Open Sea Operating Experience to Reduce Wave Energy Costs

Deliverable D7.5

H2020-OPERA Final Project Assessment and Recommendations

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EXECUTIVE SUMMARY

This document is an outcome from WP7 of the OPERA project. The main aim of WP7 is to analyse risk and cost data from WP1-WP6 and provide recommendations. In particular, deliverable D7.5 documents the final project assessment and recommendations for the sector. Taking stock of the previous tasks and the project as a whole, a final assessment of the current stage of the technologies is given. Cost-reduction pathways for these technologies and wave energy in general are updated with the newly available operating data.

After presenting the overall technical objectives, methodology and work plan of the OPERA project, the document summarises main results and assessment of the principal project components:

- Instrumentation and data collection.
- Mooring system.
- Power Take-Off.
- Advanced control algorithms.
- Application and extension of standards.
- Lifetime offshore logistics.
- Risk management, cost of energy and impacts.

The deliverable also offers some policy recommendations for the wave energy sector and final conclusions.

Project results are quite satisfactory both on the quantitative and qualitative sides. Thanks to the improvements brought about by the cost reducing innovations, the LCOE is reduced by 52-56% when compared to the benchmarking case for an array configuration of 18 MW. The biggest contributor to cost reduction is the novel biradial turbine, followed by advanced controls and the shared mooring configuration.

TABLE OF CONTENTS

EXECUTIVE SUMMARY 3
TABLE OF CONTENTS 4
LIST OF FIGURES 6
LIST OF TABLES 8
ABBREVIATIONS AND ACRONYMS 9
1. INTRODUCTION 10
2. PROJECT APPROACH 12
2.1 OVERALL TECHNICAL OBJECTIVES 12
2.2 METHODOLOGY 13
2.3 WORK PLAN 14
3. INSTRUMENTATION AND DATA COLLECTION 16
3.1 SUMMARY OF RESULTS 16
3.2 OVERALL ASSESSMENT 17
4. MOORING SYSTEM 19
4.1 SUMMARY OF RESULTS 19
4.1.1 Design, manufacture and bench-test of novel elastomeric tether 19
4.1.2 Design and manufacture of CMS 21
4.1.3 Evaluation of shared mooring system for Phase 1 and Phase 2 25
4.2 OVERALL ASSESSMENT 27
5. POWER TAKE-OFF 30
5.1 SUMMARY OF RESULTS 30
5.2 OVERALL ASSESSMENT 31
5.2.1 Biradial turbine performance 31
5.2.2 Lessons Learned 32
6. ADVANCED CONTROL ALGORITHMS 34
6.1 SUMMARY OF RESULTS 34
6.2 OVERALL ASSESSMENT 37
7. APPLICATION AND EXTENSION OF STANDARDS 38
7.1 SUMMARY OF RESULTS 38
7.2 OVERALL ASSESSMENT 39

8. LIFETIME OFFSHORE LOGISTICS 42
8.1 SUMMARY OF RESULTS 42
8.2 OVERALL ASSESSMENT 43
9. RISK MANAGEMENT, COST OF ENERGY AND IMPACTS 46
9.1 SUMMARY OF RESULTS 46
9.2 OVERALL ASSESSMENT 46
9.2.1 OPERA open sea experience 47
9.2.2 Global Economic assessment 48
9.2.3 Risk assessment 59
10. POLICY RECOMMENDATIONS FOR THE WAVE ENERGY SECTOR 61
10.1 OVERVIEW OF THE SECTOR 61
10.2 RECOMMENDATIONS FOR COMMERCIALITY 62
11. CONCLUSIONS 65
12. REFERENCES 67

LIST OF FIGURES

Figure 2.1: Research Methodology. 14
Figure 2.2: Graphical presentation of project tasks and their interrelations. 15
Figure 3.1: Screenshot of Only Data Query Tool........ 17
Figure 4.1: P2 and P3 series samples. 20
Figure 4.2: Tension-tension test machines: a) DMaC and b) Lankhorst-EUronete machine... 20
Figure 4.3: Tension-tension test machines: a) DMaC and b) Lankhorst-EUronete machine... 21
Figure 4.4: Schematic of the CMS P1 with main component labels (not to scale). 22
Figure 4.5: Re-design of J-tube (P2) to reduce stress to cabling system. 23
Figure 4.6: Schematic of the CMS P2 with main component labels (not to scale). 23
Figure 4.7: One of 4x 55t Load Shackle prior deployment........ 24
Figure 4.8: Wear and corrosion issues observed during p1, a) Marine fouling on load shackle, b) Rotation pin failure on load shackle, c) Fouling and corrosion on subsea connector. 24
Figure 4.9: Comparison of simulation results for horizontal motion a) prior calibration, b) after calibration. 25
Figure 4.10: Comparison between motion behaviour of Marmok for extreme condition between P1 and P2; a) horizontal motion (Easting), b) horizontal motion (Westing), c) heave, d) roll , e) pitch. 26
Figure 4.11: Comparison of the range of tension for P1 and P2 deployments. 27
Figure 4.12: Average maxima for Marmok tension in deployment P1 and P2. 27
Figure 5.1: Electrical generator time-averaged efficiency results for Mutriku Phases I & Ii and BiMEP. In the legend, Pi and PII denotes Phase I and Phase II. 31
Figure 5.2: Submergence limitations during tow-out. 32
Figure 6.1: Control frameworks at both Mutriku and BiMEP test sites 34
Figure 6.2: Power production of CL1 and CL2 relative to CL1 in a wide variety of sea states. 35
Figure 6.3: Comparison of PTO components efficiencies and power production by the CL in the Marmok-A-5 36
Figure 9.1: Comparison of OPEX model inputs based on initial OPERA experience with those based on final OPERA experience. 47
Figure 9.2: Annual energy production of the With Innovation scenario, at both deployment sites, calculated using both initial and final OPERA experience data in the OPEX model. 50
Figure 9.3: CAPEX breakdown of array 2 for With Innovation scenario when deployed at EMEC. 51
Figure 9.4: Non-discounted array 2 project costs for deployments at both BiMEP and EMEC. 52
Figure 9.5: Normalised LCOE impacts of each OPERA cost reducing innovations. 52
Figure 9.6: Normalised LCOE for both deployment locations based on With Innovation array scenarioes. Comparing values calcualted with the initial and fnal OPERA experience. 53
Figure 9.7: Impact of deployment locations on LCOE for With Innovations arrays scenarios. 54

Figure 9.8: Reductions in LCOE due to learning rates and economy of scales. values are normalised with the highest LCOE result (single device). 55
Figure 9.9: Gross embodied energy (left) and carbon (right) breakdown over the life-cycle, considering final OPERA experience. 56
Figure 9.10: life cycle carbon intensities of OPERA and alternative energy generation technologies [8]. 58
Figure 9.11: Summary of initial (top) and final (bottom) OPERA FMEA data 60
Figure 10.1: Stages of development of Ocean energy technologies [10]. 61

LIST OF TABLES

Table 2.1: Project innovations........ 12
Table 2.2: Technical Work Packages 14
Table 6.1: Overall Power performance comparison produced by each CL at Mutriku 36
Table 9.1: Availability values calculated by the OPEX model based on initial and final OPERA experience. 49
Table 9.2: Capacity Factor of the Bench Case and With Innovation scenarios, at both deployment sites, calculated using both initial and final OPERA experience data in the OPEX model........ 50
Table 9.3: GWP, EPBT and EROI figures calculated for the With Innovation array 2 scenario deployed at EMEC. Calculations performed based on initial and final OPERA experience. 57
Table 11.1: Progress achieved towards technical objectives 65

ABBREVIATIONS AND ACRONYMS

AEP	Annual Energy Production
ALARP	As Low As Reasonably Practicable
CAPEX	Capital Expenditure
CF	Capacity Factor
CL	Control Law
CMS	Condition Monitoring Systems
DAQ	Data Acquisition
EPBT	Energy Pay-Back Time
EROI	Energy Return on Investment
FIT	Feed in Tariff
FMEA	Failure Modes and Effect Analysis
GVA	Gross Value Added
GWP	Global Warming Potential
HSSV	High-Speed Stop Valve
IEC	International Electrotechnical Commission
IRR	Internal Rate of Return
LCA	Life Cycle Analysis
LCOE	Levelised Cost of Energy
MBL	Minimum Breaking Load
MRL	Manufacturing Readiness Level
NPV	Net Present Value
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
OWC	Oscillating Water Column
PTO	Power Take-Off
SCOE	Social Cost of Energy
TCLL	Thousand Cycle Load Limit
TRL	Technology Readiness Level
TS	Technical Specification
WEC	Wave Energy Converter
WP	Work Package

1. INTRODUCTION

This document is an outcome from WP7 of the OPERA project. The main aim of WP7 is to analyse risk and cost data from WP1-WP6 and provide recommendations. The ultimate goal of this WP is to gather all the information from the previous WPs and analyse its influence on economics and risk assessment, in order to develop guidance and recommendations from the project's unique offshore experience. Specific technical objectives are as follows:

- Assess LCOE impact of innovations and technologies tested in WP2-6.
- Reduce OPEX uncertainty with open-sea data including offshore operations from WP6
- Develop metrics in order to quantify and track the uncertainty and risk involved in all stages of the project and set appropriate mitigation measures for the identified risks
- Develop guidance from the unique sea experience at sea in order to set the path forward
- Catalogue the improvements in CO2 savings (LCA) and reduction of the energy payback period from an adequate management of the operation of the device
- Display the real cost of wave energy though the SCOE assessment and its competitiveness with respect other energy sources in the future energy mix

In particular, deliverable D7.5 documents the final project assessment and recommendations for the sector. Taking stock of the previous tasks and the project as a whole, a final assessment of the current stage of the technologies is given. Cost-reduction pathways for these technologies and wave energy in general are updated with the newly available operating data. The deliverable presents a synthesis of OPERA contributions and technological improvements from a wave energy sector perspective, energy sector perspective, business and investment decision and policy support perspective including SME support, R&D priorities, recommendations for effective support to early deployments.

Lead by UEDIN, TECNALIA assisted in synthesising output from all WPs, OCEANTEC-IDOM and KYMANER provided SME and device performance perspective, and UNEXE included mooring technology, cost and risk. Finally, DNV GL advised on risk assessment.

This document is structured in the following sections:

- **Section 2: Project approach**. It describes the overall technical objectives, methodology and work plan.
- **Section 3: Instrumentation and data collection**. It presents a summary of results and overall assessment with regard to the process instrumentation.
- **Section 4: Mooring system**. Similarly, it presents a summary of results and overall assessment for the share mooring configurations and elastomeric mooring tethers.
- **Section 5: Power Take-Off**. Same about the novel biradial air turbine-generator set.

- **Section 6: Advanced control algorithms**. In this case the result and assessment refer to the control laws customised for the floating WEC.
- **Section 7: Application and extension of standards**. Summary of the first-time real-case application of IEC Technical Specifications and recommendations.
- **Section 8: Lifetime offshore logistics**. Summary of results and learning with regards to uncertainty risk and cost reduction in offshore operations.
- **Section 9: Risk management, cost of energy and impacts**. Summary of results, open-sea experience, global economic assessment and risk assessment.
- **Section 10: Policy recommendations for the wave energy sector**. It presents an overview of the sector and recommendations for commerciality.
- **Section 11: Conclusions**.
- **Section 12: References**.

2. PROJECT APPROACH

2.1 OVERALL TECHNICAL OBJECTIVES

Real open-sea experience is essential to fully understand the challenges in wave energy device performance and lower the risks of wave energy that shall lead to harvest this vast European resource and contribute to environmental and economic goals.

The main objective of the OPERA project is to collect, analyse and share open-sea operating data and experience to validate and de-risk the following industrial innovations for wave energy, taking them from TRL3-4 to TRL5 and opening the way to long term cost-reduction of over 50%.

TABLE 2.1: PROJECT INNOVATIONS

Innovation	Short description
Novel biradial turbine	Mechanically robust and highly efficient turbine for OWC
Predictive and latching control for energy capture	Predictive control uses incoming wave information for control, applicable to all WECs. Latching (valve control) specific to OWC.
Shared mooring system	Reduces mooring line length and cost in WEC farms
Elastomeric mooring tether	Reduces peak loads at mooring and hull connection to enhance structural survivability and reduce mooring line strength requirement and cost

The specific and measurable objectives of the project are described below.

- Collect, stream and publish 2 years of open-sea operating data of both a floating WEC and a shoreline wave power plant (addressed in WP1).
- De-risk innovations that lower mooring cost over 50% and enhance survivability (addressed in WP2).
- Increase OWC power production 50% and improve reliability (addressed in WP3).
- Advance predictive and latching control to TRL5 to enable 30% increase in power production (addressed in WP4).
- Advance standards to reduce business risk and give access to lower cost capital (addressed in WP5).
- Reduce uncertainty, frequency, risk and cost of offshore operations (addressed in WP6).
- Improve risk management and cost estimation with real data (addressed in WP7).

2.2 METHODOLOGY

The overall concept of the project is to gather, share and analyse open-sea operating data of a floating OWC wave energy converter at TRL4 in a fully consented grid-connected open-sea testing facility, BiMEP, and de-risk four cost-reducing innovations for open-sea wave energy application: biradial turbine, predictive/latching control, shared mooring, and elastomeric tether.

The impact of research activities has been multiplied several-fold by testing at the shoreline wave power plant at Mutriku near BiMEP, the world's largest and first commercial wave power plant. Full exposition of power take-off components to some of the word's roughest seas was intended to uncover and rapidly weed out inevitable early engineering problems before testing on the floating device offshore, where interventions are orders of magnitude slower and more expensive.

In addition to the IP background that the Consortium partners bring up to the OPERA project, OCEANTEC-IDOM contributed with National funds for prototype conception, construction, deployment and renting of test berth. This guaranteed the baseline configuration of the floating OWC (dubbed MARMOK-A5), with shared mooring, conventional tether, Wells turbine and non-predictive control algorithms (#1 in Figure 2.1), to be tested open-sea early in the project.

Sensor integration in this baseline configuration of MARMOK-A5 allowed monitoring of the structural and power performance, as well as sub-system reliability and survivability. Field tests at BiMEP open-sea test facility provided more than one-year of baseline data for later benchmarking. Performance data was also used to accelerate the standards for the wave energy sector.

The OPERA-funded phase integrated three cost-reducing innovations into the refitted OWC, namely a biradial turbine, a novel elastomeric tether, and advanced control algorithms. These innovations underwent thorough lab-testing and prior de-risking in the Mutriku shoreline wave power plant (#2 in Figure 2.1). Field tests at Mutriku contributed to the validation of reliability and performance of the novel biradial turbine and control algorithms.

The second field test campaign at BiMEP with the new configuration (i.e. MARMOK-A5 with biradial turbine and elastomeric mooring tethers) provided further data to validate the innovations. Post-test analysis of BiMEP field tests led to the technical, economic, life-cycle and social impact assessment of the innovations as well as to foster the adoption of exploitable results (#3 in Figure 2.1).

The research methodology is visually represented in the figure below.

