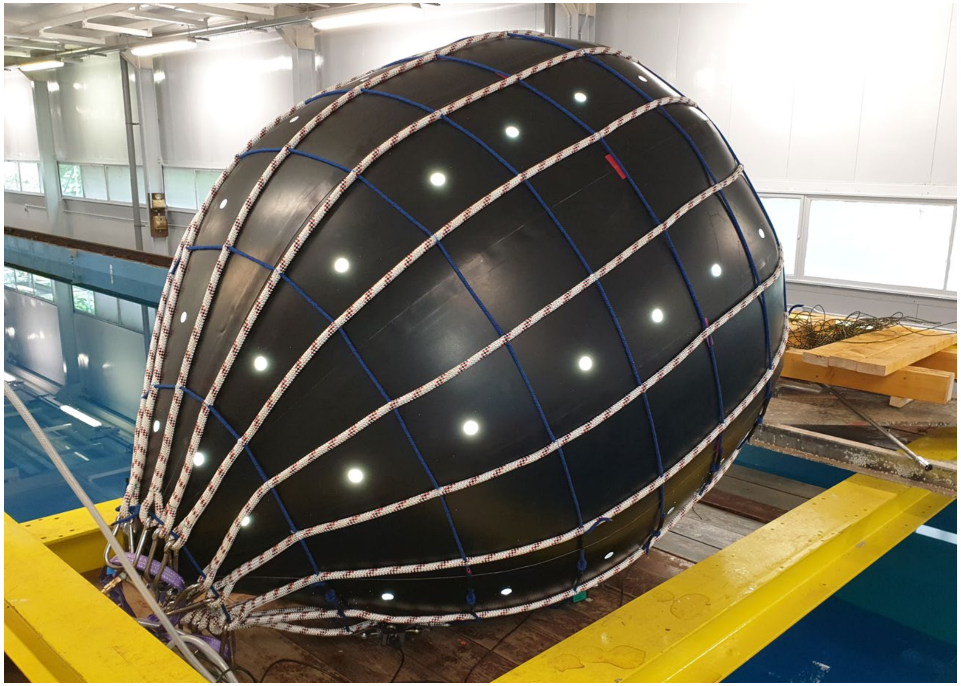
mpa The Concrete Centre British Precast
bam Infrastructure Advisory
cruz atcheson CONSULTING ENGINEERS
ARUP
Carnegie wave energy
mocean energy
AWS

WES Annual Conference 2019

Questions?

TTI NETBUOY STAGE 2 PROJECT

Lead Contractor: Tension Technology International Ltd, Inverness, www.tensiontech.com

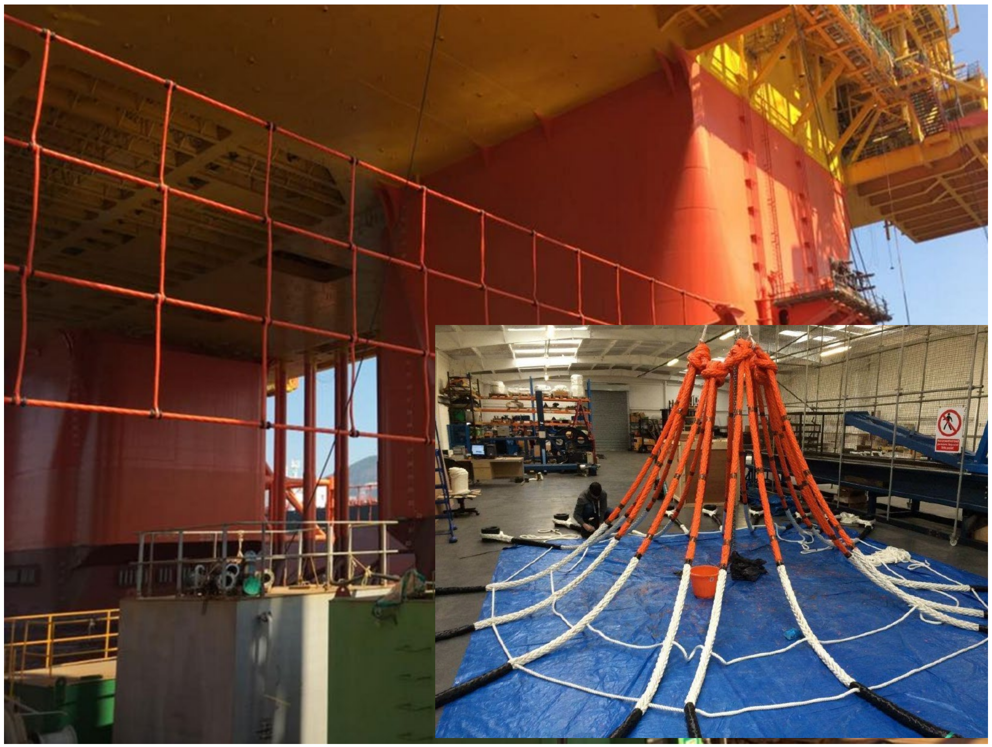


GRIFFON HOVERWORK · TUN ABDUL RAZAK RESEARCH CENTRE MALAYSIAN RUBBER BOARD · University of Strathclyde · Quoceant Innovation Offshore · Optimus Engineering with Character

Structural Materials & Manufacturing Processes

wave energy SCOTLAND

NETS & BUOYS

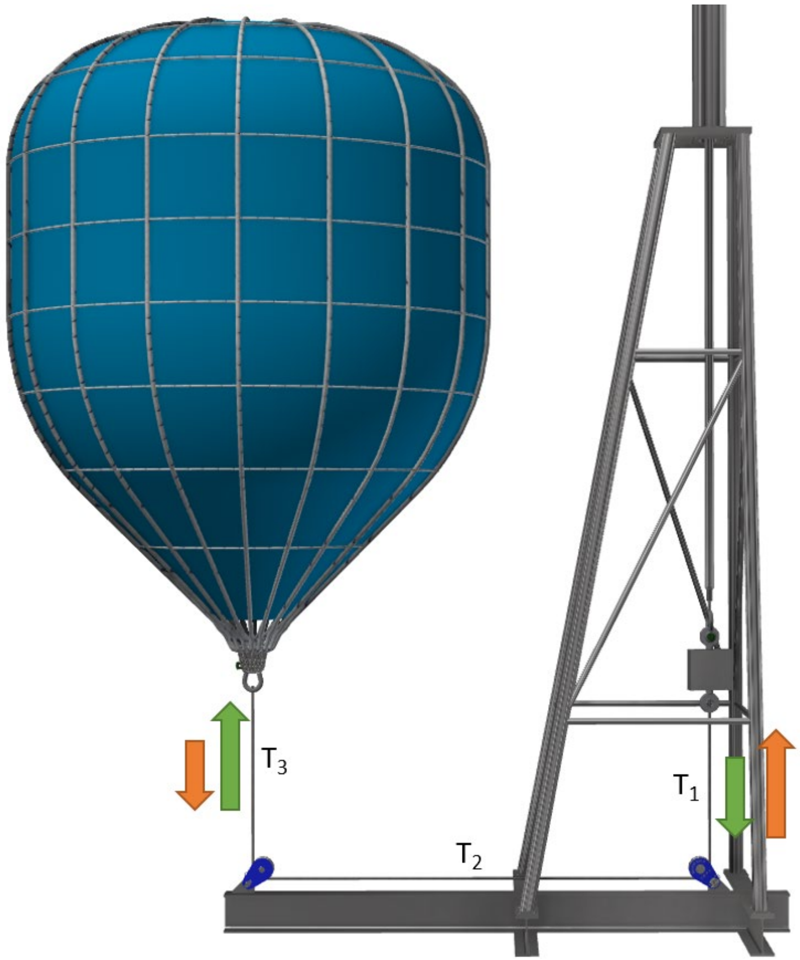


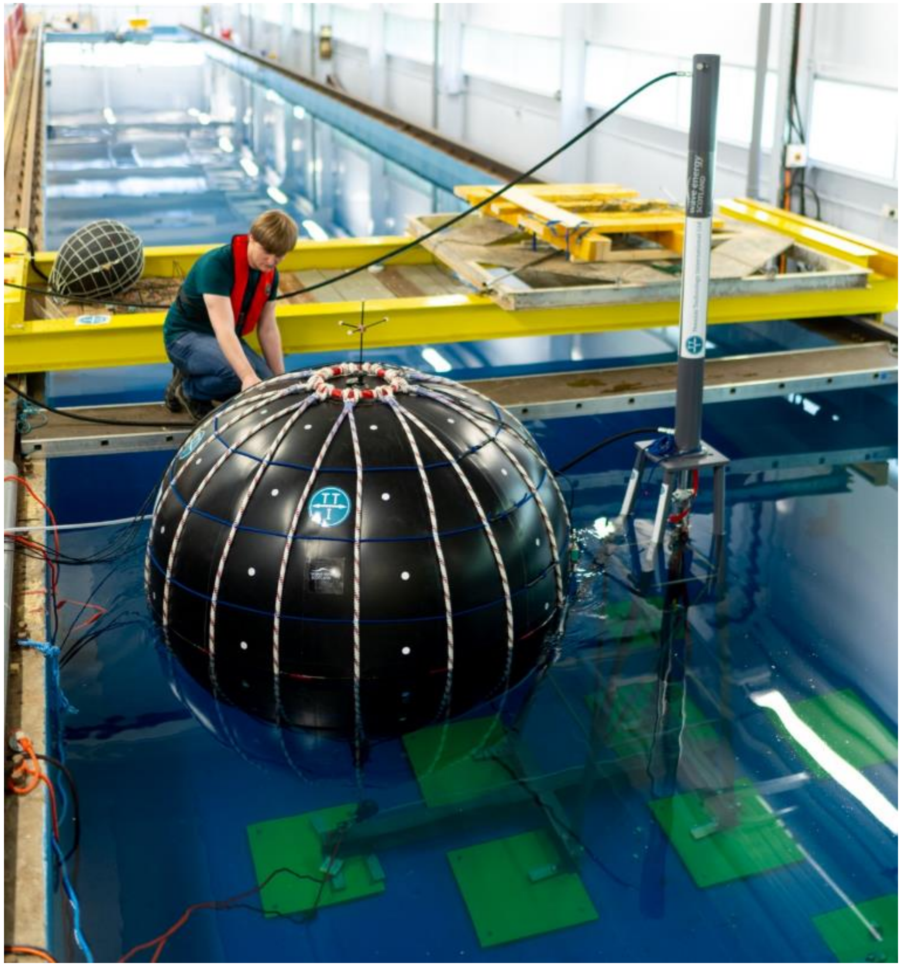
Combining TTI Net Technology with Buoy Technology