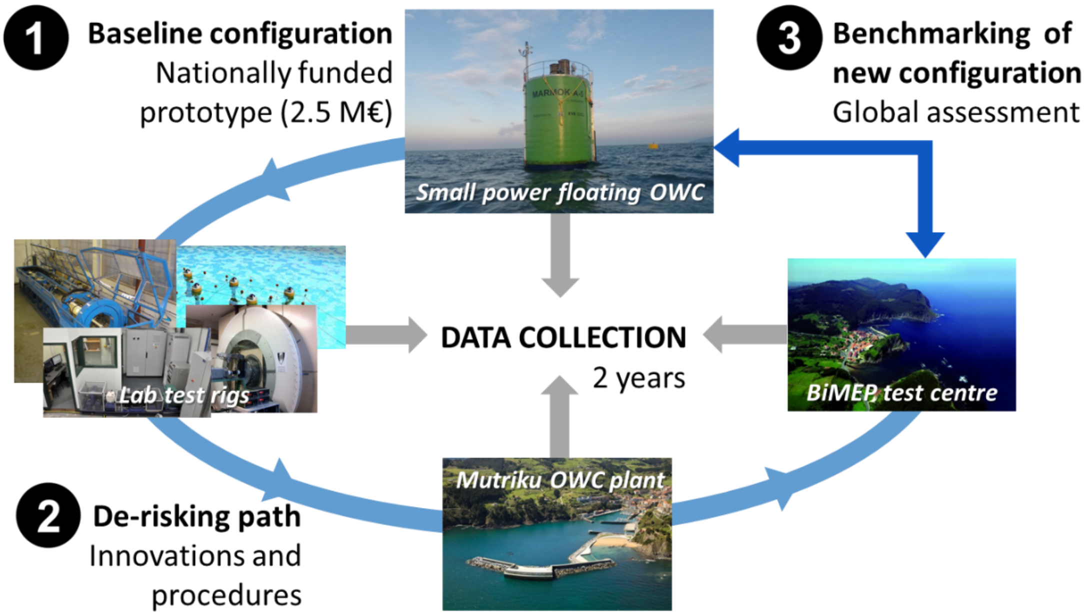


FIGURE 2.1: RESEARCH METHODOLOGY.

2.3 WORK PLAN

The work plan structure is results-based, with each work package mapping to an objective to solve a critical problem for wave energy. In addition, a number of issues are cutting across each work package, in particular: risk, costs and failure data collection. WP7 is in charge of providing consistent methodology, data collection protocol and integration of this information.

The list of technical WPs, project tasks and interrelations are presented in the next table and figure.

TABLE 2.2: TECHNICAL WORK PACKAGES

WP	Title	Lead
WP1	Collect, stream and publish open-sea operating data	IDOM
WP2	Mooring loads assessment and reduction, shared mooring validation	UNEXE
WP3	Power take-off reliability and performance, validation of new turbine	IST
WP4	Control algorithms for reliability and performance	TECNALIA
WP5	Applicability and extension of IEC technical specifications using open sea data	UCC
WP6	Lifetime offshore logistics	TECNALIA
WP7	Risk management, cost of energy and final assessment	UEDIN

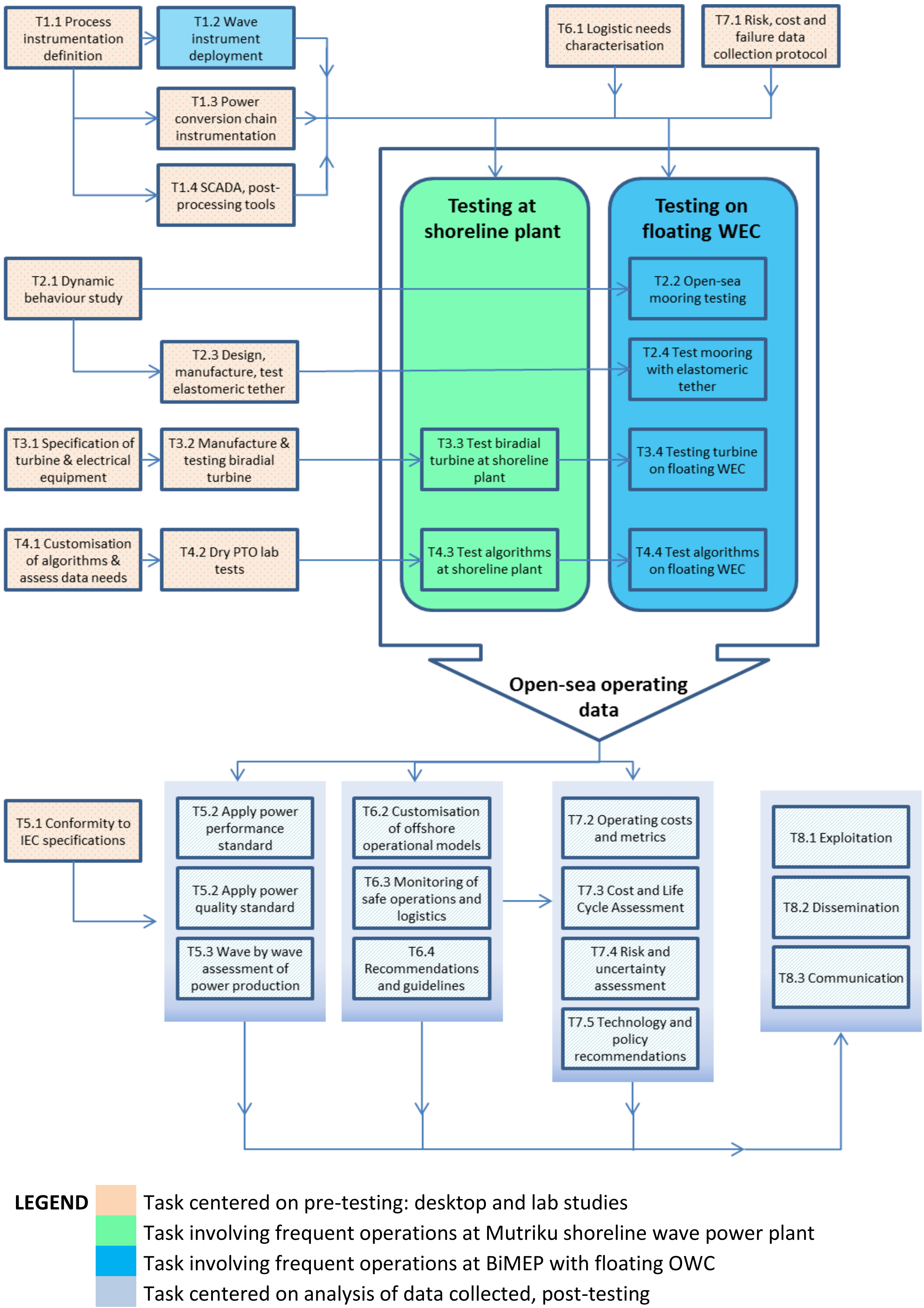


FIGURE 2.2: GRAPHICAL PRESENTATION OF PROJECT TASKS AND THEIR INTERRELATIONS.

3. INSTRUMENTATION AND DATA COLLECTION

3.1 SUMMARY OF RESULTS

Despite the significant achievements wave energy has made recently, real open-sea experience and data is needed to identify and quantify the challenges in device performance, survivability and reliability. The OPERA project ensured state of the art instrumentation was installed and operated in the harsh open-sea environment, enhancing successful development of the technical research activities of other Work Packages.

This objective was achieved through the following activities:

- Process instrumentation definition and specification of data needs (Deliverable D1.1).
- Preparation of instrumentation and control system in Mutriku for PTO and Control Law testing campaign.
- Selection and deployment of:
  - Wave measuring sensors at BiMEP (surface following buoy) and at Mutriku (offline pressure gauge), including real-time wave elevation information as input to predictive Control Laws.
  - Integrated WEC and Mooring Condition Monitoring system, across two testing campaigns, to cover standard and elastomeric tether configurations and resulting in more than 300 GB of high-resolution data collected.
  - High-Speed DAQ system for electrical power quality assessment in Mutriku according to IEC 62600-30 guidelines.
  - Operational databases to cover PTO and Control Law testing campaigns both for Mutrku and MARMOK-A-5.
- Open access publication of research datasets, including
  - Environmental data for Mutriku and BiMEP
  - Control Law testing campaign with biradial turbine in Mutriku
  - Power Quality Monitoring datasets for Mutriku
  - Control Law testing campaign with biradial turbine in MARMOK-A-5
- Periodic inspection, repair, replacement and data recovery from monitoring systems and sensors. Instrumentation System Risk Matrix and lessons learnt compilation (Deliverable D1.2).
- Development and maintenance of Online Data Access Tool to allow partners local and remote access to monitoring information (Deliverable D1.3)

The detailed results are presented in three OPERA project deliverables:

- D1.1 Process instrumentation definition (Confidential)
- D1.2 Mutriku and BiMEP operating data collection experience (Public)
- D1.3 Online data query tool (Public)

3.2 OVERALL ASSESSMENT

The ambitious instrumentation and data acquisition systems planned and deployed for field testing within the OPERA project has produced very satisfactory results. The instrumentation and data acquisition systems have proved very successful in delivering high quality field data to all the rest of the Work Packages for innovation assessment.

The use of cloud-based database services to provide a uniform, structured and integrated field data storage system has also proved its value, allowing the effective storage of several hundred Gigabytes of data.

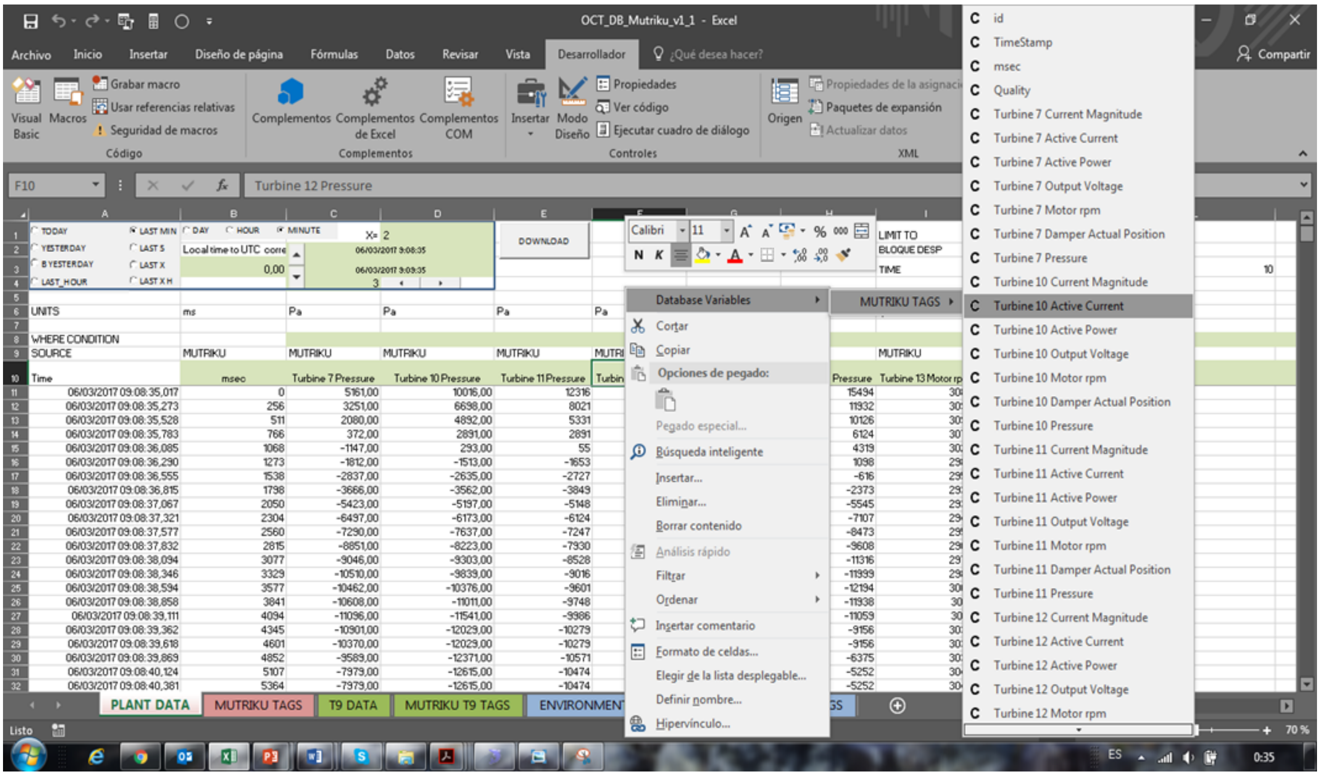


FIGURE 3.1: SCREENSHOT OF ONLY DATA QUERY TOOL

Mutriku wave power plant offered a relatively controlled and accessible test site, and a reasonably benign environment in which equipment and systems could be tested in work conditions similar to BiMEP working conditions where challenges can be overcome with more ease than with a direct BiMEP offshore deployment. O&M of the plant was planned also considering weather windows, but no limitations apply other than attaining to reasonable levels of noise hazard inside the power plant, a factor that can otherwise be mitigated with adequate corrective environment. However, in very energetic sea states combined with high tides there is a real risk of waves overtopping the breakwater.

The testing campaign in Mutriku offered an excellent opportunity to identify and mitigate risks in instrumentation, and, more generally, in innovative components, as problems encountered during these onshore tests could be solved with reasonable effort and costs. This demonstrated the crucial importance of this kind of de-risking field test campaigns, which are strongly recommended for future demonstration projects. It is also vital that these tests are performed using the same equipment configuration that will finally be deployed in the sea, providing the most realistic testing environment as possible.

Even though consortium partners had large field experience, particularly at Mutriku, the testing campaign at BiMEP presented many technical and logistic challenges. Nevertheless, an intense testing campaign was implemented, reaching the mark of 2,250 control law test runs, covering three Control Laws, including the innovative use of real-time wave elevation for excitation force prediction to improve power production under CL6.

By backing the research undergone with open-access publication of datasets, the project further pursues the future re-use of the produced research data by the wave energy community, in a sector-wide effort to steer the development of wave energy.

4. MOORING SYSTEM

4.1 SUMMARY OF RESULTS

The OPERA project aimed to de-risk innovations that lower mooring costs over 50% and enhance structural survivability. The specific objectives were to de-risk two mooring innovations, namely, the Karratu shared mooring system and the Exeter Tether elastomeric tether, through a combination of comprehensive numerical studies, an open sea demonstration and a dedicated component bench testing programme. These objectives were achieved through:

1.	Design, manufacture and bench-test a novel elastomeric tether	**√**
2.	Design, assemble and incorporate the condition monitoring systems (CMS) and the elastomeric tether in the shared mooring	**√**
3.	Evaluate shared mooring open-sea operation without (Phase 1) and with (Phase 2) elastomeric tether	**√**

The detailed results are presented in four OPERA project deliverables:

- D2.1 Mooring load and response monitoring system design (Confidential)
- D2.2 Mooring open-sea operating data analysis (Public)
- D2.3 Elastomeric tether performance and durability (Confidential)
- D2.4 Recommendations for WEC mooring guidelines and standards (Public)

4.1.1 DESIGN, MANUFACTURE AND BENCH-TEST OF NOVEL ELASTOMERIC TETHER

Testing of the 9x short Exeter Tether samples (P2, P3 and P4 series, see Figure 4.1) took place during early February 2017 (Month 13) at Dynamic Marine Component (DMaC) test facility, Penryn Campus (University of Exeter), with one additional test carried out on a full-scale (P4) sample at Lankhorst Euronete, Maia (Portugal), during early March 2017 (Month 14).

FIGURE 4.1: P2 AND P3 SERIES SAMPLES.