STAGE 2 – ¼ Scale Test

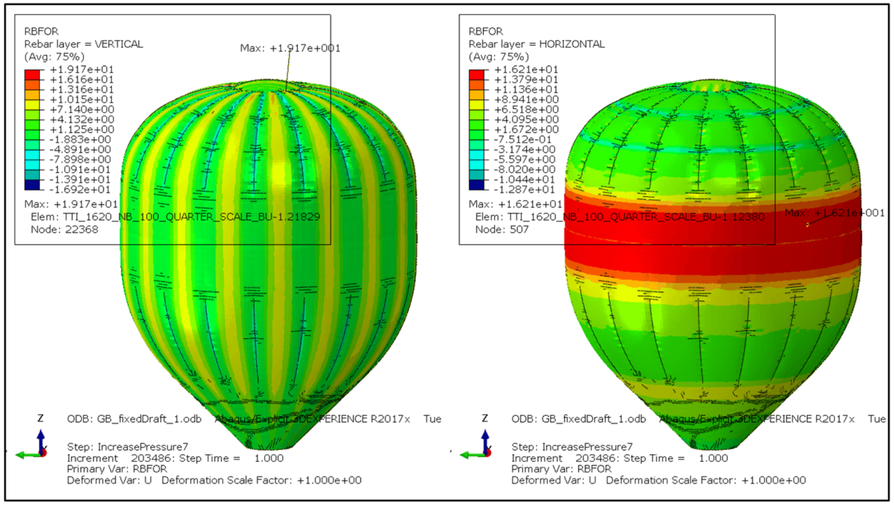
FULL SYSTEM MANUFACTURE & AIR -TEST

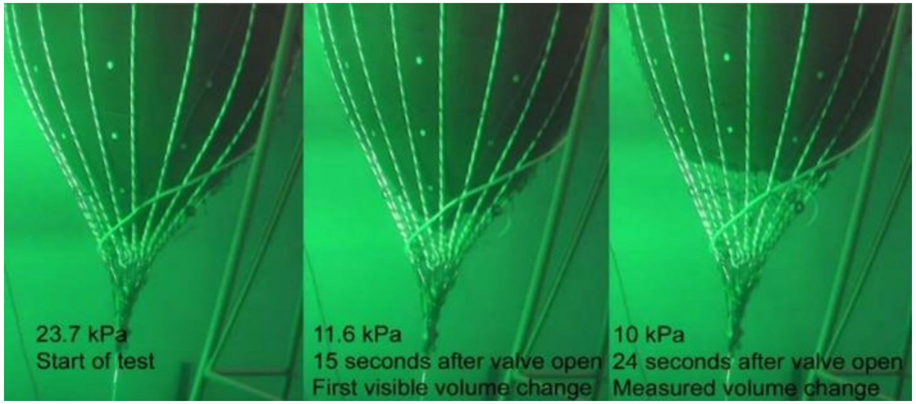
STAGE 2 – ¼ Scale Test

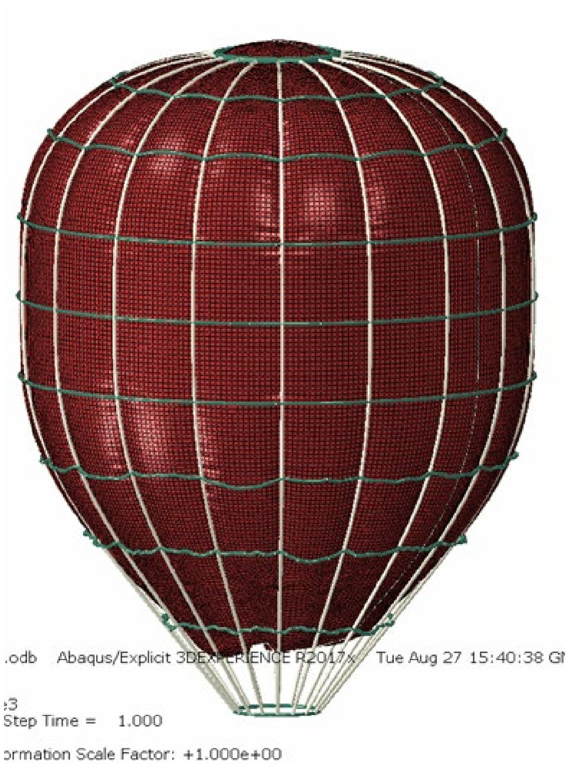




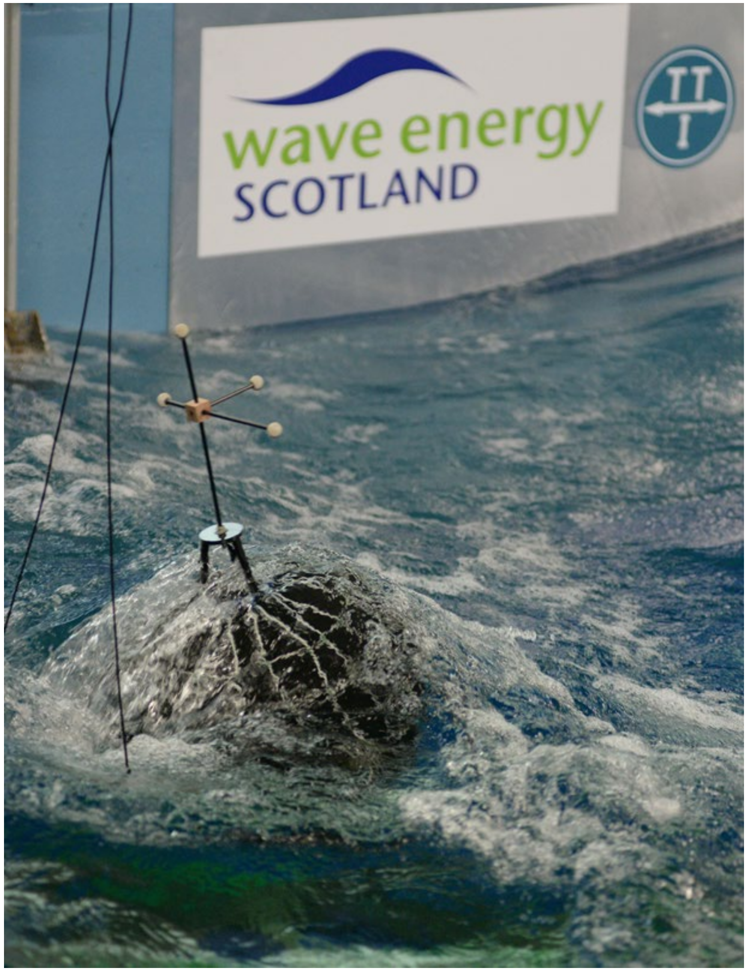
FEA of ¼ scale test

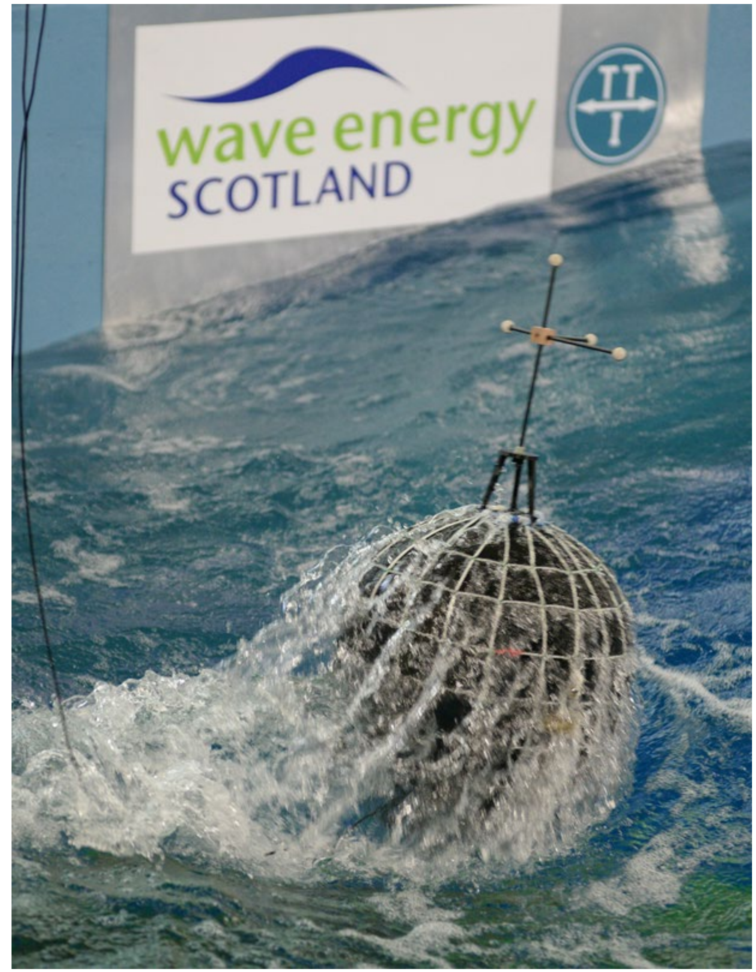




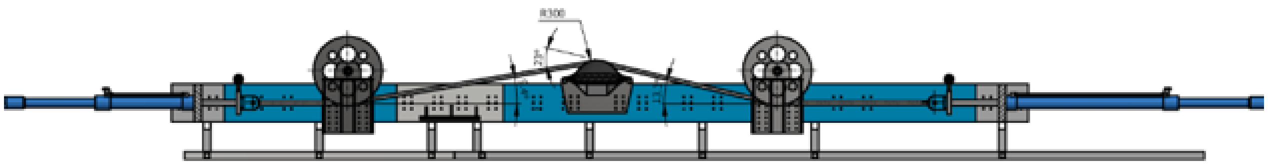


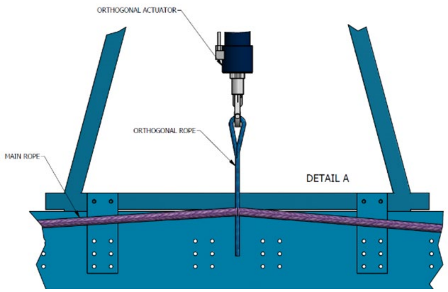
STAGE 2 – 15th Scale Tests

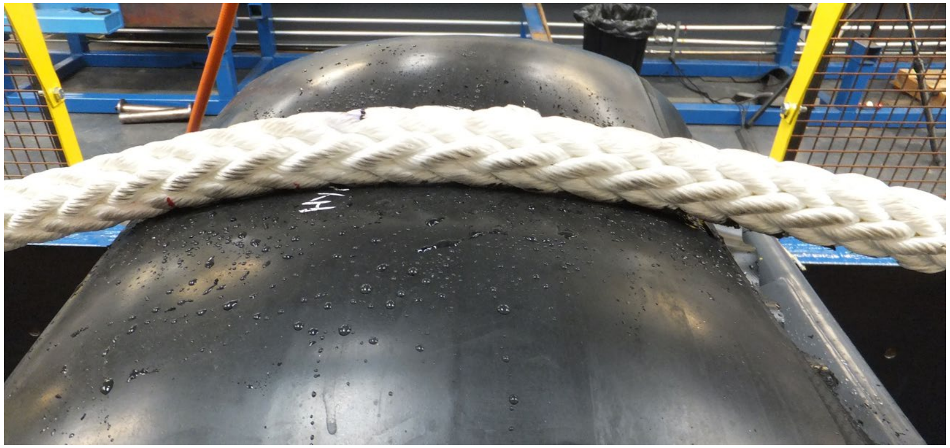




Full-Scale Subsystem Tests







Rope on Pillow Abrasion – 5 Candidate Elastomers

Net Juncture Locking Tests

NETBUOY STAGE 2

FEED

- Informed by qualification tests & FEA
- Informed by Material Selection & Manufacturing studies

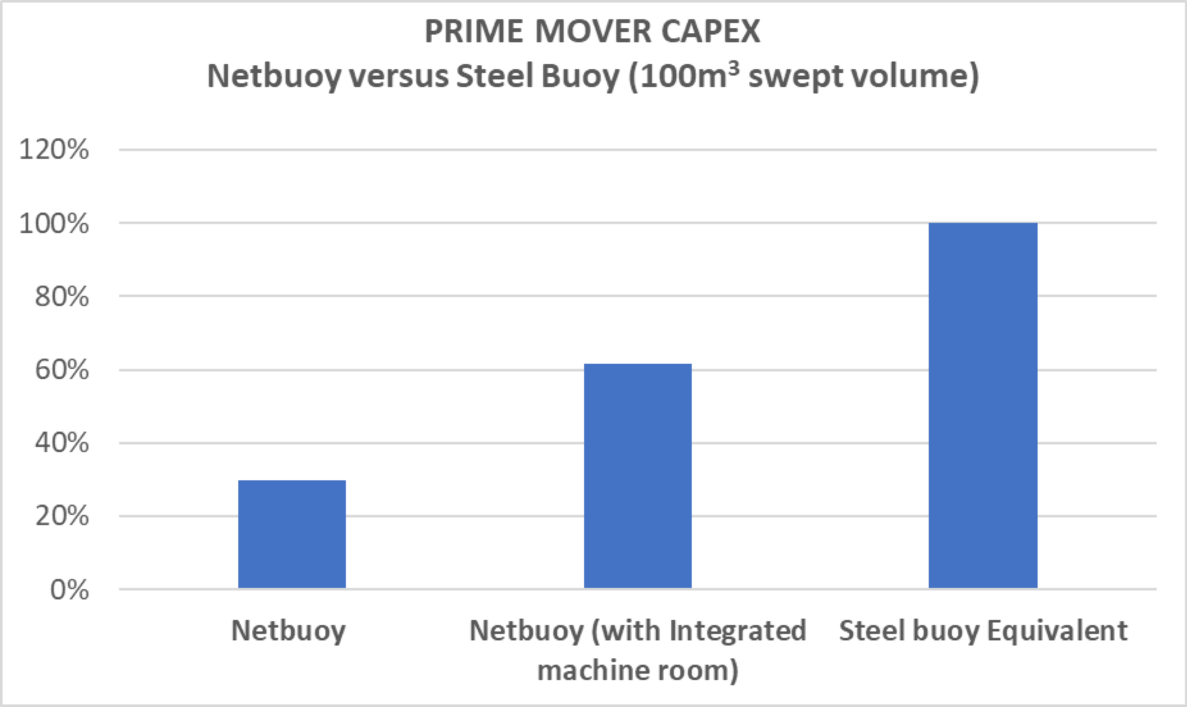
Manufacturing Studies

- **Griffon Hoverworks** conducted manufacturing and costing studies
- 3 manufacturing approaches for FOAK, 10, 100, 1000 Units
- Consideration of scale.
- TTI benchmarked against fender quotations