The majority of testing was carried out using DMaC (Figure 4.2a) with one load-to-failure test carried out at Lankhorst-Euronete (Figure 4.2b) because the expected minimum break load (MBL) was out of the working range of DMaC. A mixture of harmonic and ramp-hold-ramp load profiles were used to quantify static and dynamic stiffness of the samples. Stepped load increase/decrease were carried out to investigate contraction/expansion of the Tether cross section during loading/unloading. A Thousand Cycle Load Limit (TCLL) test was also conducted to determine fatigue performance.

Full details of the tests can be found in Deliverable 2.3 *Elastomeric Tether Performance and Durability* and only a summary of the findings is provided here. The purpose of the tests was to investigate Tether performance and durability using three geometric scales.

a) b)

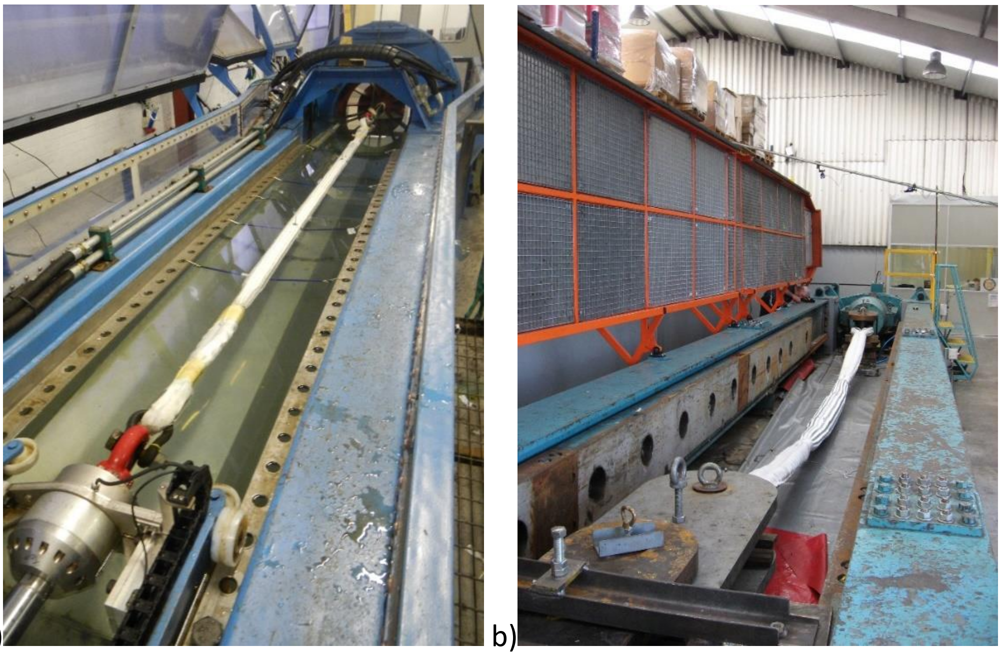


FIGURE 4.2: TENSION-TENSION TEST MACHINES: A) DMAC AND B) LANKHORST-EURONETE MACHINE.

The load-to-failure test carried out at Lankhorst-Euronete (sample: P4C) was used to confirm the break load of the Tether, albeit based on one sample. The measured MBL was 1597.5 kN, almost 23% higher than the predicted failure load.

The final manufacture of 2x 70m tethers took place at the Lankhorst's Maia, Portugal Factory (Figure 4.2a); and was delivered to Bilbao in June 2017 (Figure 4.2b). The deployment of the tether for phase 2 took place in August 2018 (Figure 4.2a, b, c).

a) b) c)

FIGURE 4.3: TENSION-TENSION TEST MACHINES: A) DMAC AND B) LANKHORST-EURONETE MACHINE.

4.1.2 DESIGN AND MANUFACTURE OF CMS

Two mooring Condition Monitoring Systems (CMS) were designed and manufactured during the OPERA Project. This was the result of an extreme event at the end of Phase 1 resulting in the catastrophic failure of the CMS system. The loads exceeded the maximum CMS design loads, which were chosen on based on sacrificial design criteria in order to protect the MARMOK device for dangerous loads.

The CSM design for Phase 1 (P1) included 4 55t Load Shackle where the cables were routed back from Node 1 and Node 4 to the MARMOK hull (Figure 4.4). A Wire Rope 'Cradle' system was used to support the Load Shackle Cable run back to the MARMOK. At the MARMOK hull, a J-Tube was used to route the Load Shackle Cables up the outside of the WEC to a Junction Box. From the Junction Box, one common cable takes the signal from all four Load Shackles back to the DAQ system.

Full details of the CMS design can be found in Deliverable 2.1 *Mooring load and response monitoring system design* and only a summary of the findings is provided here.

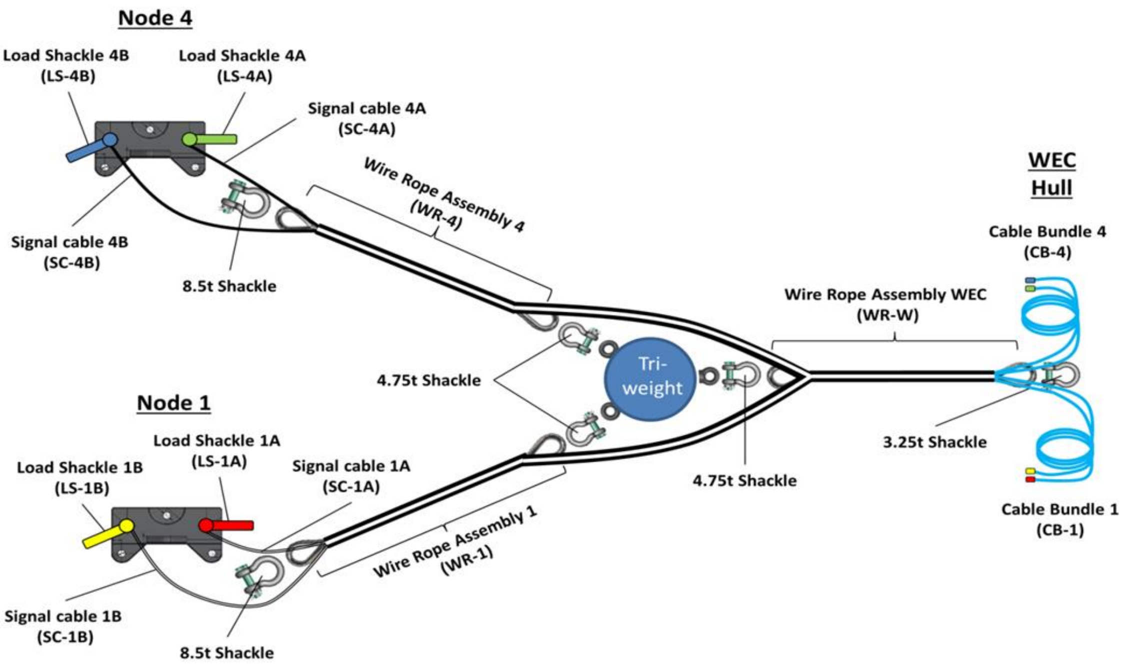


FIGURE 4.4: SCHEMATIC OF THE CMS P1 WITH MAIN COMPONENT LABELS (NOT TO SCALE).

The re-designed system (P2) comprised two armoured cables which run directly from Node 1 and Node 4 to the junction box on MARMOK via the J-tubes (Figure 4.6). The Load Shackles were re-calibrated and used again as well as the DAQ system. The bottom of the J-tubes has been modified to include composite bell mouths in order to reduce bending stresses and abrasion during use (Figure 4.5).

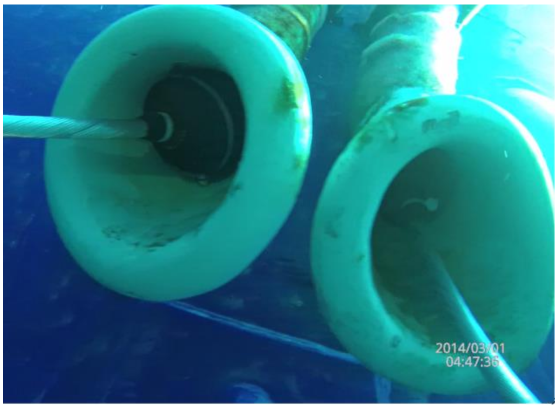


FIGURE 4.5: RE-DESIGN OF J-TUBE (P2) TO REDUCE STRESS TO CABLING SYSTEM.

Unlike the first design, which had separate steel wire cables and a Tri-weight, the new design utilises the cable's armouring strands to support the hanging catenary. Aramid cable grips are used to transfer loads from the armouring to the Node and MARMOK attachment points.

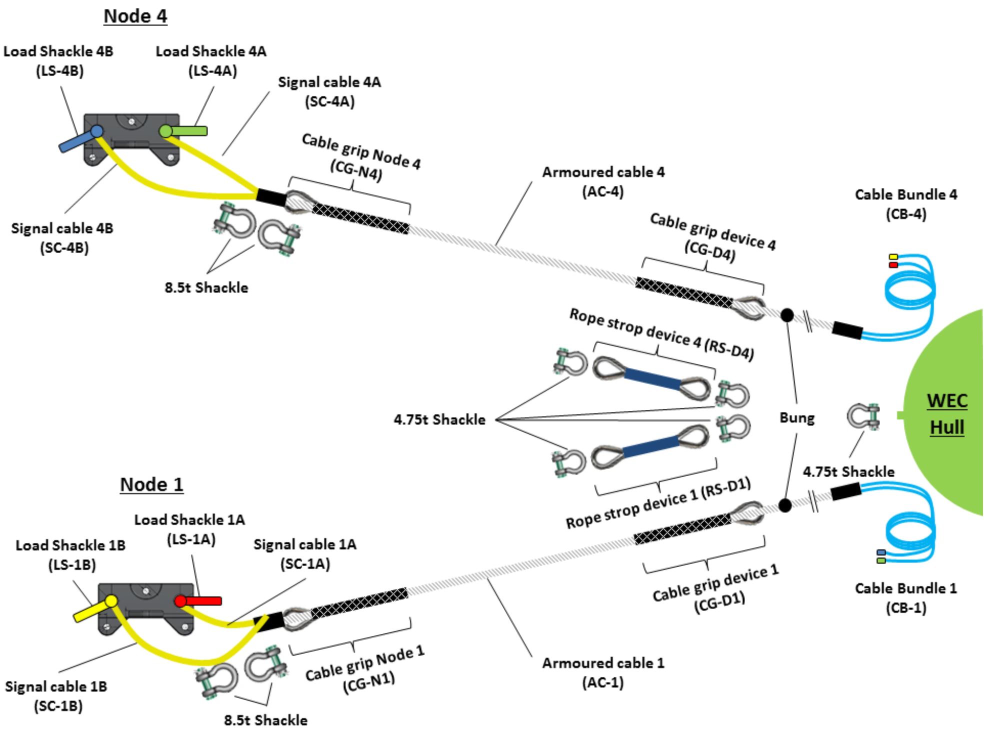
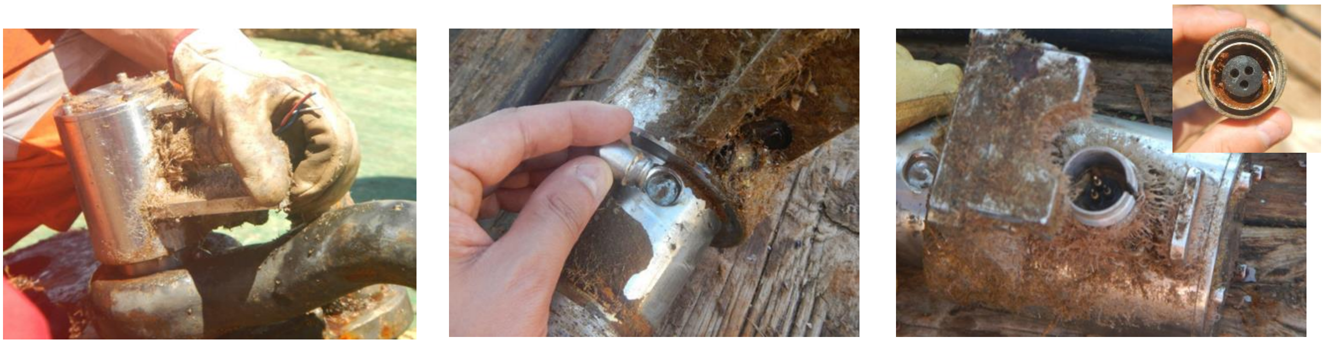


FIGURE 4.6: SCHEMATIC OF THE CMS P2 WITH MAIN COMPONENT LABELS (NOT TO SCALE).

A 55t Green Pin® (Figure 4.7) standard bow shackle with safety bolt is specified for the load shackle design. The pins supplied with the shackles are to be replaced with load pins, manufactured from 17-4PH H1075 Stainless Steel to match the specific dimensions of each shackle. The use of this steel maintains the specified Safety Factor of 6 on the Green Pin® shackle specification. Given the working load limit of 55t this equates to a minimum breaking load of 330t.

FIGURE 4.7: ONE OF 4x 55T LOAD SHACKLE PRIOR DEPLOYMENT

Various wear and corrosion issues were identified after Phase 1 (Figure 4.8), which were recorded for further recommendation (see deliverable D2.4).



a) b) c)

FIGURE 4.8: WEAR AND CORROSION ISSUES OBSERVED DURING P1, A) MARINE FOULING ON LOAD SHACKLE, B) ROTATION PIN FAILURE ON LOAD SHACKLE, C) FOULING AND CORROSION ON SUBSEA CONNECTOR.

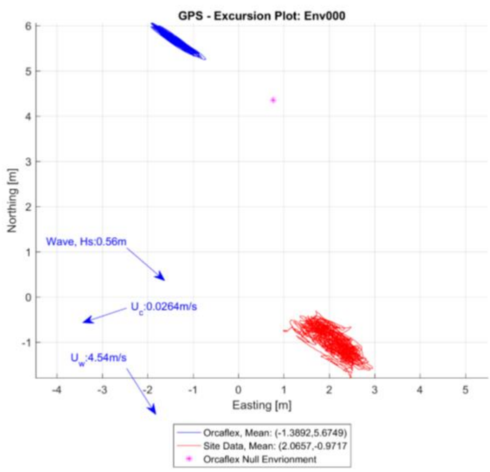
4.1.3 EVALUATION OF SHARED MOORING SYSTEM FOR PHASE 1 AND PHASE 2

Mooring data was collected at the offshore side of the MARMOK device during Phase 1 (without elastomeric tether) and Phase 2 (with elastomeric tether) over a period from 13/12/2016 to 11/12/2017 and 15/11/2018 and 28/01/2019, respectively. The OrcaFlex simulations for P1 are validated from data collected from continuous load monitoring of the shared mooring system during phase 1. A similar validation practice for P2 utilises the shorter record of field data was conducted.

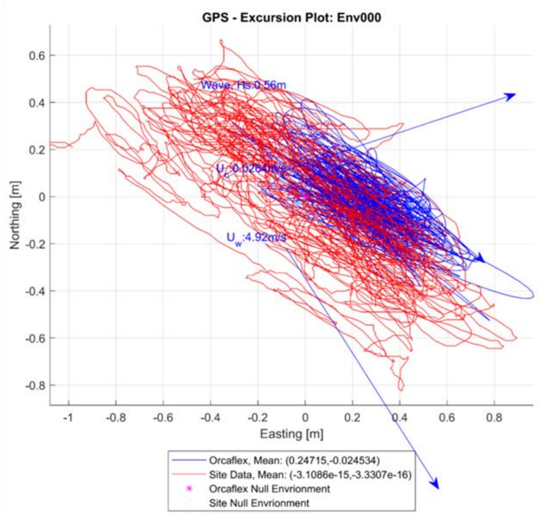
Full details of the analysis can be found in Deliverable 2.2 *Mooring open-sea operating data analysis* and only a summary of the findings is provided here.