LCOE

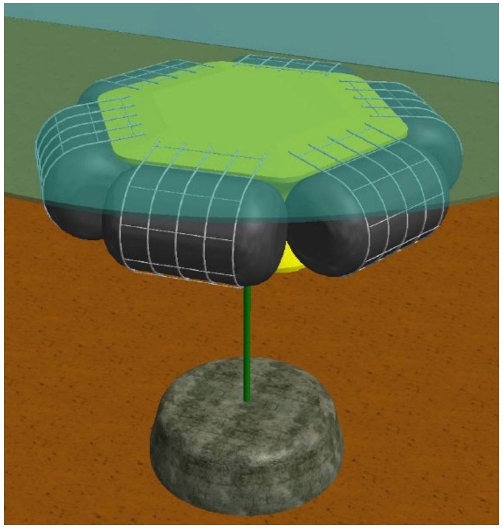
- Based on FEED & Manufacturing studies
- Based on Transportation & Marine Operations study (**Quoceant**)

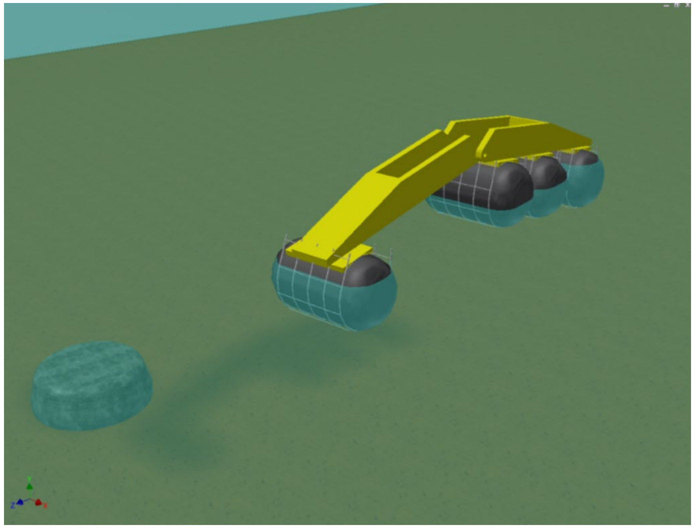
NETBUOY Costs

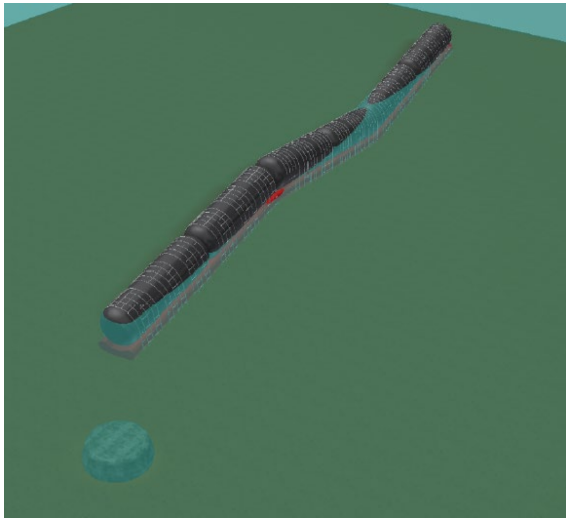


- Road transport of 10 x Netbuoys between 9% & 34% cost of Steel WECs
- Sea transport of 10 x Netbuoys between 19% & 57% of Steel WECs
- Installation cost up to half that of Steel Buoy
- Improved limiting seastates and availability

NETBUOY Applicability

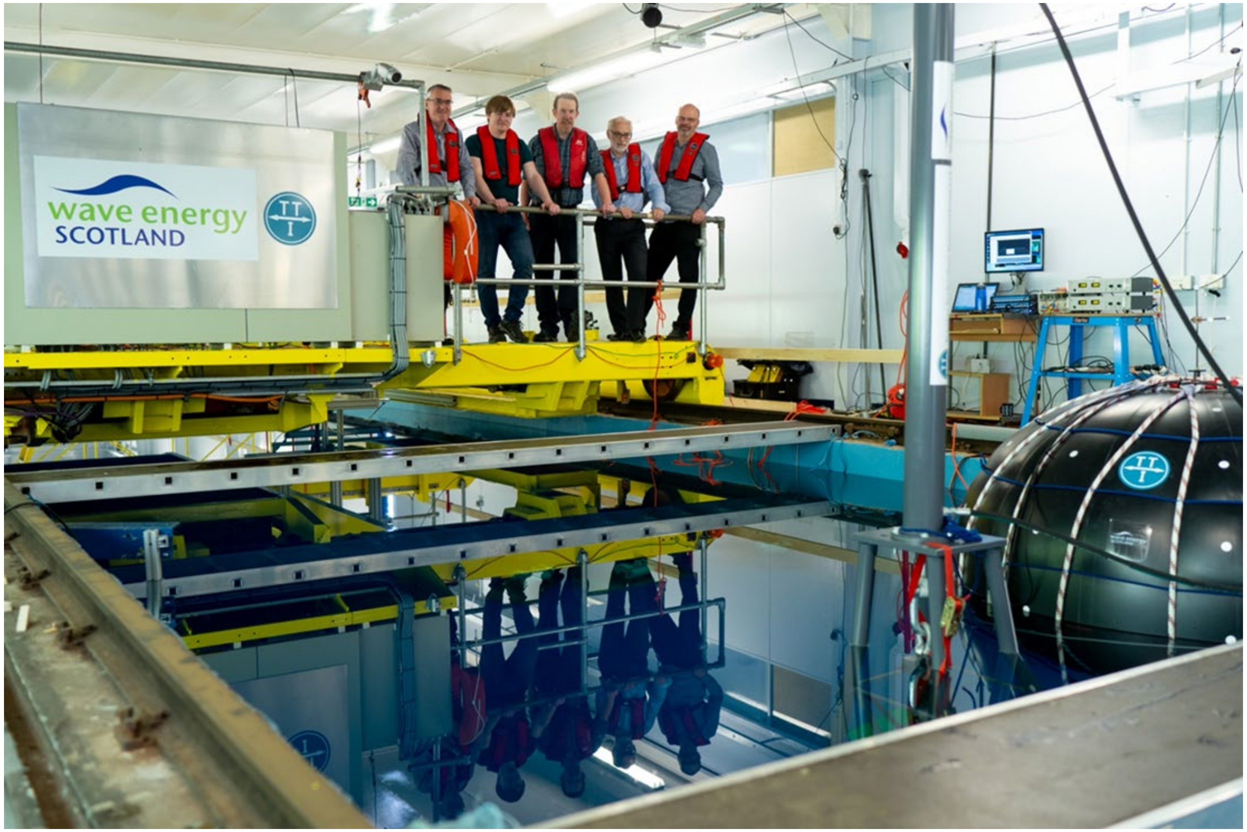






Applicability of Netbuoy technology to other WEC categories

Thank You!



Ben Yeats
yeats@tensiontech.com

Tom Mackay
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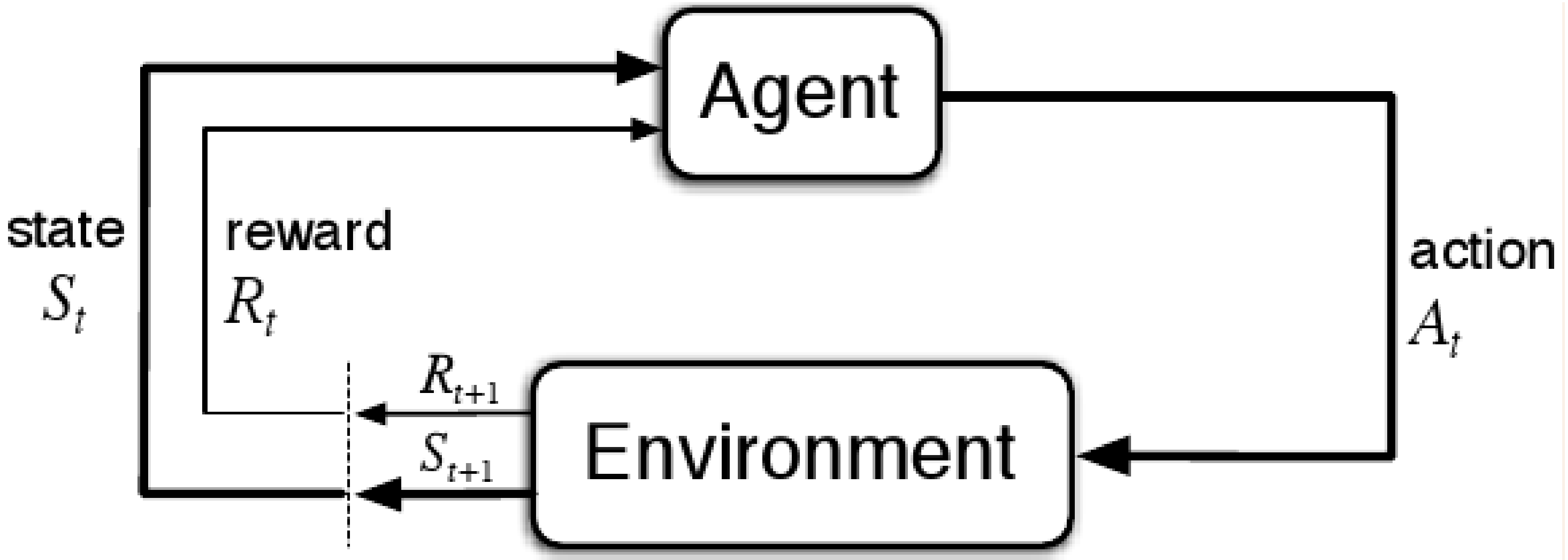
Outline

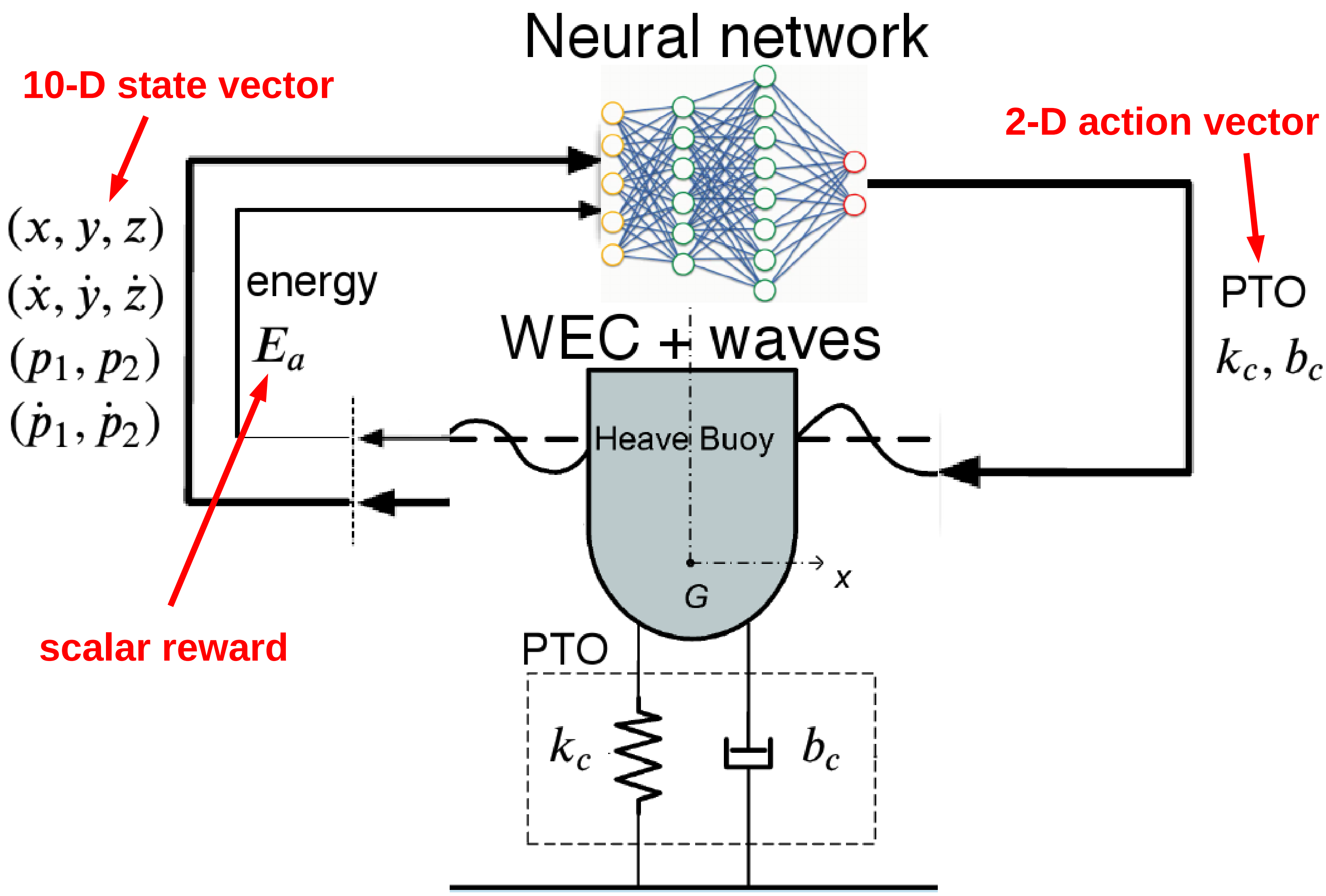
- Explain reinforcement learning (RL) and how it can be applied to WECs.
- Discuss theoretical upper bounds on absorbed power for heaving buoy in regular waves.
- Verify code against theory in regular waves.
- Compare the best constant-control policies with RL-derived policies in irregular waves.

What is Reinforcement Learning?

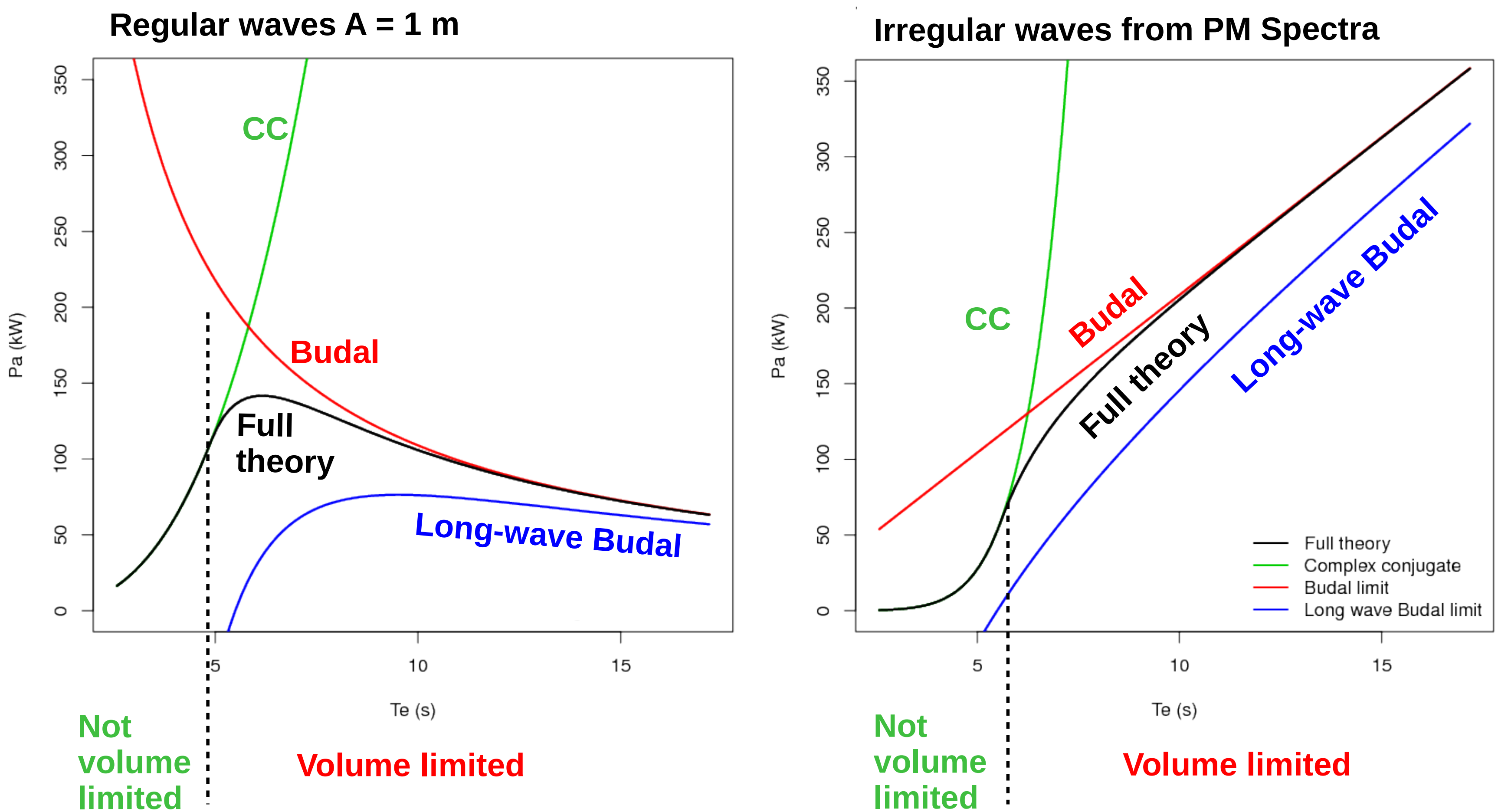


- The agent
- Interacts with its environment
- To **maximise** the **long term** sum of tiny rewards