The two deployment phases, Phase1 and Phase 2, were initially independently analysed and secondly results were compared for similar environmental conditions.

The comparisons between field data and simulations are completed for phase 1, which have been focused on a medium-sized storm which occurred in June 2017 and also a calm period in May 2017. The latter comparison has been applied to investigate the mean position of MARMOK and pre-tensions. Initial large discrepancies between the measured and simulated positions (Figure 4.9 a, b) have been investigated in detail and significant improvements have been achieved, making critical improvements the simulation model. It has also highlighted the need to quality check the measurement data over longer timescales than what has been considered previously. This has necessitated the creation of a local version of the database and automation scripts. The outcome of the studies has informed a technical note and a journal publication has been submitted.



a)



b)

FIGURE 4.9: COMPARISON OF SIMULATION RESULTS FOR HORIZONTAL MOTION A) PRIOR CALIBRATION, B) AFTER CALIBRATION.

A comparative study of the two deployment phases was conducted using low, medium and extreme environmental conditions with similar, but not identical, environmental conditions. The environmental conditions that occurred during Phase 1 and Phase 2 were at no time the same during the measurement campaign, and hence only similar conditions were identified for a low, medium and extreme sea condition.

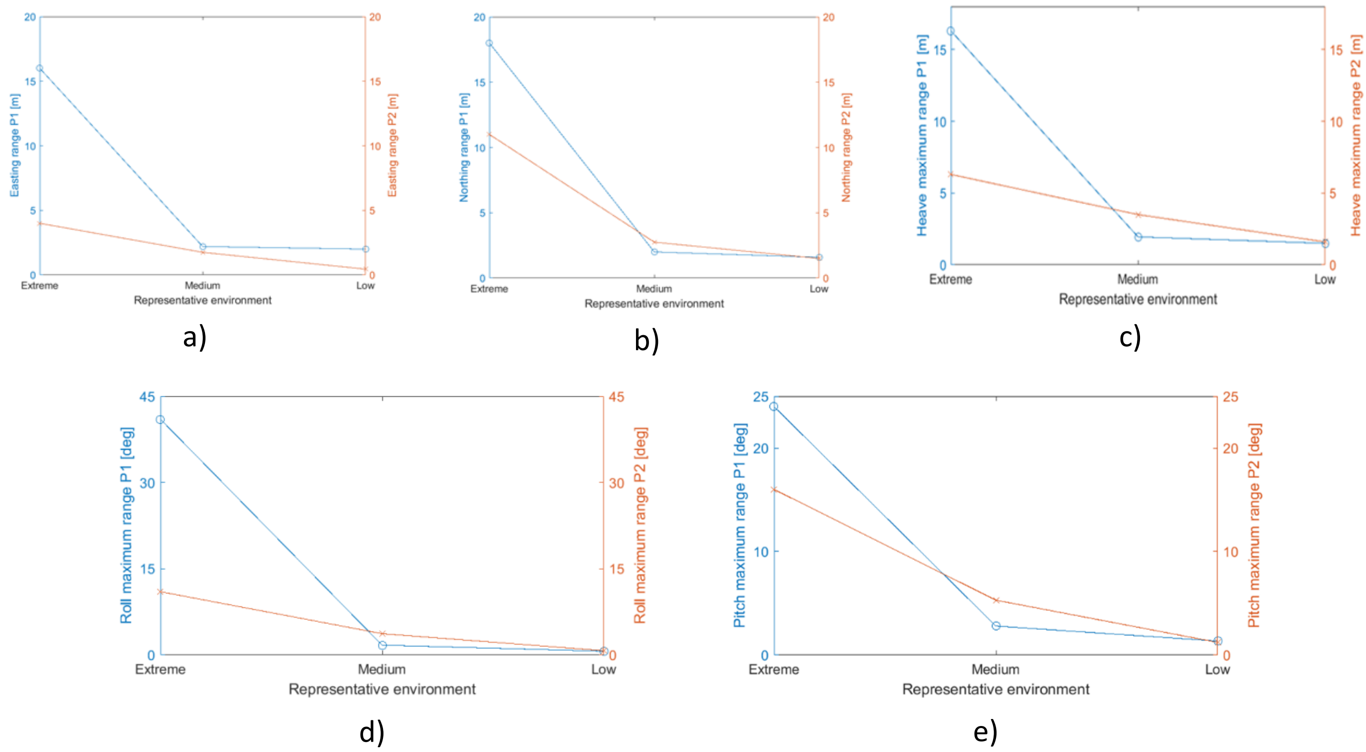


FIGURE 4.10: COMPARISON BETWEEN MOTION BEHAVIOUR OF MARMOK FOR EXTREME CONDITION BETWEEN P1 AND P2; A) HORIZONTAL MOTION (EASTING), B) HORIZONTAL MOTION (WESTING), C) HEAVE, D) ROLL , E) PITCH.

Generally, a reduction in motion (Figure 4.10 a-e) and tension was observed for extreme sea conditions. Hereby, the tension was found to be reduced by ~50% during phase 2, compared to tension measured at similar extreme environmental condition during phase 1 (Figure 4.11 & Figure 4.12).

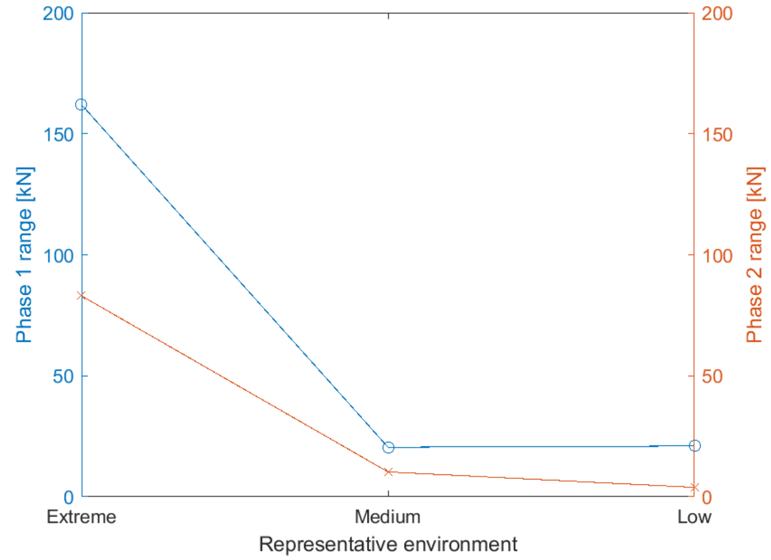


FIGURE 4.11: COMPARISON OF THE RANGE OF TENSION FOR P1 AND P2 DEPLOYMENTS.

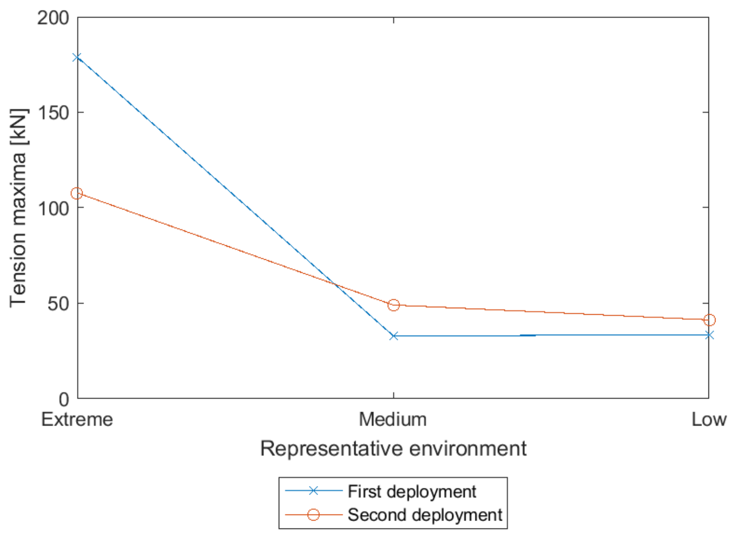


FIGURE 4.12: AVERAGE MAXIMA FOR MARMOK TENSION IN DEPLOYMENT P1 AND P2.

4.2 OVERALL ASSESSMENT

Key findings regarding the above described results are listed below:

DESIGN, MANUFACTURE AND BENCH-TEST OF NOVEL ELASTOMERIC TETHER

- Performance testing using harmonic displacement- and force-controlled tension-tension tests were used to quantify axial stiffness for three different Exeter Tether scale prototypes. The axial stiffness of samples is highly dependent on previous loading, to a much greater degree than conventional synthetic ropes.

- A Thousand Cycle Load Limit test was carried out on the smallest prototype size (estimated MBL = 222kN) and failure occurred after 1087 cycles (1000 cycles at 1-50%MBL and 87 cycles at 1-60%MBL).
- Inspection of the failed sample suggests that failure occurred in proximity to the end of the elastomeric cores. Minor design changes, including providing a chamfer on the end of the exposed cores and modification of the layer topology have since been implemented to mitigate the risk of this occurring in service.
- A full-scale (in terms of diameter) sample was pulled until failure and achieved a break load of 1597.5kN (or 162.9 Tonnes), which is almost 23% higher than the predicted failure load. This is encouraging for the second OPERA deployment as it provides a suitable Factor of Safety based on numerical simulations of the MARMOK-A5 device and Karratu mooring system.
- Deconstruction of the failed sample has highlighted several potential design improvements that will be included in the final OPERA design.

DESIGN AND MANUFACTURE OF CMS

- Peak load calculation for CMS requires fully dynamic cable simulation: using appropriate environmental parameters and informing design load cases for the condition monitoring system;
- Introduction of sacrificial CMS load design limits are essential to protect main station keeping system and WEC device; sacrificial CMS weak points should apply;
- Load shackles were found the optimum choice, maintaining the load path of the existing mooring infrastructure and allowing a direct replacement without the need for a safety line;
- Due to identified design conflicts, it was considered necessary to locate the load monitoring shackles at the mooring system nodes as opposed to the WEC hull; the associated cable route back to the DAQ from the nodes is challenging and various options are considered;
- Full system specification of load monitoring equipment is essential to inform user and deployment contractor; including selected cable routes with support system, J-tube design and signal system;
- The signal output from the load shackles and the data logging requirements for the system needs to be carefully considered;
- Detailed deployment options need to be discussed ahead of deployment with the selected offshore operations contractor;
- Specific consideration needs to be given to Load Shackle pin rotation to avoid measurement errors;
- J-tube design needs to be carefully considered to avoid stress on cable system;

- Corrosion and wear characteristics are undesirable criteria, contributing significantly to accuracy and reliable signal monitoring issues;
- Load shackle location should be carefully considered and if possible to be chosen closest to the WEC device in order to avoid long distance monitoring cable designs.

EVALUATION OF SHARED MOORING SYSTEM FOR PHASE 1 AND PHASE 2

- Identify the potential causes of discrepancies between the numerical model simulation results and field data as result of environmental input constrains and analysis method;
- Validated/calibration of numerical simulation is an essential part in the assessment of the MARMOK device using Karratu mooring system;
- Horizontal motion in Northing and Easting were found to be reduced during phase 2;
- Heave motion was reduced for the extreme environment condition during phase 2, limited effect was observed for low and medium environmental condition;
- Roll motion was reduced for the extreme environment condition during phase 2, limited effect was observed for low and medium environmental condition;
- Pitch motion was reduced for the extreme environment condition during phase 2, limited effect was observed for low and medium environmental condition;
- The tension range was reduced for extreme, medium and low environmental condition during phase 2. The tension was found to be reduced by ~50% during phase 2, compared to tension measured at similar extreme environmental condition during phase 1.

5. POWER TAKE-OFF

5.1 SUMMARY OF RESULTS

The OPERA project also aimed to assess open-sea operating conditions of the power chain components to determine design requirements and improve their power performance, reliability and lifetime, optimise the trade-off between generator performance and capacity factor vs. lifetime and design, manufacture and assess performance in open-sea operation of a new biradial turbine.

This project component had multiple interactions with other activities (i.e. collection and analysis of all relevant operating data, advanced control algorithms, risk management and offshore logistics) to ensure the success of the project and the usefulness of the information generated.

Main results concerning the Power Take-Off for OWC wave energy devices were as follows:

- Aerodynamic design of novel air turbine and specifications of electrical equipment.
- Mechanical design and manufacture of biradial turbine (Deliverable D3.1).
- Turbine-generator set lab testing in variable unidirectional flow (Deliverable D3.2).
- Successful completion of at-sea testing campaign for the turbine-generator set in the Mutriku Wave Power Plant (Jun17-Jul18) and at the BiMEP test site (Oct18-Jun19).
- Real operating conditions at the Mutriku power plant and at the BiMEP test site improved the reliability of the power take-off, collected and shared electrical component operating data, identified failure modes, their causes and tested solutions.
- Biradial turbine exhibits a mean efficiency higher by a factor of 1.55 in comparison with the current Wavegen Wells turbines installed at the Mutriku shoreline Wave Power Plant.
- Biradial turbine and generator set operation was validated in shoreline plant and at the BiMEP test site (TRL5). The capability to produce electric power in a production relevant environment was also demonstrated (MRL6).

The detailed results are presented in four OPERA project deliverables:

- D3.1 Biradial turbine-generator set (Confidential)
- D3.2 Turbine-generator set laboratory tests in variable unidirectional flow (Public)
- D3.3 Turbine and electrical equipment performance and reliability in shoreline OWC wave plant (Public)
- D3.4 Open-sea performance and reliability of OWC turbine and electrical equipment (Public)

5.2 OVERALL ASSESSMENT

5.2.1 BIRADIAL TURBINE PERFORMANCE

The Biradial turbine operated for about two years at the Mutriku Power Plant and at the IDOM MARMOK-A-5 deployed at the BiMEP test site. The main features of this turbine are the high efficiency, the axial-compactness and its capability to easily accommodate a high-speed safety valve. The turbine exhibited a mean efficiency higher by a factor of 1.55 in comparison with the Wells turbines installed at the Mutriku Power Plant.

For the sea trials at the BiMEP test site, the biradial turbine was installed in a floating OWC (the IDOM MARMOK-A-5) characterized by significant increase in the available pressure head in comparison with the Mutriku power plant. The sea trials confirmed the Biradial turbine performance obtained at the Mutriku sea trials.

The generator control laws tuned during the Mutriku sea trials were the same used in the IDOM MARMOK-A-5 buoy, despite the much larger pressure head available.

The installation set up of the dV/dt filter in Phase II of the Mutriku sea trials had a significant impact on the performance of the PTO system. This is particularly evident in the generator time-averaged efficiency. The filter was also used during the BiMEP sea trials. The results obtained with the filter show that the present set up should not be an option for future applications.

The maximum turbine efficiency at Mutriku Phase I was 62%, while for Mutriku Phase II and BiMEP it was 59%. The performance of the Biradial turbine was better in Phase I of the Mutriku tests in comparison with the Mutriku Phase II and BiMEP due to the tighter control of the generator torque laws in Mutriku Phase I.