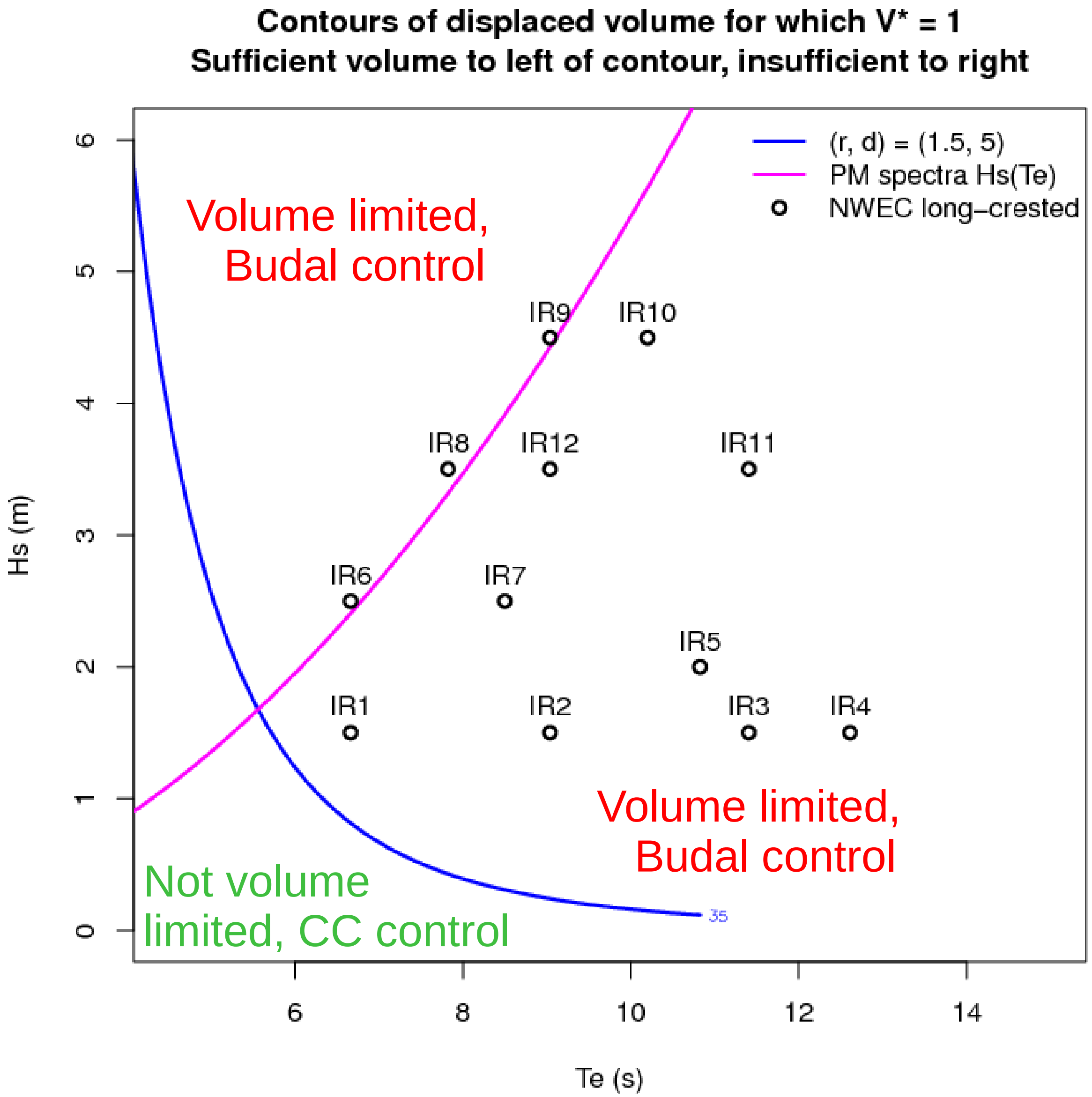
RL Applied to Wave Power



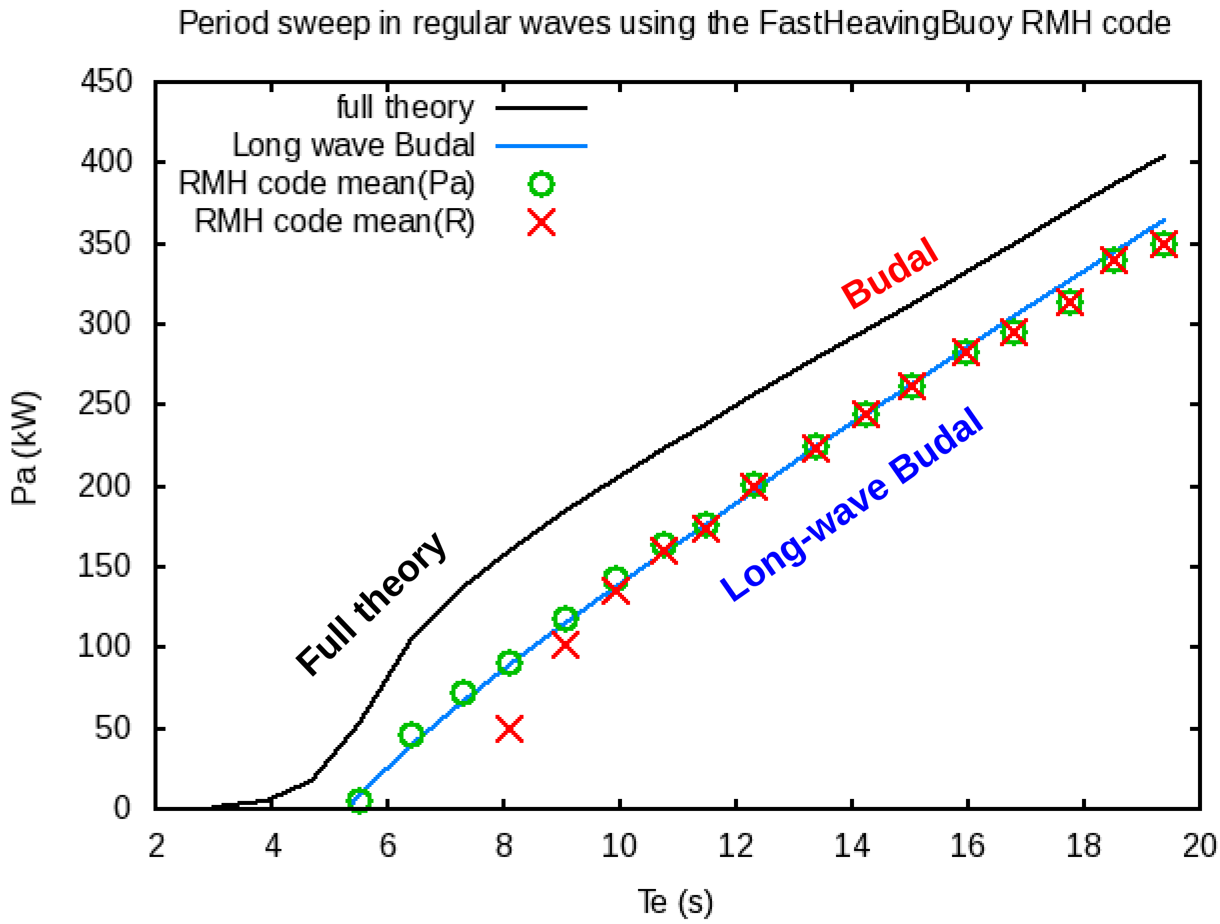
Theoretical Upper Bounds



WES NWEC Sea States

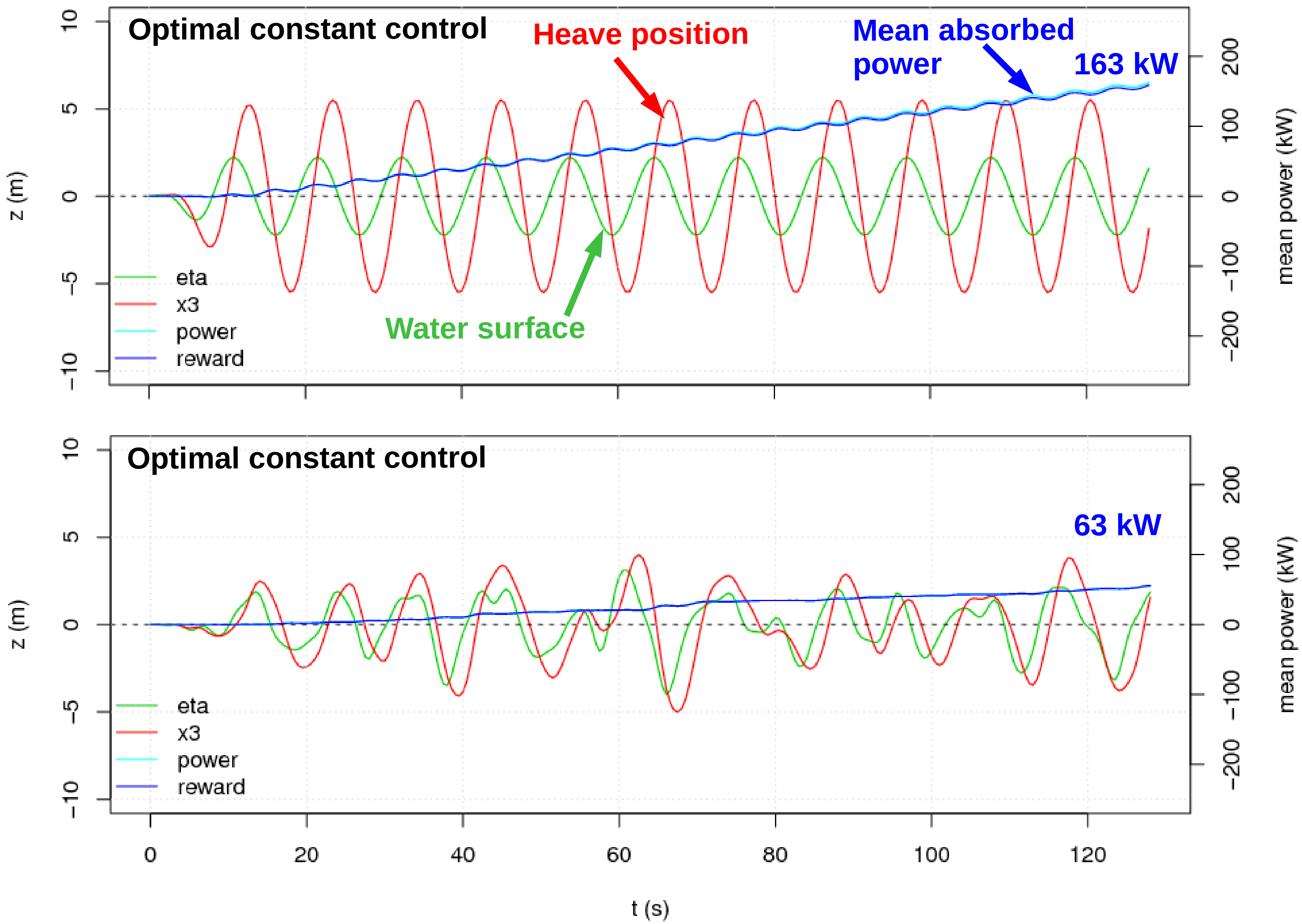


Simulation vs Theoretical Bounds

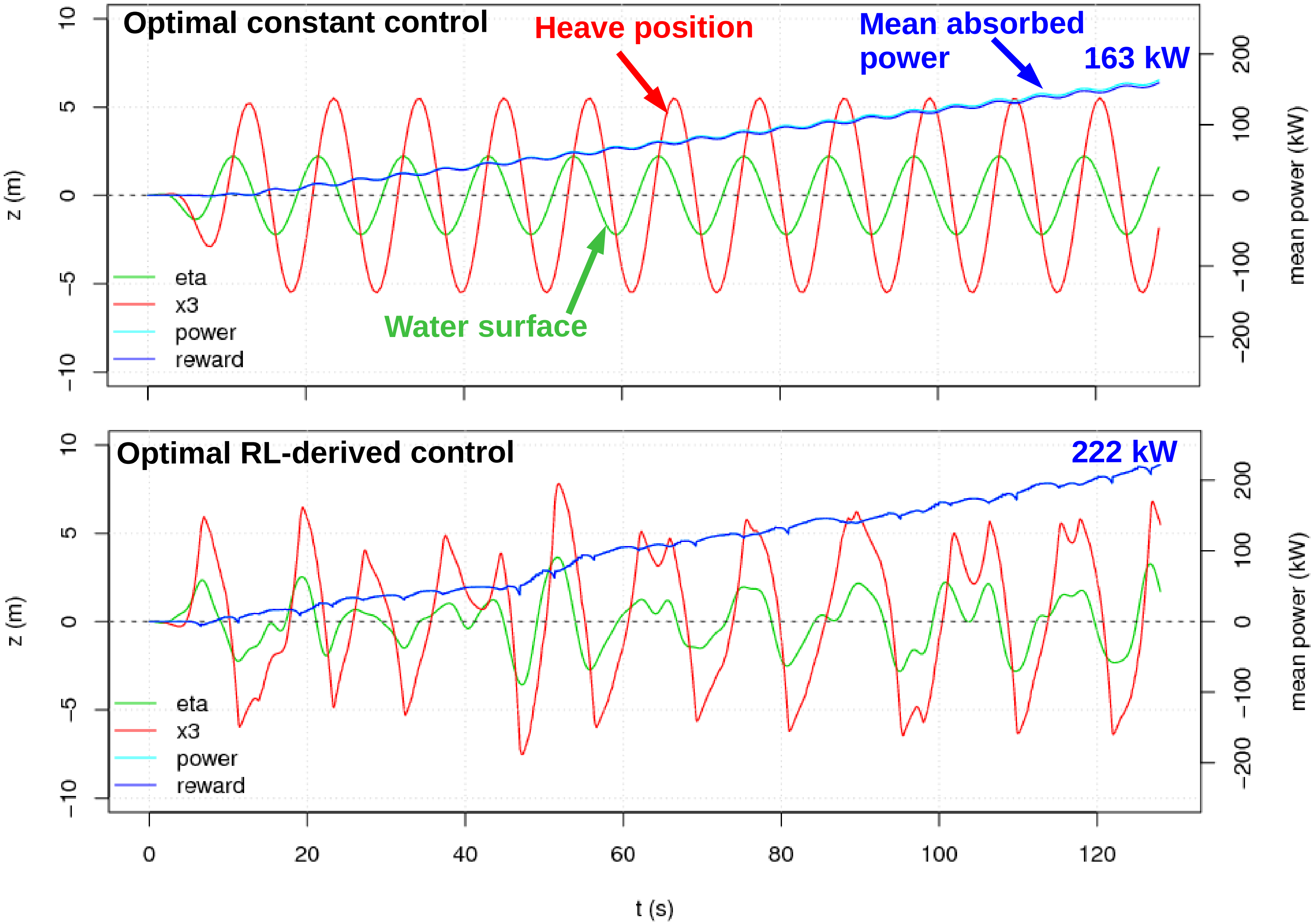


- Code uses relative motion hypothesis (fast code)
- Regular waves (all wave power at single frequency)
- Analytical solution for best controls