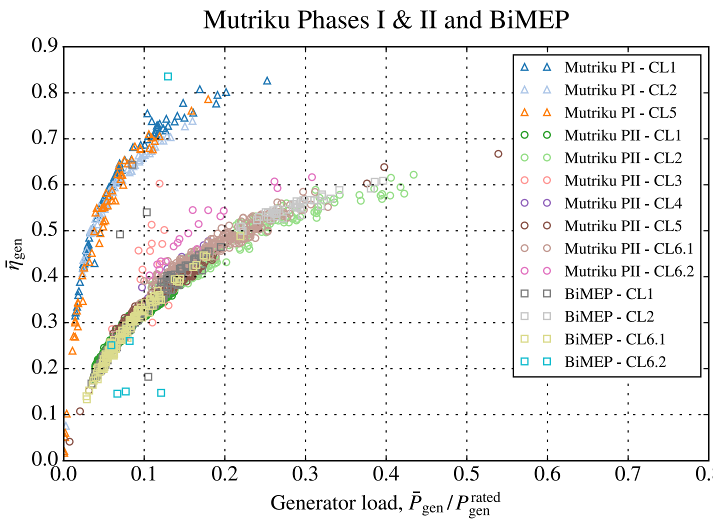


FIGURE 5.1: ELECTRICAL GENERATOR TIME-AVERAGED EFFICIENCY RESULTS FOR MUTRIKU PHASES I & II AND BIMEP. IN THE LEGEND, PI AND PII DENOTES PHASE I AND PHASE II.

5.2.2 LESSONS LEARNED

Drawing from the experience gathered during the design, manufacture testing stages, some lessons learned are worth mentioning:

- The de-risking approach of the OPERA project is a powerful approach that should be followed whenever possible for new concepts.

- Nevertheless, every time the testing environment changes new risks emerge (some unexpected).

- The voltage peaks in Mutriku were well mitigated by the interposition of a dv/dt filter between the frequency converter and the generator and this is a clear lesson learned to be repeated in future installations.
- The tow-out plan was of paramount importance to avoid a serious condition danger for the PTO, keeping the turbine nacelle protected from the effect of the towing generated waves.

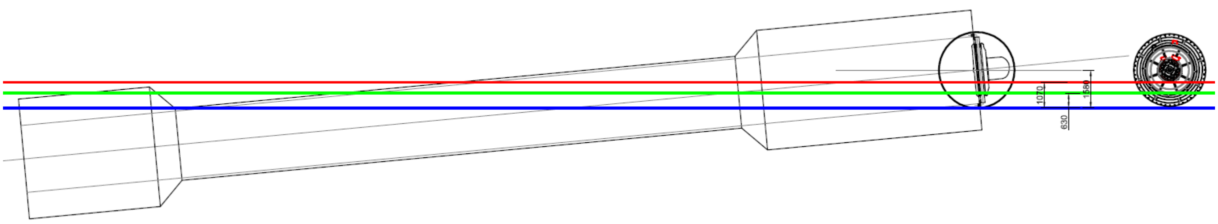


FIGURE 5.2: SUBMERGENCE LIMITATIONS DURING TOW-OUT.

- The circulation of interface drawings for Mutriku shoreline wave power plant and the MARMOK-A-5 baseline configuration were not enough to avoid last minute surprises:
  - In Mutriku the width of the balcony was smaller than expected
  - The mating flange between the turbine and the MARMOK-A had a mismatch in 10% of the holes

- There were issues related with the high-speed stop valve (HSSV) linear actuators, all related with the electrical connections and this topic must be looked into seriously in future projects:
  - The access cover of the turbine was kept open during the Mutriku Tests and this should never have happened. The dirt accumulated inside the nacelle and the easy access to the connections of the HSSV actuators may explain some of the problems encountered.
  - The connectors of the HSSV actuators are fragile and do not endure plugging and unplugging without extreme care. In future installations a particular

attention will be devoted to this topic. Do not rely on terminal boxes as a Plug&Play heaven.
    - Kymaner should have provisioned a spare set ready for installation despite the contrary advice from the actuators' supplier. The delay in the delivery caused a significant disturbance in the BiMEP test program.

- A spare parts policy, together with the reduction of the use of terminal boxes for electrical connections will provide the means to a trouble-free operation of the PTO.

6. ADVANCED CONTROL ALGORITHMS

6.1 SUMMARY OF RESULTS

OPERA has conducted the first implementation at-sea of various promising control algorithms that act throughout the power conversion chain: from the hydrodynamics of wave absorption, to turbine aerodynamic and electrical equipment efficiency. Algorithms have been assessed, compared and improved in terms of risk and failure, power production, reduction of peak loads, other drivers of component fatigue, and overall cost-reduction potential for wave energy.

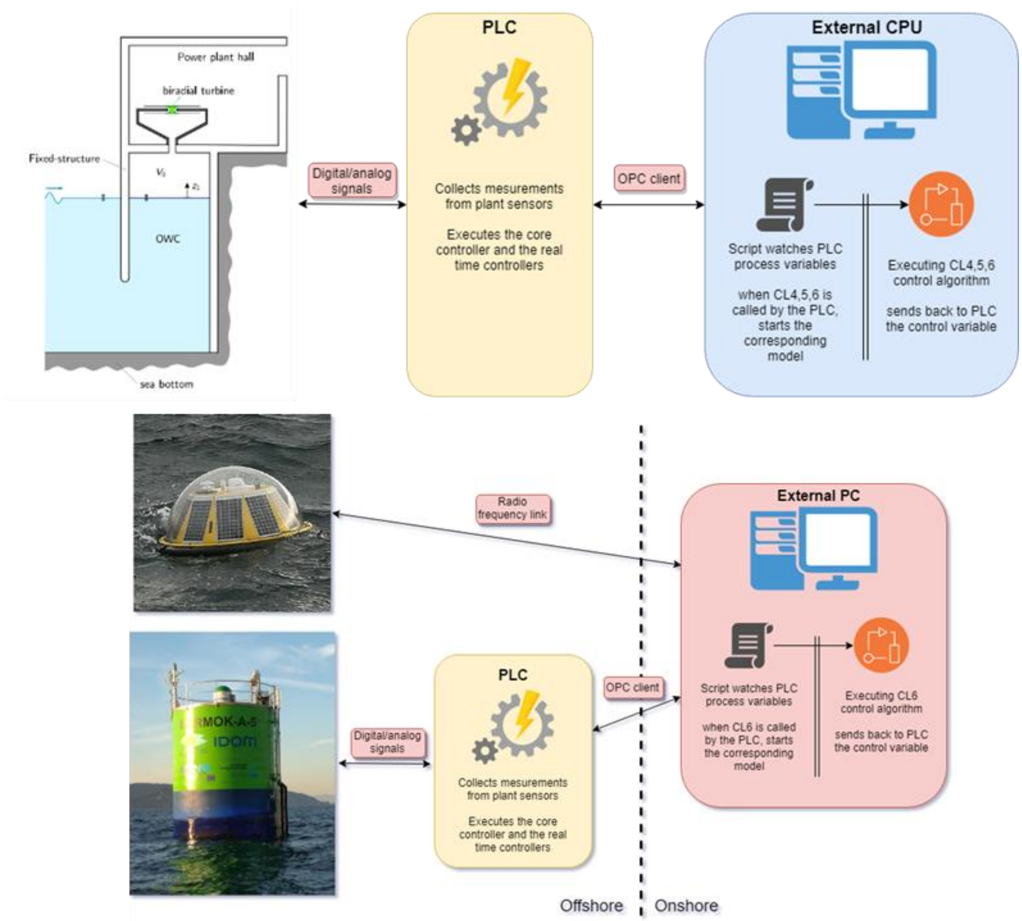


FIGURE 6.1: CONTROL FRAMEWORKS AT BOTH MUTRIKU AND BIMEP TEST SITES

The following list present a summary of main results:

- Customisation of seven control algorithms and instrumentation, and dry power take-off lab tests to prepare open-sea operation (Deliverable D4.1).
- Open-sea testing of six control laws at the Mutriku shoreline wave power plant.

- First implementation at-sea of adaptive and predictive controls. Five adaptive and one predictive controllers have been tested for over one year at the Mutriku Wave Power Plant (Jun17-Jul18).
- Latching controls were ineffective at Mutriku as already anticipated by numerical modelling.
- The best in class predictive (CL6) and adaptive (CL2) controls outperformed CL1 power production by 30% and 20% respectively during the Mutriku testing. However, the predictive control could only be tested in a limited number of sea states.
- Open sea testing of 3 control laws (CL1, CL2 and CL6) to control the PTO installed in the Marmok buoy during 1.5 months.
- Performance results show higher power production from CL2 compared to CL1. The predictive algorithm CL6 performed similarly to the base reference CL1.
- Control laws reliability and power quality have also been assessed. (deliverables D4.2 and D4.3).

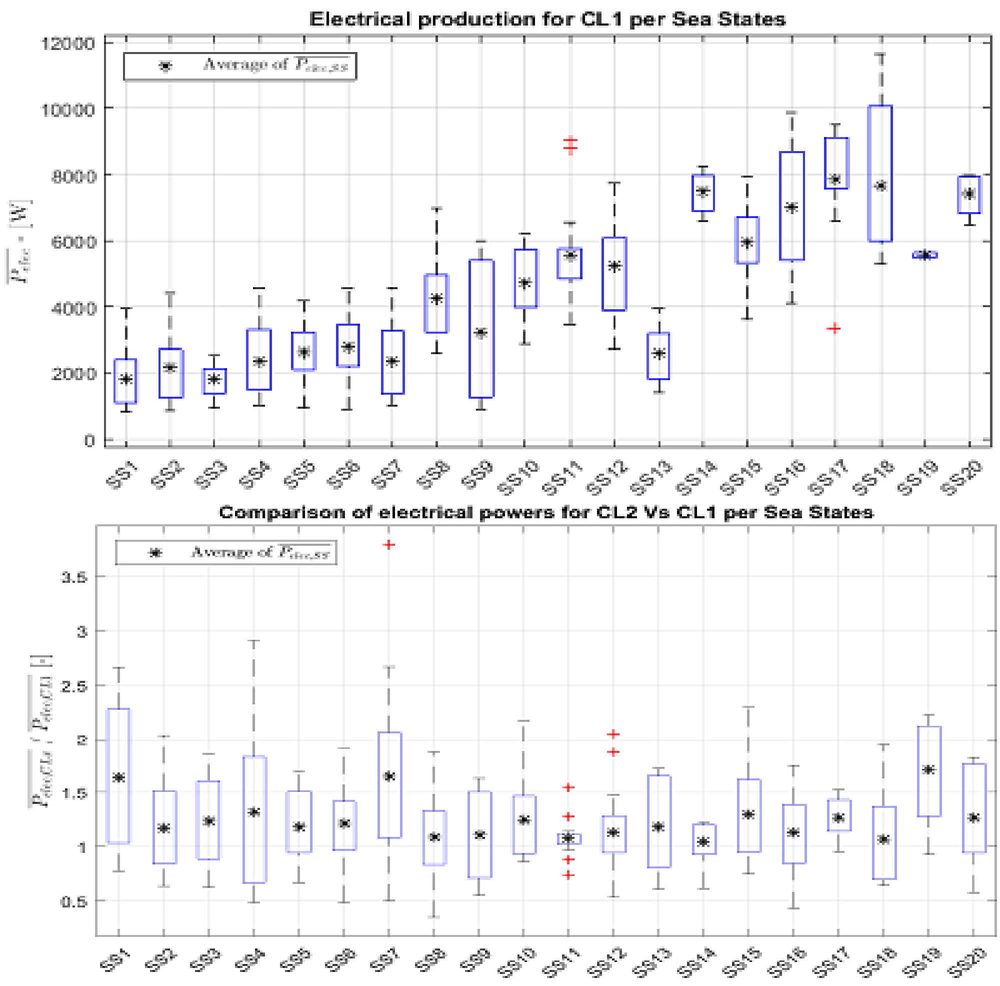


FIGURE 6.2: POWER PRODUCTION OF CL1 AND CL2 RELATIVE TO CL1 IN A WIDE VARIETY OF SEA STATES

TABLE 6.1: OVERALL POWER PERFORMANCE COMPARISON PRODUCED BY EACH CL AT MUTRIKU

CL1	CL2	CL3	CL4	CL5	CL6
1	1.22	0.63	0.85	1.1	1.31

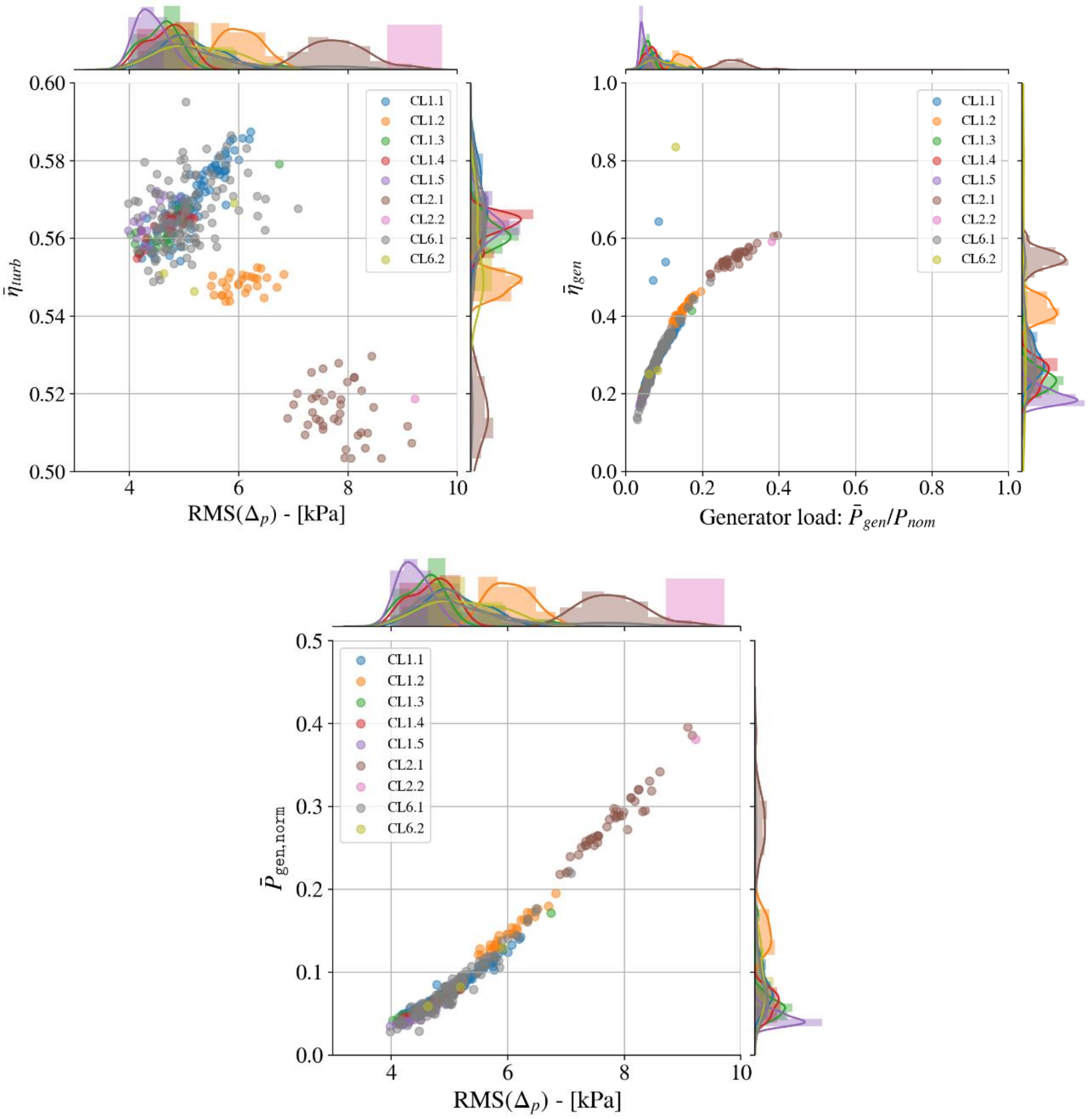


FIGURE 6.3: COMPARISON OF PTO COMPONENTS EFFICIENCIES AND POWER PRODUCTION BY THE CL IN THE MARMOK-A-5

The detailed results are presented in three OPERA project deliverables:

- D4.1 Customisation of OWC control algorithms with numerical models and PTO lab tests (Confidential)
- D4.2 Shoreline OWC wave power plant control algorithms (Public)
- D4.3 Floating OWC control algorithms (Public)

6.2 OVERALL ASSESSMENT

During the one-year testing period of the biradial turbine at Mutriku OWC plant, completed by the sea trials at BiMEP, valuable experience was gained. The recommendations for future projects and the challenges faced along the way are listed below:

- Importance to rely on a consistent data acquisition system and a cloud database to collect and process efficiently the operational data.
- Dispose of a fully customisable control framework in the PLC control environment designed to simplify the deployment and customisation of the control algorithms.
- Testing real-time controllers with the innovative biradial turbine equipped with a series valve used for safety and latching control. For the first time, latching algorithms were operational in an OWC plant although there are best fitted for a floating device. First of its kind predictive control algorithm for OWC control both in the nearshore and the offshore plants using up-wave measurement.
- Rely on accurate numerical models to customise the controllers. The controllers had to be fine-tuned after implementation to correct the model assumptions.
- Generator failure. After a 3 months period in the Mutriku plant, a shortcut damaged the generator. The quality of winding insulation associated with high voltage peaks generated by the electronics seemed to be the source of the failure. After the repair, the generator never failed, thanks to special care while rewinding and the installation of an electrical filter that forced to re-calibrate the low-level control in the power electronics. This affected the accuracy in applying the reference-controlled torque computed by the control algorithms in low operation ranges.
- Reliability on some key operational data. During the tests, drifts in pressure sensors were discovered and had to be cancelled in the post processing which proved the paramount importance of sensor redundancy. The processing approach was also adapted to avoid being penalised by the lack accurate application of the controlled torque.
- In Mutriku the failure of the offline wave elevation sensor reduced the amount of wave resource data and complicated the performance assessment. Delays on the installation of the online wave elevation sensor reduced the test duration of the predictive algorithm.
- The wave elevation measured by the Triaxys buoy at BiMEP was efficiently accessible for the real time predictive control.
- Uncertainty in the power production results inside a same sea state was witnessed in the Mutriku plant
- Intellectual property concerns prevented a full comparison with the algorithms in BiMEP, namely to associate the wave resource with the CL production.

7. APPLICATION AND EXTENSION OF STANDARDS

7.1 SUMMARY OF RESULTS

Application and extension of IEC standards is an important part of the OPERA project. Actually, a Work Package of the project was entirely dedicated to the application and development of the International Electrotechnical Commission (IEC) Technical Specifications (TS) for sea trials of wave energy converters. It aimed at reducing the uncertainties in their application and provide recommendations to the relevant marine technical committee of the IEC (TC114) that will accelerate the establishment of standards based on these technical specifications.

The following IEC TS are studied within OPERA:

- 62600-10 Part 10: Assessment of mooring system for marine energy converters.
- 62600-30 Ed. 1.0 Part 30: Electrical power quality requirements for wave, tidal and other water current energy converters.
- 62600-100 Ed. 1.0 Part 100: Electricity producing wave energy converters -Power performance assessment.
- 62600-101 Ed. 1.0 Part 101: Wave energy resource assessment and characterization.
- 62600-102 Ed. 1.0 Part 102: Wave energy converter power performance assessment at a second location using measured assessment data.

The methodology to comply with those TS was developed at the beginning of the project and reported in deliverable D5.1. This deliverable summarises the technical requirements and suggests how these will be met in the OPERA project testing campaigns or describes variations due to technical limitations or highlights limitations in the specifications which make its application difficult. All recommendations listed in D5.1 were then used to carry OPERA work from other work packages following IEC documents.

At the end of the project, experience from the documented application of TS was documented in Deliverables D5.2, D5.3, D5.4 and D5.5. These deliverables present the work done, feedback from experience gained within the project and suggestions to the IEC technical committees to improve the corresponding TS.

The detailed results are presented in five OPERA project deliverables:

- D5.1 Wave energy measurement methodologies for IEC/TS (Public)
- D5.2 Recommendations to TC114 from real-case applications of wave energy technical specifications (Public)
- D5.3 Uncertainty in wave energy converter power performance assessment (Public)
- D5.4 Extending wave energy converter power quality dataset (Public)
- D5.5 Fault ride-through demonstrator (Public)

7.2 OVERALL ASSESSMENT

The main output from the real-case application of IEC Specifications are recommendation to the IEC technical committee aimed at accelerating the development of the relevant Technical Specification (TS). This was documented in the deliverables and a summary of key findings is provided below.

62600-100 ED. 1.0 PART 100: ELECTRICITY PRODUCING WAVE ENERGY CONVERTERS - POWER PERFORMANCE ASSESSMENT

Wave measurement sub-section

- More specific information on the wave measurement requirements is need. Recommendations are difficult to fulfil and may not be justified.
- Measurement duration does not match well established standards used with measurement buoys
- Consider giving conditions for which a numerical model to correct on wave interference with measurement buoy is not required.
- Consider accepting use data provided by commercial buoys which may be calculated using proprietary undisclosed algorithms but have published documentation attesting the quality of their data. This may include external quality certification when available.
- Recommend limiting the use of Acoustic Doppler Current Profiler (ADCP) to location of 30m depth maximum. Manufacturers sometime increase this value to up to 100m. but experience shows that data quality reduces with increasing water depth beyond 30m.

Electrical power output measurement sub-section

- WEC power output measurement does not present significant difficulties, however it is recommended to provide more information on the measurement of reactive power which has the potential to significantly influence the WEC impact on the grid.
- Some sensors used adhered to different standards from those recommended in TS100. This should be discussed in the TS.
- Some variations might be necessary for an early stage developer using pre-existing on onshore infrastructure. There may be limitations to what the developer can do to the landing point of the cable i.e. in the installation of dump load.

Sea state characterisation sub-section

- Work carried out in OPERA to identify additional sea state characteristics that impact the performance of WECs did not lead into sufficient improvements. More work is required to develop TS100 but, as these characteristics are WEC specific, this work should be led by developers and they should feedback to TC114.

Uncertainty analysis

- There is no section dedicated on uncertainty analysis in TS100, therefore a review of the document structure on uncertainty of power performance results and energy yield is recommended.

62600-101 ED. 1.0 PART 101: WAVE ENERGY RESOURCE ASSESSMENT AND CHARACTERIZATION.

- For the shoreline device tested, it was found that the 0.5 m resolution in significant wave height (Hs) is insufficient at low wave heights. This is because incoming wave energy increase manifold between the low Hs side and high Hs side of the same cell. Despite the low hourly energy production, due to their high frequency of occurrence these cells contribute significantly to annual energy production. Reducing bias there by increasing the resolution in wave height may thus be beneficial for more accurate yield prediction.

62600-102 ED. 1.0 PART 102: WAVE ENERGY CONVERTER POWER PERFORMANCE ASSESSMENT AT A SECOND LOCATION USING MEASURED ASSESSMENT DATA.

- Guidance should be provided on how to determine if a site is suited to a WEC's characteristics, i.e. advice on differences acceptable for location 2 to be considered similar to location 1.
- Consideration should be made on the applicability of this TS to early stage devices, when performance data is limited or changes are made to the WEC.
- The TS should consider in more detail on-shore devices

62600-30 ED. 1.0 PART 30: ELECTRICAL POWER QUALITY REQUIREMENTS FOR WAVE, TIDAL AND OTHER WATER CURRENT ENERGY CONVERTERS.

- More clarity is required for the wave resource classification for wave energy devices, which was described more in detail in the TS 100 analysis.
- Sample reporting in the Annex section of the TS30 focuses solely on the Flicker reporting. An expanded template which includes all aspects of the TS30 would be useful when generating results and reporting following data analysis.
- The costs associated with implementing the TS30 for the required IEC documents, equipment, data storage, and manpower may not be suitable for early stage or prototype development lead by small companies. If possible, guidance for lower cost power quality monitoring during prototype development should be included in TS30.

62600-10 PART 10: ASSESSMENT OF MOORING SYSTEM FOR MARINE ENERGY CONVERTERS

- Different safety factors should be considered based on risk criteria, where higher uncertainties should demand higher safety factors. Therefore, if novel mooring components and configurations are used, larger safety factor must be applied to ensure structural integrity due to increased risks;
- Fully dynamic simulations need to be performed to assess coupled behaviour between condition (mooring) monitoring system (CMS) and moored system during the design phase;
- For appropriate risk mitigation of novel components, it is recommended that numerous component and performance test campaigns must be run;
- CMS designs need to include enhancement of components to reduce loss of data due to corrosion and marine fouling;
- The CMS should at no time compromise the main mooring configuration and sacrificial weak points should be designed into the CMS;
- Fatigue factors must be assessed, and cable clashing and minimum bending radius identified for the CMS and auxiliary power for the DAQ.
- Marine growth has a significant impact and it is recommended that this is appropriately incorporated in the modelling process particularly for long-term deployments for the longer-term analysis.
- Simulation accuracy is sensitive to simulation length, occurring of peak wave crest, variation in number of wavelets, but not to time step or element density;
- An appropriate understanding of the response of the WEC, mooring line tension, number of elements, and simulation length is required before committing to a peak design tension.

8. LIFETIME OFFSHORE LOGISTICS

8.1 SUMMARY OF RESULTS

In offshore wind OPEX is roughly a third of cost of energy, of which offshore operations typically is the major contributor. Offshore operations also have a major impact on Life Cycle CO2 emissions. Although similar importance is expected in wave energy farms, the lack open-sea experience shared across the sector introduces major uncertainty on expected OPEX in wave farms, which introduces a costly business risk in wave energy projects. Documenting and sharing information on offshore operations in OPERA is a major opportunity to achieve decisive progress on this front.

The OPERA project focused on offshore logistics of the floating OWC with a goal to reduce the uncertainty on, and optimise, the risk and cost of offshore operations.

The summary of main results is provided below:

- Detailed characterisation of the installation, operation, maintenance and decommissioning of the device (Deliverable D6.1).
- Development of an operational model for the estimation of the OPEX from data collected under real operating conditions (Deliverable D6.2).
- Perform, improve and document required offshore operations during the open-sea testing period.
- Dissemination of lessons learnt to minimise risk and cost of offshore operations for wave energy (outcomes of 1^{st} industrial workshop OPERA Technical Note [1]).
- Calibration of OPEX cost model based on the analysis of operating data gathered from offshore operations carried out.
- Monitoring of safe operations and logistics: O&M planned activities at the WEC device and the changeover, deployment of a new online pressure sensor at Mutriku or the deployment of the elastomeric mooring tethers at BiMEP.
- Identified and documented improvements in offshore methods.
- Produced a first set of recommendations to minimize risk and costs of offshore operations.

The detailed results are presented in three OPERA project deliverables:

- D6.1 Requirements for offshore operations for wave energy converters (Confidential)
- D6.2 Operational model for offshore operation for wave energy converters (Public)
- D6.3 Recommendations and guidelines for offshore operations for wave energy converters (Public)

8.2 OVERALL ASSESSMENT

During the OPERA project more than 90 offshore operations have been performed in three years. In 2018 more than 50% (43) of the operations were performed, almost 20 in 2017 and a similar number in the first half of 2019.

The following general conclusions have been obtained:

- There is not a direct relation between the three months with the best weather accessibility (June, July, August) and the three months with highest activity (April, June and November). Only June is correlated. This is because many activities during the project lifetime have been related with the commissioning of the device and not determined by the O&M plan which would take into account the weather conditions in the different seasons of the year.
- In order to define a more detailed O&M time schedule, more years of experience ought to be accumulated.
- Out of five different groups of operations included in OPEX model, the PTO is the group accounting for the highest number of operations.
- The three years' experience of offshore operations has helped to establish a practical criterion to define a suitable sea state to carry out the different types of operations. The experience has shown that not only is the maximum significant wave height (H_s) the parameter to consider, but also wind conditions. It is worth noting that short wave peak periods (T_p) are directly related with wind conditions in the area.
- PTO and control activities required a lower H_s and higher T_p on average. Essentially this is because the work inside the device requires more restrictive conditions. It is suggested as future work to perform a combined analysis of H_s and T_p.
- No injuries have been reported along the offshore operations in the OPERA project. Therefore, the main principle of SAFETY FIRST have been achieved.
- On the top of this, no loss of any assets (i.e. WEC, mooring tethers or biradial turbine) have occurred during the offshore operations.

COST REDUCTION FOR OFFSHORE OPERATIONS

- Real operations have been analysed with a view to reducing logistic time and associated equipment requirements thus resulting in a more cost-effective and risk-free solution that can be applied to other floating wave energy converters.
- The greater knowledge of component performance has been reflected in the final O&M model by means of a lower uncertainty level or a longer mean time between failures. Open-sea experience has permitted a better estimation of 11 operational parameters. They translated into a 4% availability increase and a 20% cost reduction compared with the initial version of the O&M model at the beginning of the project.
- The limited open-sea experience (three years) does not comprise the full diversity of lifetime operations and necessary resources to carry them out. Nonetheless, it

contributes to improve the knowledge base for a better planning of future offshore operations.

- The experience from the offshore operations performed during OPERA points out that the availability of the device can be increased, and the operation costs reduced by grouping compatible operations. The typical operations that could be grouped are inspections since they can be planned (i.e. preventive maintenance) and focus on activities whose duration can be accurately quantified.
- Despite three years is a relative short time compared with a 25-year project lifetime, the information collected has been very useful for tuning the O&M model. It reflects a realistic percentage of failures per main group of operations.
- For a real achievement of a relevant cost reduction in the offshore operations, and hence in the LCOE of the wave energy devices, it is paramount to promote the transparency in the logistics cost, especially at the base harbours, which has not been the case in all the marine operations along the OPERA project. This transparency could be achieved if real competition in the service providers is facilitated and promoted. In this sense, it is recommended to make use of storage or manufacturing areas operated by private stakeholders better than from the public sector.
- In terms of the type of contracts to negotiate with the marine contractors, at the end of the project it would be recommended to agree on a lump sum contract instead of open books. The open books type of contract is recommended at the beginning of the project if the activity to be carried out has some novelty.
- With regards to the suppliers or manufacturers of critical equipment or components for the offshore operation, it is recommended to choose companies in the area or region of the operation. This facilitates the communication, management and potentially reduces over costs (shipment and taxes).