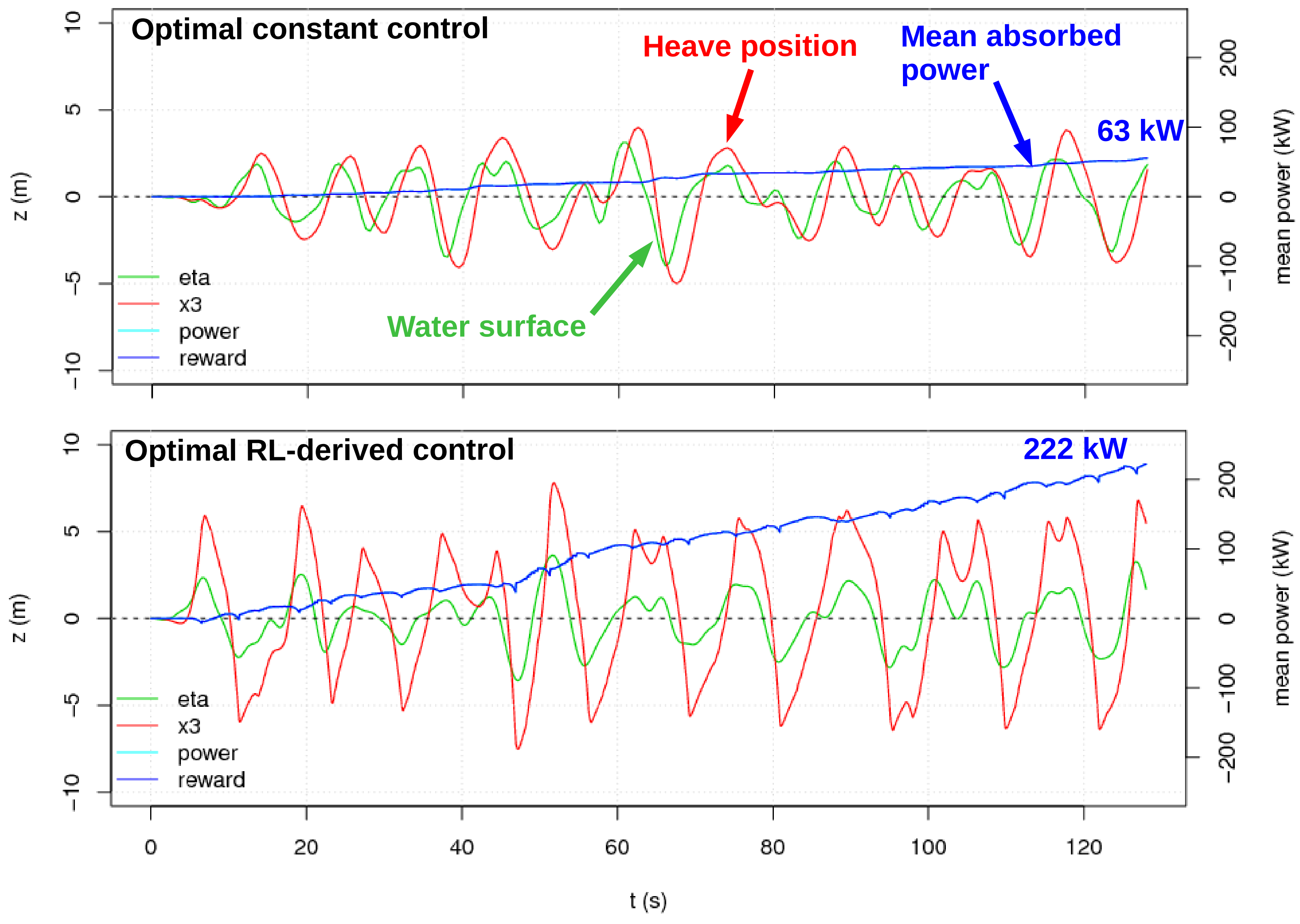
Simulation Time Series 1



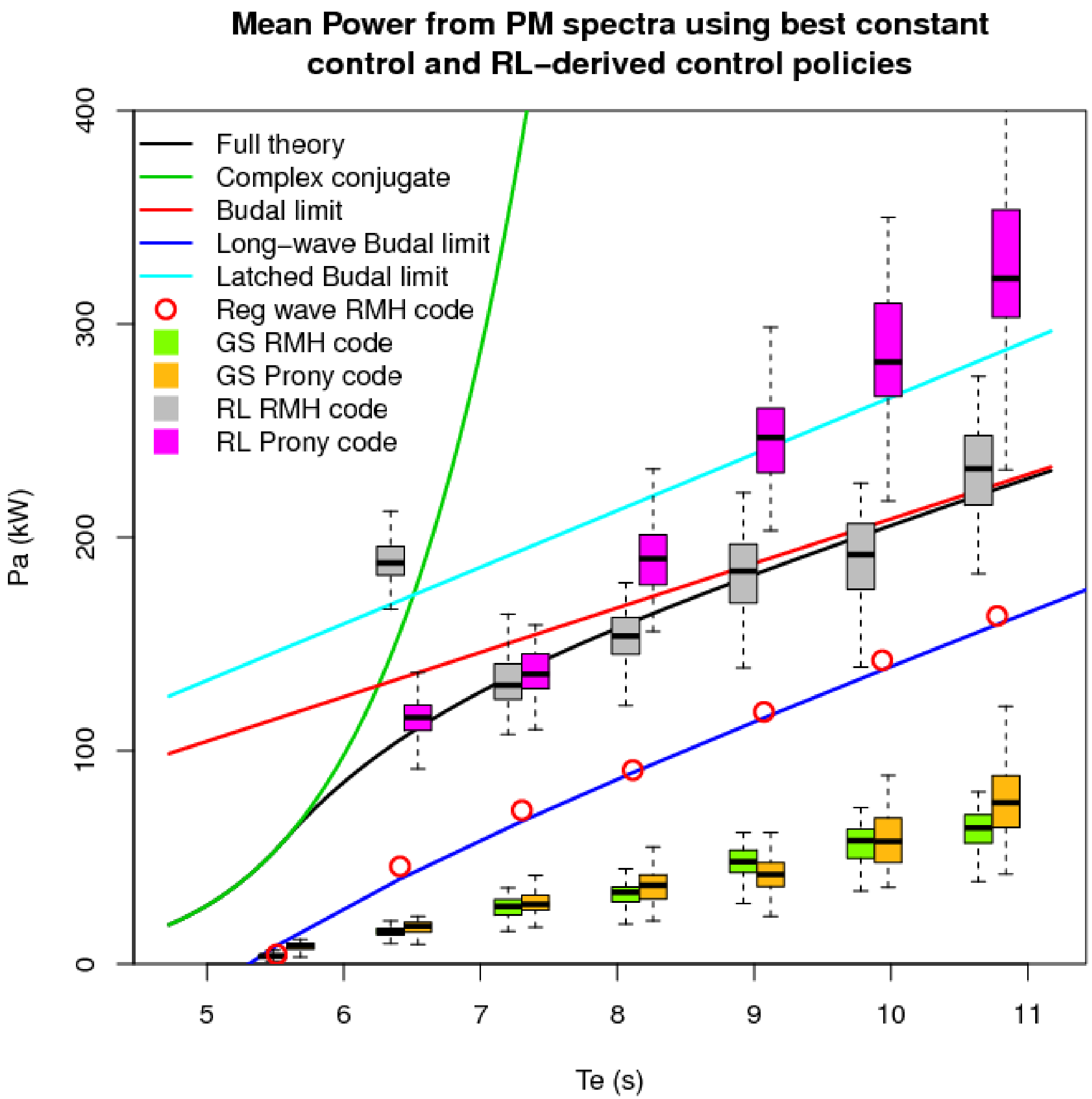
Simulation Time Series 2



Simulation Time Series 3



RL Simulation vs Theoretical Bounds



1) In volume-limited conditions the WEC should use all of its volume.
2) Best **constant controls** give **high power** in **regular waves** by using all the volume.
3) Best **constant controls** give **low power** in **irregular waves** because not using all the volume.
4) **RL** can find **control policies** that give **high power** in **irregular waves** as they use all the volume.
5) Power uplift 3 to 5 times.

Goals of Stage 3

Levelised Cost of Energy

$$\text{LCOE} = \frac{\text{CAPEX} + \text{OPEX}}{\text{AEP}}$$

CAPEX dominates OPEX, therefore

$$\text{LCOE} \approx \frac{\text{CAPEX}}{\text{AEP}}$$

Goals:

- Higher power for same loads (increase AEP)
- Lower loads for same power (decrease CAPEX)

CEORL

Cost of Energy Optimised by Reinforcement Learning

AQUAHARMONICS

Wave Conundrums CONSULTING

REOPTIMIZE SYSTEMS

THE UNIVERSITY of EDINBURGH

Contact: paulstansell@gmail.com

Adaptive Hierarchical Model Predictive Control of Wave Energy Converters

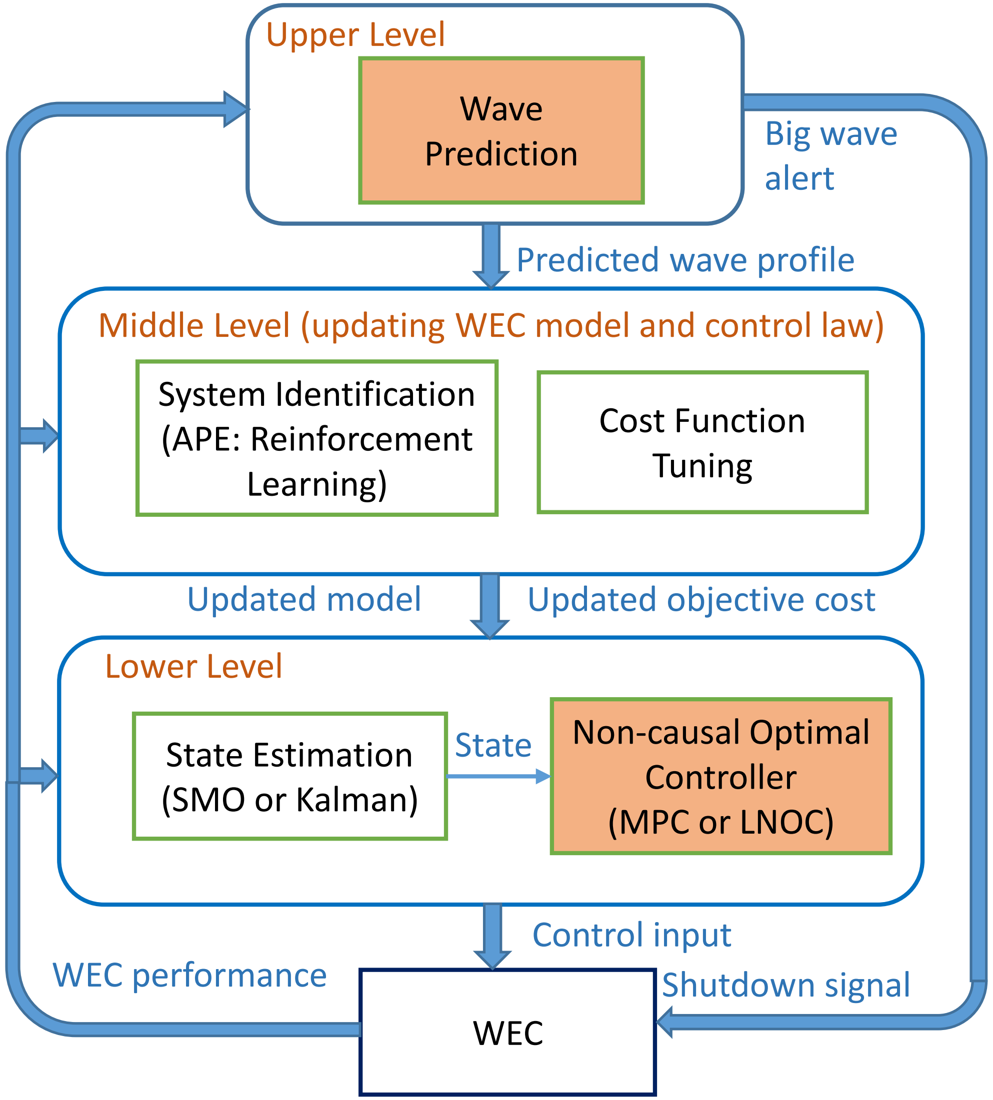
STAGE 3 Control System Programme of Wave Energy Scotland

Queen Mary University of London
Mocean Energy Ltd
University of Exeter
05/Dec/2019

Accomplishments of Stage 2 (Recap)

- An efficient and reliable **control framework** was developed and numerically validated on a **full scale** numerical model of the **attenuator** WEC developed by Mocean Energy Ltd.
- Control of an attenuator is much more challenging.
- Our control framework can be extended to other types of WECs.
- The framework mainly addresses the following major control issues commonly shared by most WECs:
    1. Energy maximisation problem;
    2. Non-causal control – current control action relies on future incoming waves;
    3. Subject to constraints on actuator and float motions, etc. for safety;
    4. WEC modelling complexities – varying dynamics, uncertainties and nonlinearities at different seat states;

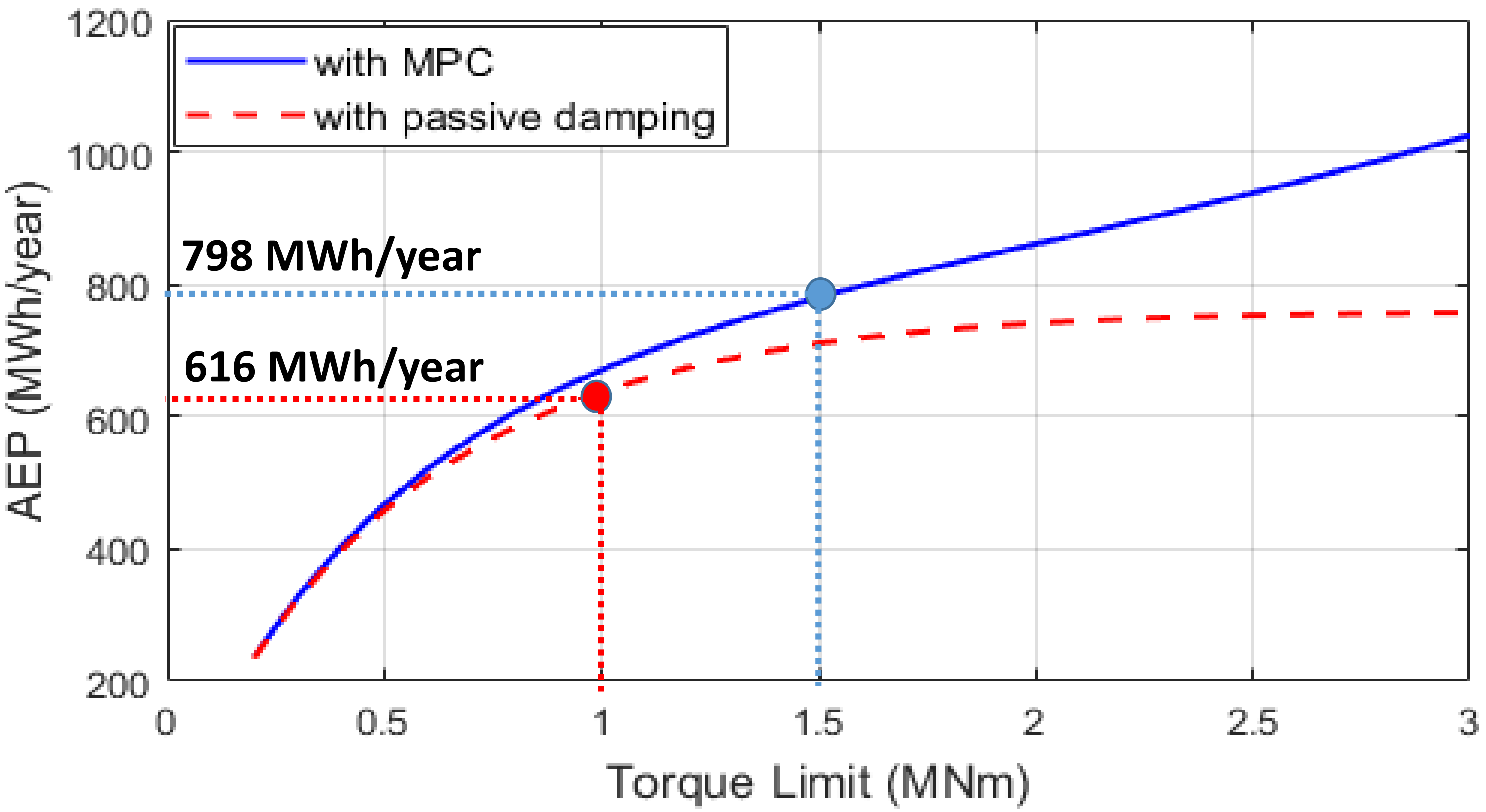
The proposed control framework



<u>How it works:</u>

- ***Upper level – wave prediction***
  i. Quiescent Period Wave Prediction technique to send detrimental wave alert to shut down WEC.
  ii. Deterministic Sea Wave Prediction to predict wave profile.
- ***Middle level – update WEC model and control law***
  i. Online WEC model identification using reinforcement learning based adaptive parameter estimation.
  ii. Adaptive tuning of control law.
- ***Lower level – energy maximisation control***
  i. Accurate estimation of excitation force and states by Siding Mode Observer.
  ii. Non-causal energy maximisation control, with candidates: Model Predictive Control (MPC), Adaptive Dynamic Programming, Sliding Mode Control Linear non-causal optimal control (LNOC).