HEALTH AND SAFETY

- Current standards and regulations for the offshore industry in regard to offshore installation and O&M operations have been analysed, checking them against those applied for the installation of the OPERA OWC at the BiMEP testing site.
- The applicability of the existing guidelines will be reviewed, particularly considering specific H&S requirements for renewables. For reference, a full list of operations as well as the regulations and standards considered during the installation process at BiMEP can be found in Deliverable 6.1.

LESSONS LEARNED FROM OFFSHORE PARTICIPANTS

- Lessons learned from offshore participants have been documented. They come from two workshops hosted during the project lifetime as well as from partners' exchange of practical experiences.

- Practical guidance is gathered for the future planning of operations, data acquisition, meteorological conditions, grouping of operations, O&M recommendations, mooring and costs.
- Detailed planning of operations is paramount for avoiding any risks and uncertainties at sea, along the different phases of the offshore operations.
    - During the Planning Phase of the operations, be sure that all the involved parties are informed and check twice.
    - During the Engineering activities: identify clearly the riskier and/or novel activities in the plan. A focus in the contingency plans are recommend.
    - Preparation activities: perform tests/training before onshore.
    - Execution: small delays can lead to a big delay, so it is important to identify the critical path/activity.
- Offshore operations have to be considered as a specific project and hence with its specific engineering activities. Some good practices for performing these engineering activities are proved below:
    - Follow the Technical Notes/Specifications from the Original Equipment Manufacturer (OEM).
    - Plan the appropriate means/equipment for handling/loading the different components and equipment.
    - Be sure that the OEM and/or is informed and approves the installation procedure
    - Prepare a comprehensive logging to document the operation
    - Explore the spot market for the vessel (professional agent/logistic company) and aggregate offshore operations.
- The marine operations and O&M have to be considered in the design of the ocean energy device (e.g. available resources in the area, accessibility for maintenance).
- Document everything. Changes to the prototype should be logged very carefully.
- Allow for mistakes since mistakes most certainly will happen and have sufficient resources (technical and financial) to deal with problems

9. RISK MANAGEMENT, COST OF ENERGY AND IMPACTS

9.1 SUMMARY OF RESULTS

The OPERA project gathered all the information from the previous activities and analysed its influence on economics and risk assessment, in order to develop guidance and recommendations from the project's unique offshore experience.

Significant results and main achievements are as summarized follows:

- Protocol to analyse and manage technical risk and uncertainty arising from the project innovations and activities.
- Global model of LCOE, LCA and SCOE for wave energy that integrates operating data.
- Continual technical risk identification and mitigation during the open-sea testing phase of the project using the protocol developed in OPERA to track uncertainty and risk.
- Economic, life-cycle and social impact of innovations and technologies tested in the project.
- Assessment of sensitivity and long-term cost reduction pathways due to learning and economies of volume.
- Reduction of uncertainty in OPEX calculations using open-sea data of offshore operations.
- Final project assessment and recommendations.

The detailed results are presented in five OPERA project deliverables:

- D7.1 Initial risk and failure data collection protocol for H2020-OPERA project (Confidential)
- D7.2 Operating data input for models of levelised and society cost and life cycle assessment for wave energy (Public)
- D7.3 Tracking metrics for wave energy technology performance (Public)
- D7.4 Risk and uncertainty assessment and management for wave energy (Confidential)
- D7.5 H2020-OPERA final project assessment and recommendations (Public)

9.2 OVERALL ASSESSMENT

This section presents updated economic, environmental and socio-economic impact results, obtained through an analysis of the Idom-Oceantec Wave Energy Converter (WEC) tested during OPERA. Initial results were presented in Deliverable D7.3 which was finalised whilst the Idom-Oceantec WEC was still operating. Therefore, this deliverable updates the global economic assessment in light of the final learnings gained during OPERA's operational phase.

9.2.1 OPERA OPEN SEA EXPERIENCE

This section compares the OPEX model inputs estimated at the beginning of the project (initial OPERA experience) with those complied at the end of the project (final OPERA experience) based on the OPERA operational phases. Experience of offshore operations, gained through two separate WEC deployments and retrievals, has developed the knowledge base on WEC project at sea operations in a number of capacities. For example, in one area it has helped in establishing a criterion to define an adequate sea state to carry out different types of operation. The experience has shown that not only should significant wave height (H_s) be considered when planning offshore operations, but that wind, which is directly related with short peak periods (T_p), should also be considered.

In the OPEX model developed through OPERA, 16 distinct offshore operations were defined and gathered in five groups, namely mooring, structure, umbilical, control and PTO. Based on the real sea experience of working with the Idom-Oceantec WEC, the following H_S and T_P thresholds were recommended for all the operations grouped in the mooring, structure and umbilical groups; H_s = 1.3 m and T_p = 9 s, i.e. work can only be undertaken if the sea state's H_s is less than 1.3 m and the T_p is greater than 9 s. In the case of operations that have to be performed inside the WEC, the wave height and period are recommend being H_S = 0.8 m and T_p = 10.8 s respectively.

The knowledge of component performance has been reflected in the model with the uncertainty level and mean time between failures. Open-sea experience has permitted a better estimate of values associated with of 11 components. Figure 9.1 compares OPEX model inputs based on the initial OPERA experience with inputs based on final OPERA experience.

		Uncertainty level		Mean time between failures 1/years	
		After	Before	After	Before
Structure - Structural	Structural component	1	1	0,04	0,04
Structure - Structural	Inspection	1	2	0,5	1
Structure - Corrosion	All the structure	1	3	0,36	0,36
Mooring - Connector	Connector or polyester rope	1	1	1	0,4
Mooring - Buoys -Wire break	Mooring wear out	2	4	0,16	0,16
Mooring -Mechanical Failure	Mooring mechanic failure	2	4	0,0045	0,0045
PTO - Power Electronics	Power electronics	1	3	0,2	0,54
PTO - Generator	Generator, Mechanical components, Bearings	2	4	0,2	0,52
PTO - Turbine	Turbine, Blade	1	1	0,2	0,2
PTO - Valves	Valves	2	3	0,2	0,2
PTO - Global	Turbine / Back to back / Generator / bilge system	1	2	1,9	1,9
Electric - Umbilical	Umbilical degradation inspection	2	2	1	0,6
Electric - Umbilical	Cable	4	4	0,008	0,008
Electric - Umbilical	Replace element	2	3	0,2	0,2
CONTROL- Inspection	Inspection	1	2	2	1
CONTROL - Damage	Control & sensors / Protection function. Electric device problems	4	4	0,05	0,05

FIGURE 9.1: COMPARISON OF OPEX MODEL INPUTS BASED ON INITIAL OPERA EXPERIENCE WITH THOSE BASED ON FINAL OPERA EXPERIENCE.

It is understood that not all failures or WEC project operations were observed during the two deployment windows that were achieved during OPERA. Nonetheless, the experience gained through the real sea operation contributes to expanding the knowledge base for a better definition of future offshore operations. For example, knowledge has been developed on which ship to select for installation and decommissioning operations and how this can reduce operation times. For example, an operation that might take 4-5 days to complete if using a smaller vessel might only take 2 days to complete with a larger specialised vessel. The use of bigger ships reduces the uncertainty level and the weather window waiting time but increases the vessel charter rate. The final costs of these two distinct approaches are quite similar. Therefore, it might be recommended to use bigger ships as far as possible to improve the operation quality, provided the total costs are not penalized.

The experience gained from the real sea operations carried out during the OPERA project emphasise that device availability can be increased and operation costs reduced by grouping compatible operations. The typical operations that could be grouped are the inspections, since they can be planned (i.e. preventive maintenance) and the duration of their activities can be accurately quantified.

9.2.2 GLOBAL ECONOMIC ASSESSMENT

The global-economic model analysed the performance of the Idom-Oceantec WEC from three perspectives: economic, social and environmental. The model was used to investigate three scenario groups namely: technology stage (*Bench case* and *With innovation*), location (BiMEP and EMEC) and the number of devices deployed in an array (Single device - 250 kW, array 1 - 10 MW and array 2 - 18MW).

A description of the OPERA global economic model was presented in Deliverable D7.2, while results from the OPERA model are shown in Deliverable D7.3. The results presented in D7.3 were generated using the OPEX model that was calibrated with initial OPERA experience data. This deliverable updates the global economic model results in light of the final OPERA experience gained during the operational phases of the project.

9.2.2.1 ECONOMIC MODULE

This section presents updates of the intermediate (energy generation and expenditures) and final economic metrics (LCOE) presented in D7.3.

ENERGY GENERATION

- **Availability**

Table 9.1 lists the availability values calculated by the OPEX model for each of the number of devices deployed scenarios and both locations: those based on the initial OPERA experience and those based on final OPERA experience.

TABLE 9.1: AVAILABILITY VALUES CALCULATED BY THE OPEX MODEL BASED ON INITIAL AND FINAL OPERA EXPERIENCE.

Scenarios	Initial OPERA experience		Final OPERA experience	
	EMEC	BiMEP	EMEC	BiMEP
Single device (250 kW)	75%	88%	92%	96%
Array 1 (10 MW)	79%	90%	94%	96%
Array 2 (18 MW)	79%	90%	94%	96%

Availability values generated by the OPEX model were higher at BiMEP than EMEC, regardless of the data type; based on initial or final OPERA experience. However, the difference in availability between the two sites was observed to be smaller when using the data based in final OPERA experience.

When compared to the initial OPERA experience OPEX model, the EMEC availability values generated using the final OPERA experience were at around 20% greater whilst the BiMEP values increased by roughly 7%.

- **Annual Energy Production**

The change in availability values directly influences Annual Energy Production (AEP). AEP is calculated by multiplying the availability figures by the ideal AEP value. Ideal AEP values for both sites were provided by Idom-Oceantec and were presented on D7.3. The AEP values calculated for the *With Innovation* scenario (the scenario in which the cost reducing innovations were installed on the Idom-Oceantec WEC) at both deployment locations, based on the initial and final OPERA experience OPEX values are presented in Figure 9.2.

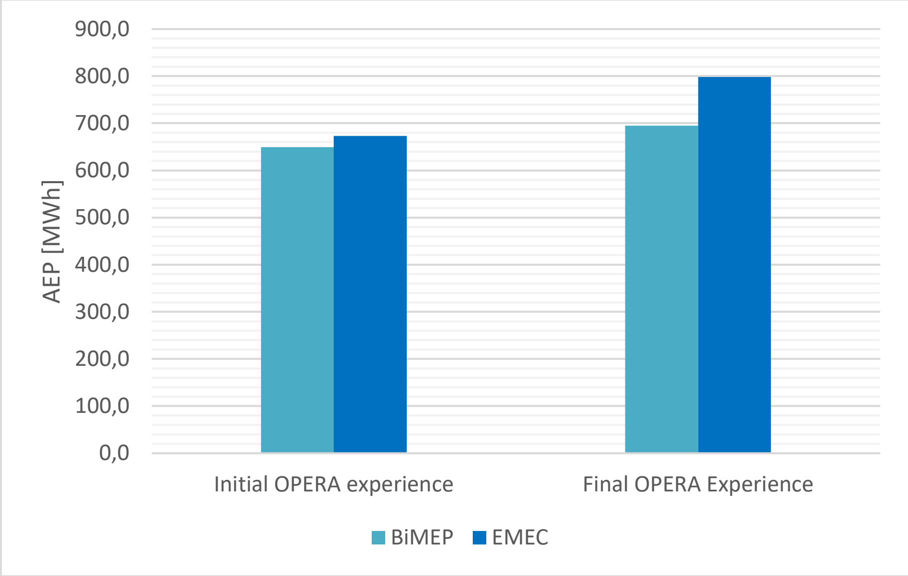


FIGURE 9.2: ANNUAL ENERGY PRODUCTION OF THE WITH INNOVATION SCENARIO, AT BOTH DEPLOYMENT SITES, CALCULATED USING BOTH INITIAL AND FINAL OPERA EXPERIENCE DATA IN THE OPEX MODEL.

Based on the final OPERA experience, the difference between BiMEP and EMEC AEP was calculated to be 18% by the global economic model's economic module. When using the initial OPERA experience data, due to the different availability figures, the difference between BiMEP and EMEC AEP was 6%.

- **Capacity Factor**

Table 9.2 presents the Idom-Oceantec WEC's Capacity Factor (CF) figures.

TABLE 9.2: CAPACITY FACTOR OF THE BENCH CASE AND WITH INNOVATION SCENARIOS, AT BOTH DEPLOYMENT SITES, CALCULATED USING BOTH INITIAL AND FINAL OPERA EXPERIENCE DATA IN THE OPEX MODEL.

Location	Initial OPERA experience		Final OPERA experience	
	Bench case	With Innovation	Bench case	With Innovation
BiMEP	16%	31%	17%	33%
EMEC	17%	33%	21%	39%

When compared with initial OPERA experience, the difference between CF values calculated by the global economic model for the *Bench Case* and *With Innovation* scenarios has increased. This is a result of the difference in availability calculated by the OPEX model, as explained above.

- **Discussion**

The final OPERA experience has expanded the knowledge of component performance, permitting a more reliable estimate of energy capture values (see Figure 9.2). The experience has demonstrated better than previously estimated availability and consequently greater than previously estimated AEP and CF.

EXPENDITURES

- **CAPEX and Decommissioning**

A detailed non-discounted CAPEX breakdown for the array 2 (*With Innovation* scenario) when deployed at EMEC can be seen in Figure 9.3. The most significant contribution comes from the WEC structure, PTO and installation costs, which represent around two thirds of the total CAPEX. These are followed by decommissioning, electrical, fees and mooring costs. Plots of each of the scenarios are presented in D7.3.

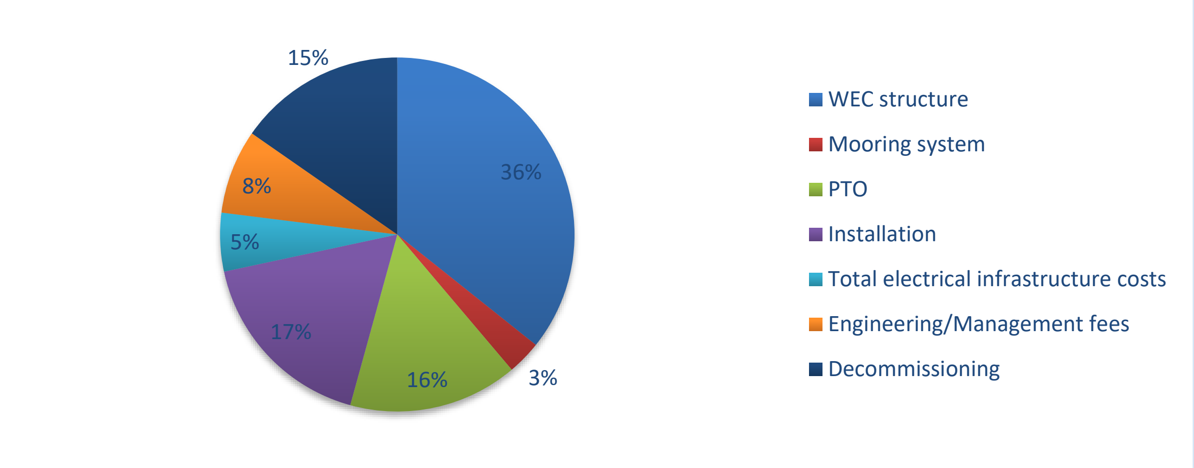


FIGURE 9.3: CAPEX BREAKDOWN OF ARRAY 2 FOR WITH INNOVATION SCENARIO WHEN DEPLOYED AT EMEC.