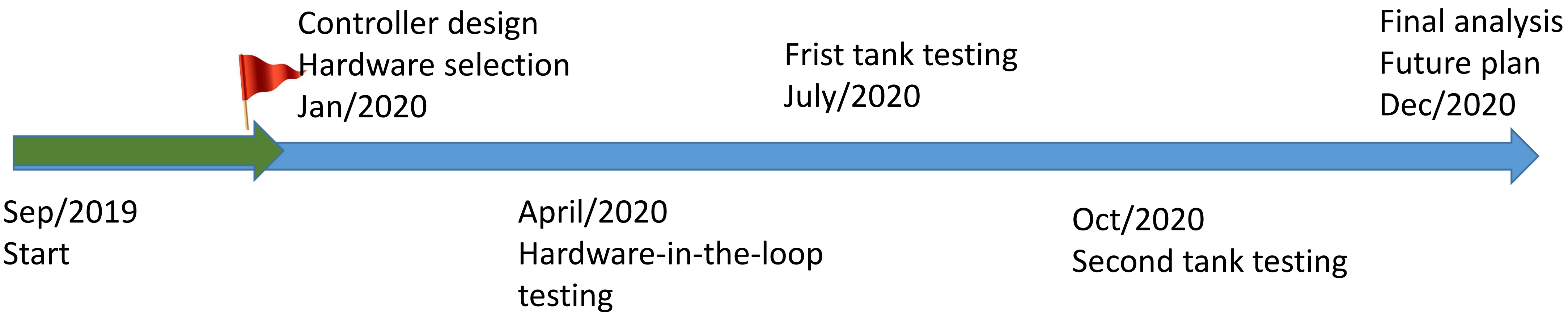
Control Improves AEP from 616 MWh/year to 795 MWh/year (equivalent to 30% increase)



The improvement of energy conversion efficiency using control over no-control increases with the torque limit.
Note: 1. The values are only for qualitative demonstration purpose and do not reflect the real WEC performance. 2. The selected torque limits for each case can result in the lowest unit cost after considering the PTO cost, which is proportional to its capacity.

Stage 3 objectives and work packages

Objective: To validate the proposed control techniques by **experiments** (tank testing) on a **1/20th scale physical WEC model**.



Modelling and simulations on 1/20th device

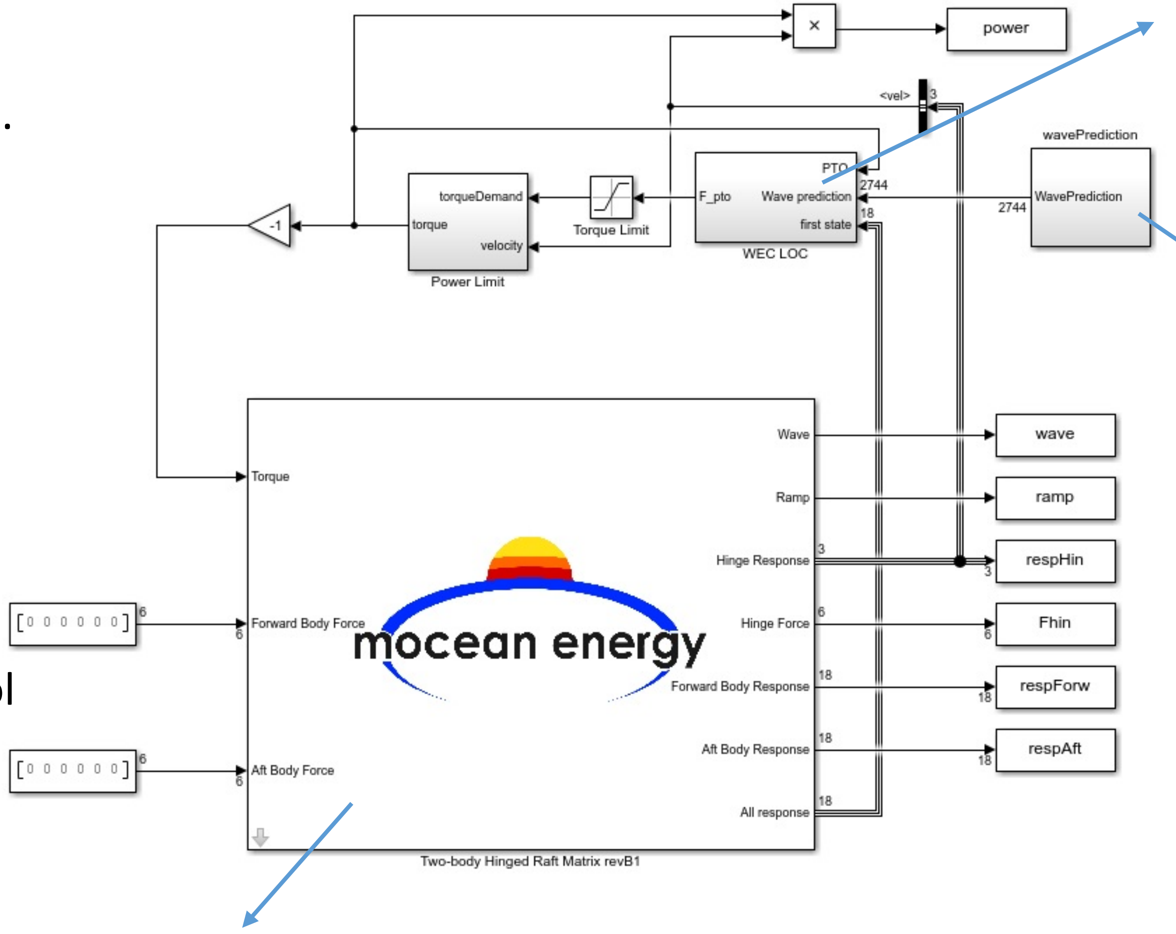
- Previous tank experiment data by Mocean Ltd. validate the fidelity of the scaled numerical WEC model (Simulink block)

- Flexibility simulation platform for different controllers' design

- Control performance is not affected by WEC model scales

- Confidence for proceeding to real-time control implementation

Control block



Wave prediction block

Numerical WEC model by Mocean Ltd

Performance on 1/20th WEC (LNOC part)

Comparing to a well-tuned passive linear damper

Wave height Hs = 0.05m (0.2m full scale)
Peak period Tp = 1.6s (7s full scale)
PTO torque limit 6 NM

Mean power from 0.68W to 0.94W.
(full scale 24KW to 32KW, 33% increased)

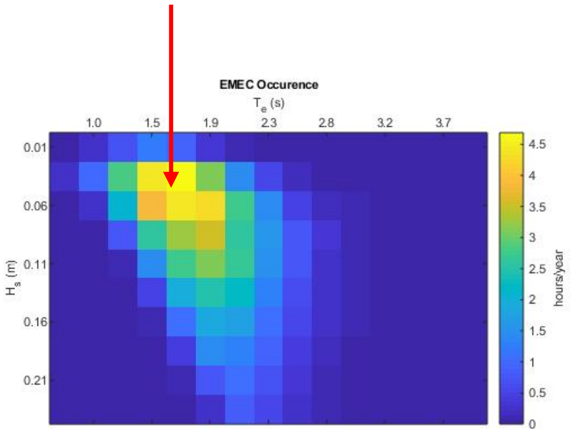


Fig. EMEC Occurrence.

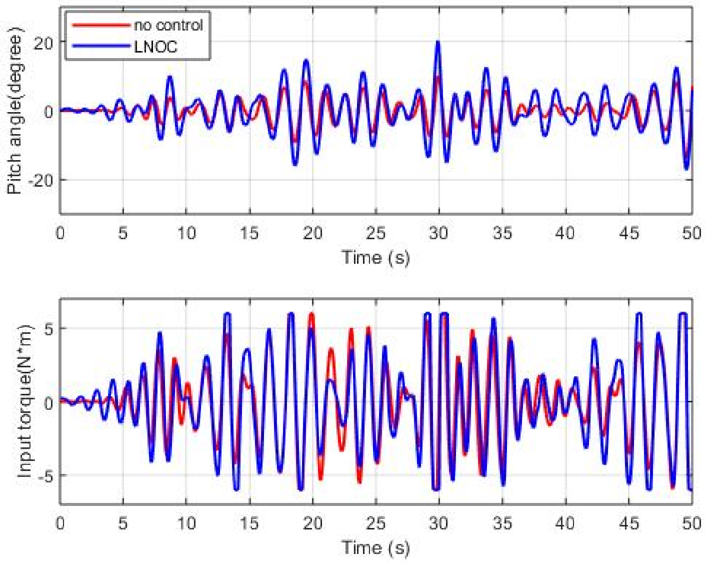


Fig. Pitch angle and control input.

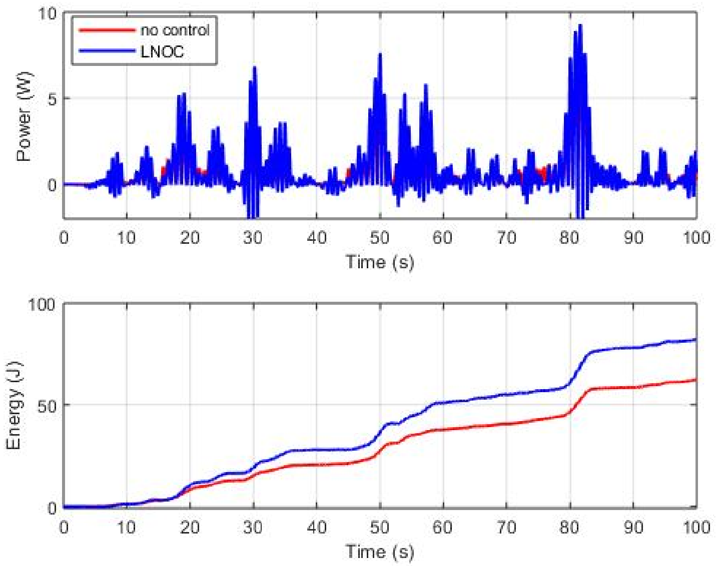


Fig. Instant power and energy captured.

LNOC

- Expected overall performance

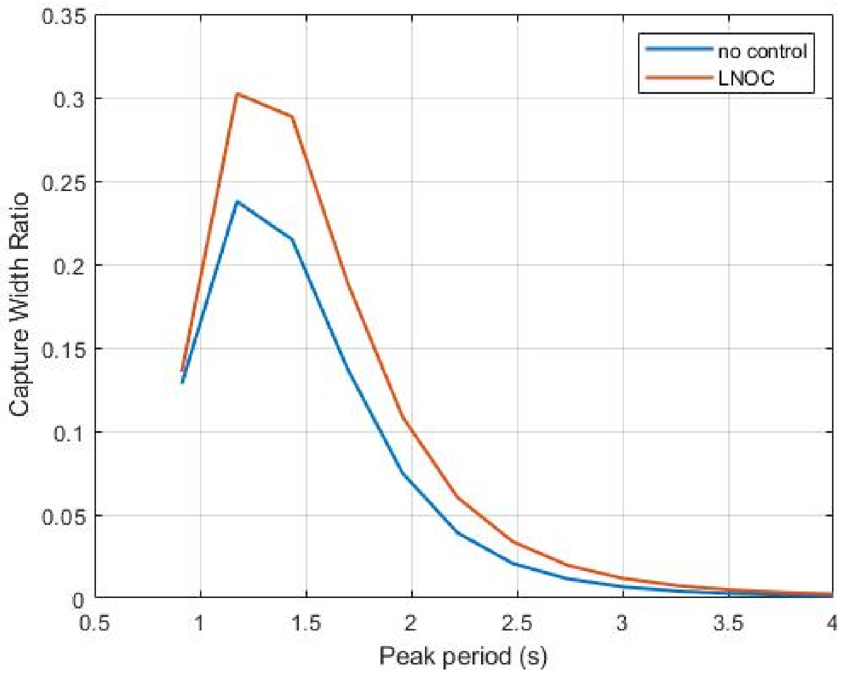
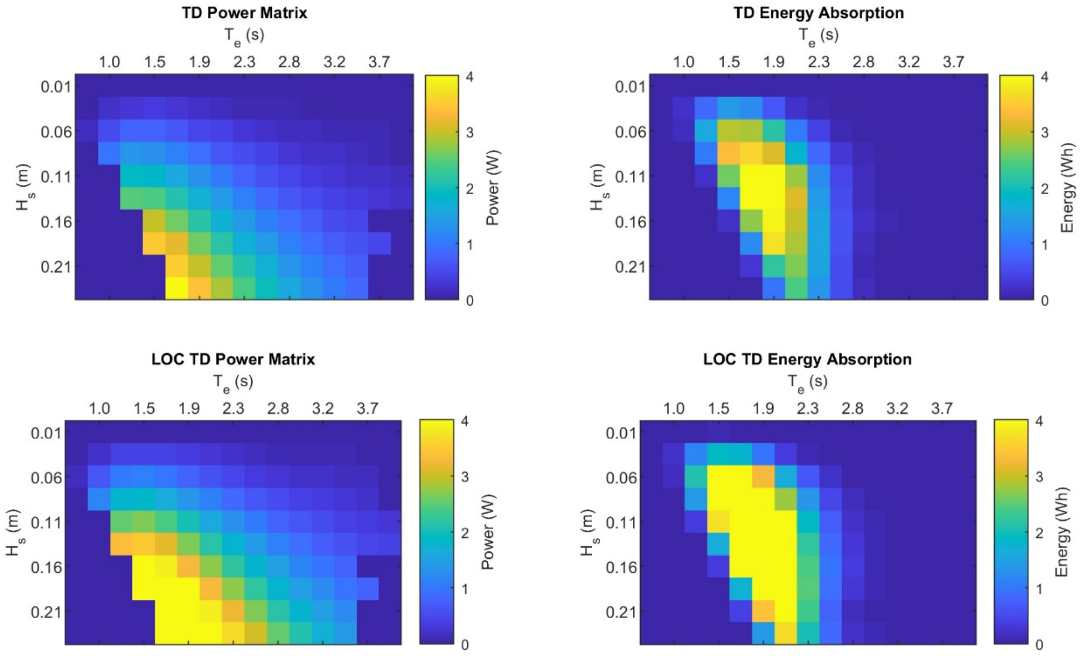


Fig. Capture width ratio performance of LNOC. (input constraint not active.)



Linear Passive damper

LNOC controller

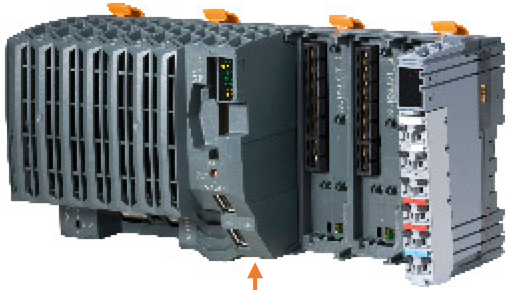
Fig. Power and energy map for each sea state. Bottom is the expected LNOC performance.

Broader operational band and higher energy capture ratio

Hardware components testing (ongoing)

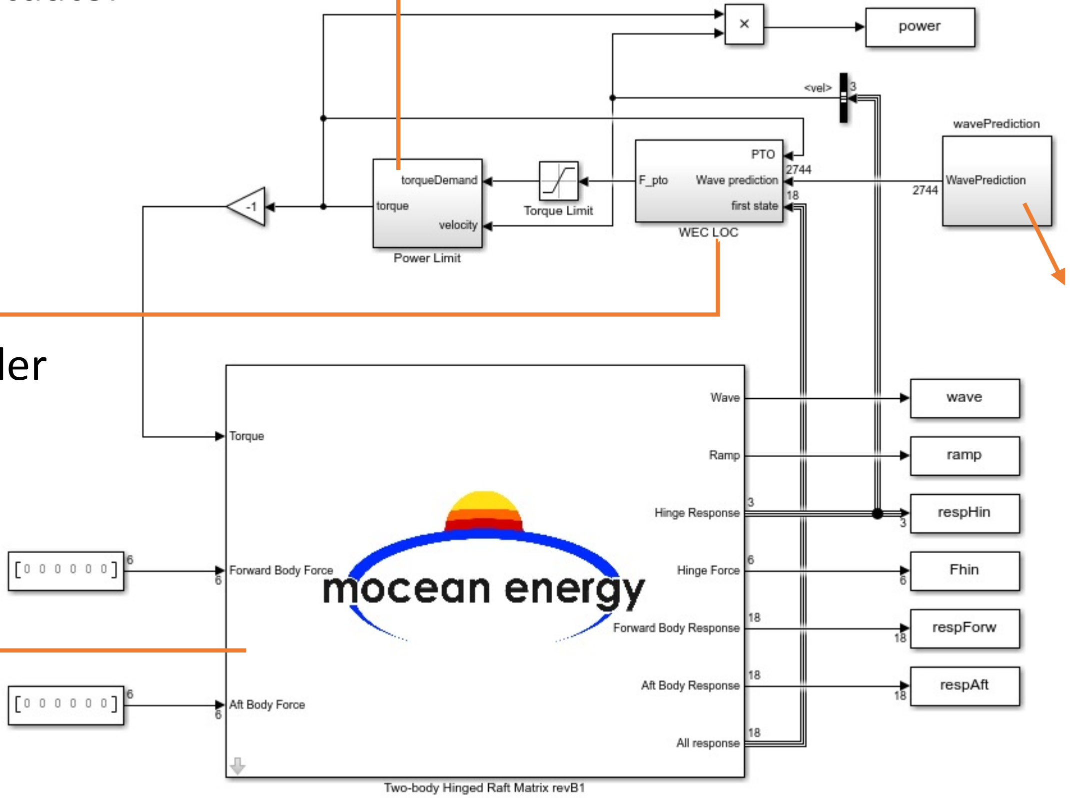
Actuator

DC motor

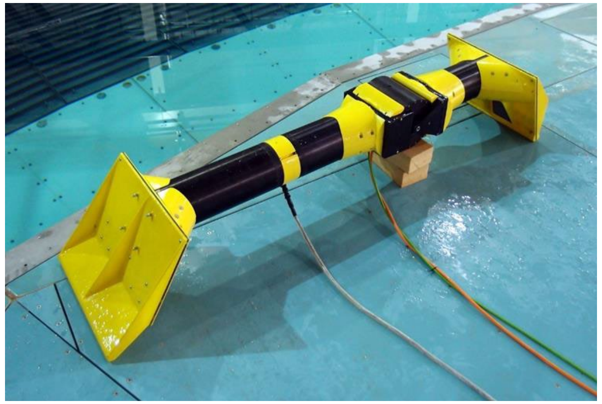


Hardware controller

Controller



DSWP prediction by Exeter

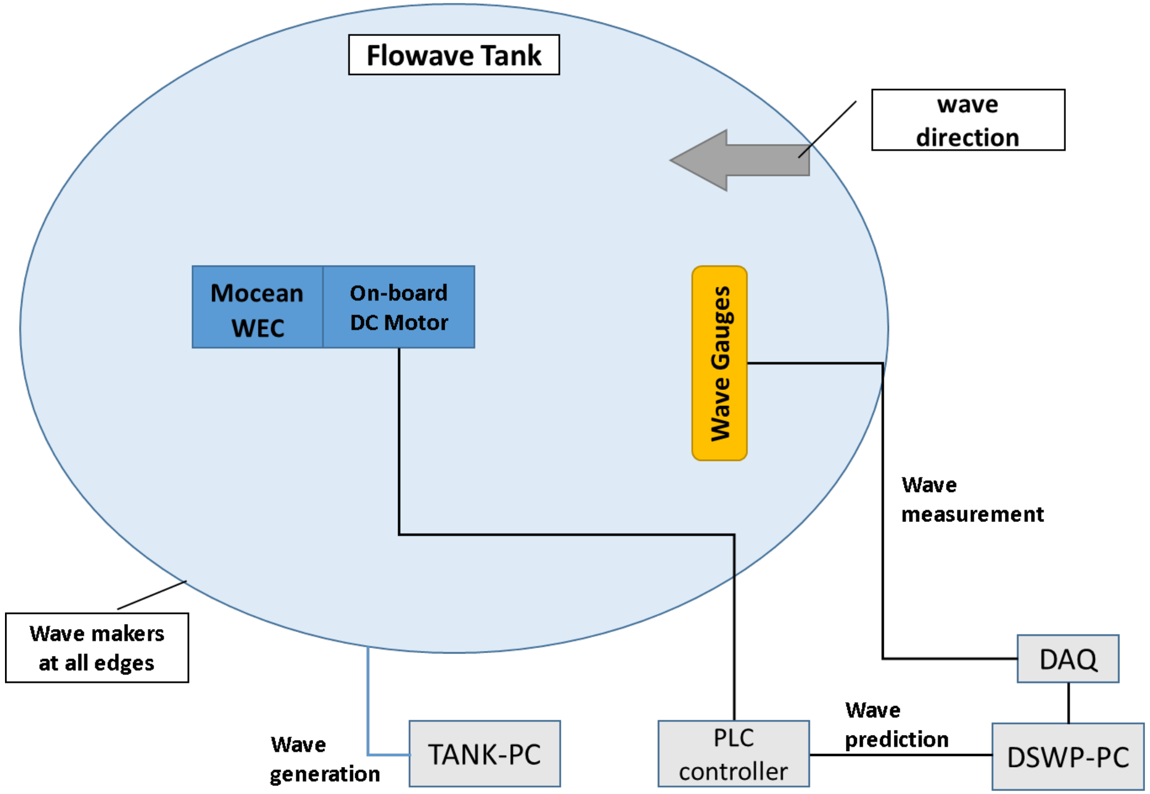


WEC

M100 device (1/20th scaled)

Tank testing prospect

Chosen facility for tank testing: FloWave Ocean Energy Research Facility in Edingburgh



Demonstrative diagram of tank testing hardware setup

Tank testing schedule

- Testing week 1: July 2020
- Testing week 2: October 2020

Selected Publications

1. Y. Zhang and G. Li (2019). Non-causal Linear Optimal Control of Wave Energy Converters with Enhanced Robustness by Sliding Mode Control, *IEEE Transactions on Sustainable Energy*, in press.

2. Y. Zhang and G. Li (2019), Robust Excitation Force Estimation and Prediction for Wave Energy Converter M4 Based on Adaptive Sliding-Mode Observer, *IEEE Transactions on Industrial Informatics*, in press.

3. S. Zhan, J. Na and G. Li (2019). Nonlinear Noncausal Optimal Control of Wave Energy Converters via Approximate Dynamic Programming, *IEEE Transactions on Industrial Informatics*, vol.15(11), pp 6070-6079.

4. S Zhan, G Li and C Bailey (2019). Economic feedback model predictive control of wave energy converters. *IEEE Transactions On Industrial Electronics*, published online.

5. Z. Liao, N. Gai, P. Stansby and G. Li (2019), Linear non-causal optimal control of an attenuator type wave energy converter M4, *IEEE Transactions on Sustainable Energy*, published online.

6. S. Zhan, G.Li, J Na and W He (2019). Feedback noncausal model predictive control of wave energy converters. *Control Engineering Practice* vol. 85, 110-120.

7. S. Zhan, J. Na , G. Li and B. Wang (2019), Adaptive Model Predictive Control of Wave Energy Converters, *IEEE Transactions on Sustainable Energy*, in press.

8. J Na, G Li, B Wang, Guido H and S Zhan (2019). Robust Optimal Control of Wave Energy Converters Based on Adaptive Dynamic Programming. *IEEE Transactions On Sustainable Energy,* vol 10(2), pp. 961-970.

9. J Na, B Wang, G Li, S Zhan and W He (2019). Nonlinear Constrained Optimal Control of Wave Energy Converters With Adaptive Dynamic Programming. *IEEE Transactions On Industrial Electronics,* vol. 66 (10), pp. 7904 – 7915.

10. S. Zhan and G. Li (2019), Linear optimal noncausal control of wave energy converters, *IEEE Transactions on Control Systems Technology*, vol 27(4), pp 1526 - 1536.

11. Y. Zhang and G. Li (2019), Wave Excitation Force Estimation for Wave Energy Converters Using Adaptive Sliding Mode Observer, American Control Conference, Philadelphia.

12. S. Zhan, B. Wang, J. Na, G. Li*, Adaptive Optimal Control of Wave Energy Converters, to be presented at the 11th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles, Opatija, Croatia, Sep. 10-12, 2018.

13. Z. Liao, G. Nian,P. Stansby and G. Li (2018). Control-Oriented Modelling for Wave Energy Converter M4, the 4th Asian Wave and Tidal Energy Conference (AWTEC 2018), Taipei, Taiwan, Sep. 9-13.

14. J. Na, G. Li*, S. Zhan, Online Optimal Control of Wave Energy Converters Via Adaptive Dynamic Programming, American Control Conference, Milwaukee, June, 2018.

Thanks!