- **OPEX**

The final OPERA experience has expanded the knowledge of component performance. The expanded knowledge of component performance has resulted in OPEX reductions of around 20% when compared with the initial OPERA experience.

Figure 9.4 presents the total non-discounted expenditures for the Array 2, *With Innovation* scenario.

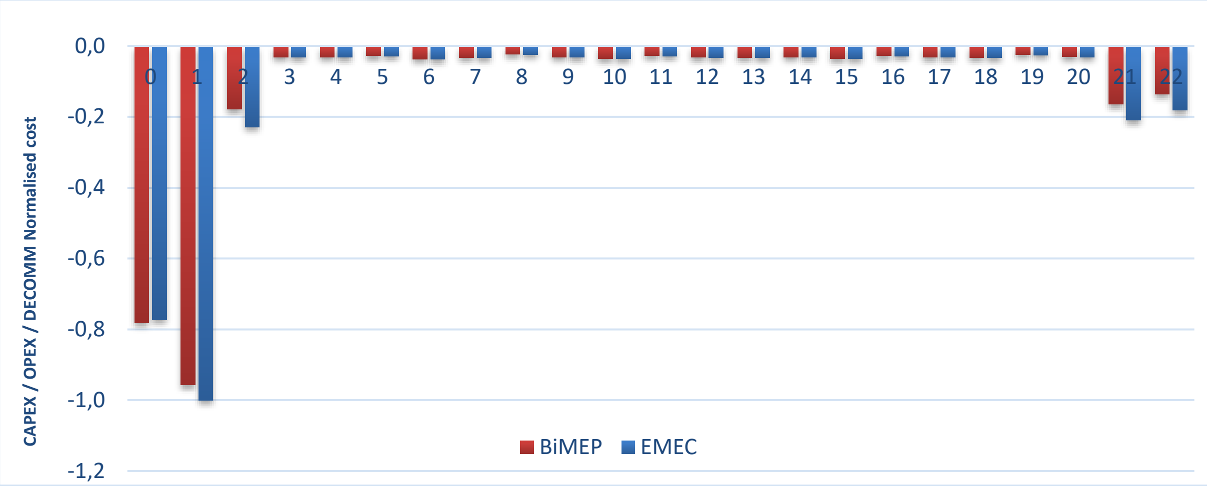


FIGURE 9.4: NON-DISCOUNTED ARRAY 2 PROJECT COSTS FOR DEPLOYMENTS AT BOTH BIMEP AND EMEC.

LEVELISED COST OF ENERGY (LCOE)

- **Bench Case vs With Innovation**

The Levelised Cost of Energy (LCOE) results for the array cases (array 1 and 2) achieve the proposal's headline LCOE reduction target of 50% when transitioning from the *Bench Case* to the *With Innovation* scenario. Thanks to the improvements brought about by the OPERA cost reducing innovations (novel bi-radial turbine, advanced control strategies and shared mooring configuration) the *With Innovations* scenario's LCOE's is reduced by 52 – 56 % when compared to the *Bench Case* LCOE, for the array cases. Figure 9.5 shows the LCOE reduction for the array of 18MW deployed at BiMEP.

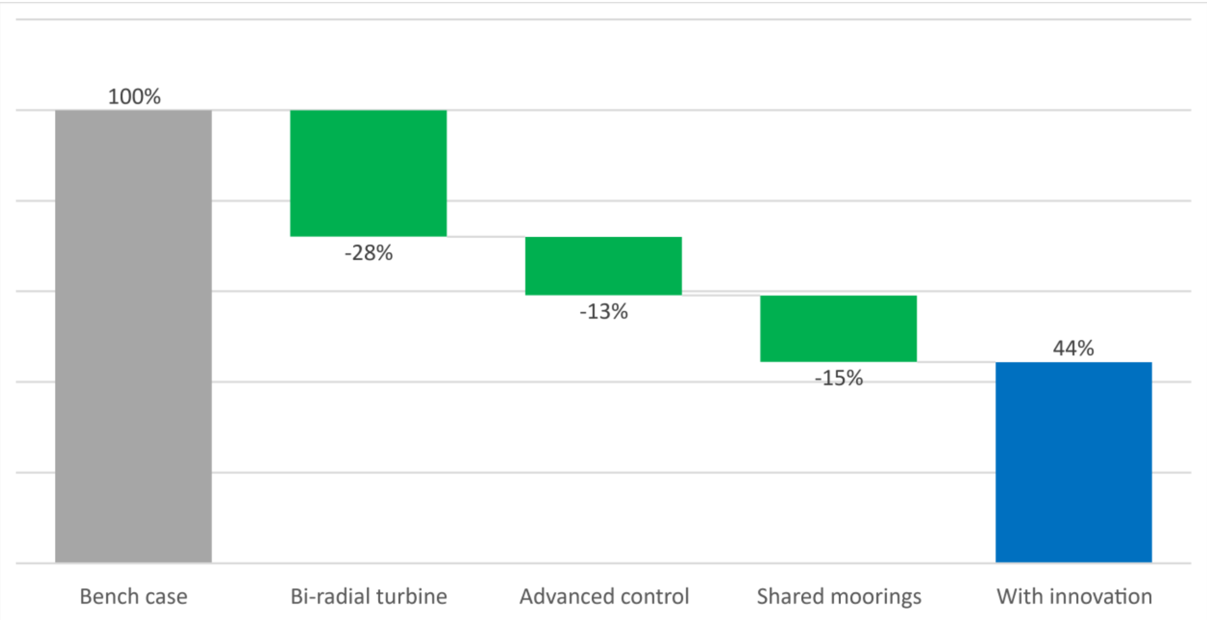


FIGURE 9.5: NORMALISED LCOE IMPACTS OF EACH OPERA COST REDUCING INNOVATIONS.

Results of the LCOE modelling are aligned with the initial objectives and show that further LCOE reductions could be achieved if the assumption of the increased reliability is accomplished. It was proved during the OPERA experience that the elastomeric mooring tether can contribute to the improvement of structural reliability. The improvement on reliability also has an impact on the capital cost of the WEC structure due to a reduction of reduction of peak loads. The project reports a reduction on the mooring lines' extreme loads of 50%. However, at this stage of the project the impact of this innovation on LCOE was disregarded as there are too many layers of uncertainty to estimate how CAPEX reduces with the new mooring, but it has shown the potential to reduce the cost of the floater, mooring system itself and ancillary system, such as mooring connectors.

- **Initial vs final OPERA operational experience**

Figure 9.6 presents the LCOE reductions for the *With Innovation* scenario, due to the transfer from initial to final OPERA experience. Values are normalised with the LCOE calculated using the initial OPEX experience.

As seen throughout the energy generation section, LCOE was observed to reduce when calculated using the OPEX values based on the final OPERA experience i.e. OPEX was observed during the operational phases to be lower than initially expected. LCOE reduced by 8% for devices deployed BiMEP and 18% for devices deployed at EMEC.

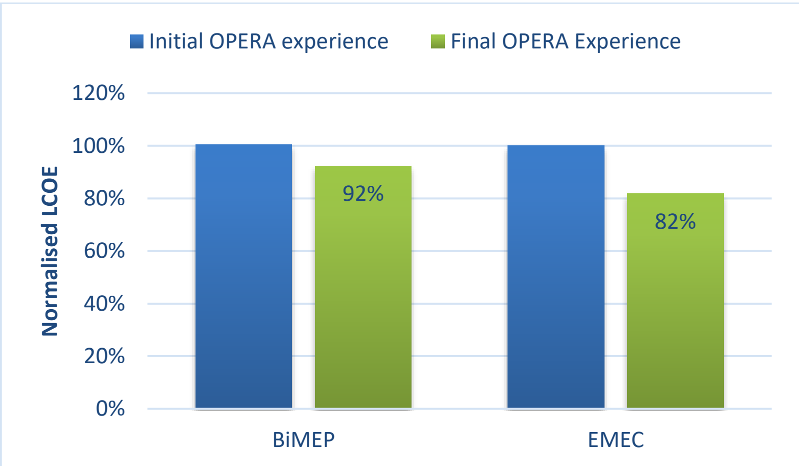


FIGURE 9.6: NORMALISED LCOE FOR BOTH DEPLOYMENT LOCATIONS BASED ON WITH INNOVATION ARRAY SCENARIOES. COMPARING VALUES CALCUALTED WITH THE INITIAL AND FNAL OPERA EXPERIENCE.

- **BiMEP vs EMEC**

Figure 9.7 shows the normalised LCOE calculated for the two deployment locations - *With Innovations* array scenarios. When using the final OPERA experience data in the OPEX model, LCOE was observed to be lower at EMEC when compared with BiMEP. This is different from what was observed when using the initial OPERA experience data and is due to how the differences in data impact the availability and OPEX figures calculated by the OPEX model.

The LCOE figures presented in Figure 9.7 are normalised using the LCOE calculated for BiMEP.

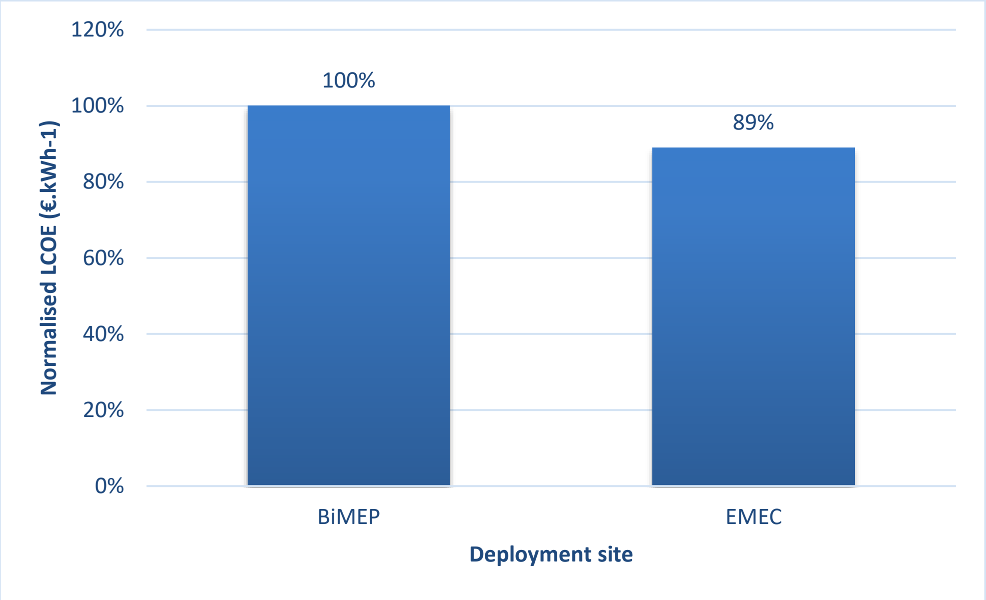


FIGURE 9.7: IMPACT OF DEPLOYMENT LOCATIONS ON LCOE FOR WITH INNOVATIONS ARRAYS SCENARIOS.

- **Long term cost reduction**

LCOE will reduce further as the industry progresses to the stage of a global market maturity, benefiting from cost reductions resulting from learning effects, economies of volume and economies of scale. The three scenarios for different array capacities and industry stages are considered here:

- Single device (SD): single device of 250kW, deployed today
- Array 1 (A1): deployed after an installed capacity of 10MW
- Array 2 (A2): deployed after an installed capacity of 18MW

OPERA's economic assessment estimated a 62% reduction in LCOE when a comparing single device deployed to a 100 MW array and a 75% reduction of cost when comparing a single device deployed to a 1GW installed. The biggest reduction on LCOE comes from cost reduction due to cumulative experience (learning by research, learning by doing and economies of scale) and to a lesser extent array capacity. See Figure 9.8.

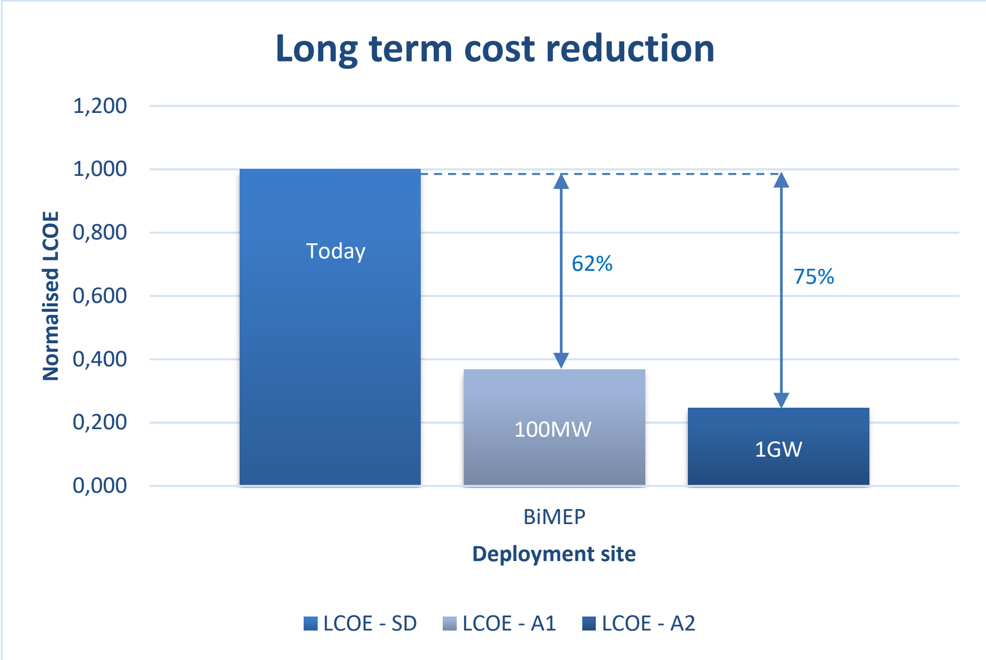


FIGURE 9.8: REDUCTIONS IN LCOE DUE TO LEARNING RATES AND ECONOMY OF SCALES. VALUES ARE NORMALISED WITH THE HIGHEST LCOE RESULT (SINGLE DEVICE).

The LCOE values achieved by the OPERA arrays (*With Innovation* scenarios deployed at both sites), are aligned with the values of the *second demonstration projects* in [2].

- **Sensitivity assessment**

The sensitivity study presented in D7.3 was used to rank input parameters in terms of impact on LCOE. The input parameters tested, ranked from greatest to least influence, are as follows: AEP, discount rate, WEC costs, operational period, PTO costs and insurance costs.

The sensitivity analysis showed that the AEP has the most significant effect on LCOE. Increasing efficiency and maximising AEP should be a focus for development.

The second most influential parameter was the discount rate. The discount rate reflects how the investment risk is perceived by investors. Besides finance availability and market factors, developers need to prove the reliability of components through established mechanisms and reduce uncertainty in parameters. WEC developers should seek certification to minimise the risk as perceived by the potential investors in order to lower the discount rate.

- **Other metrics**

The OPERA techno-economic assessment also presented alternative financial indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR).

In light of the final OPERA experience, the NPVs calculated for the array 1 scenario when deployed at both locations are now positive, indicating that these projects would bring a gain for the investors. As shown in D7.3, array 2 yields positive NPV figures in both deployment locations. The LCOE values calculated for these scenarios are smaller than the assumed electricity price of £0.305/kWh, hence leading to profitable investments. The highest NPV was calculated for EMEC in the Array 2 case, with an associated IRR of 19%.

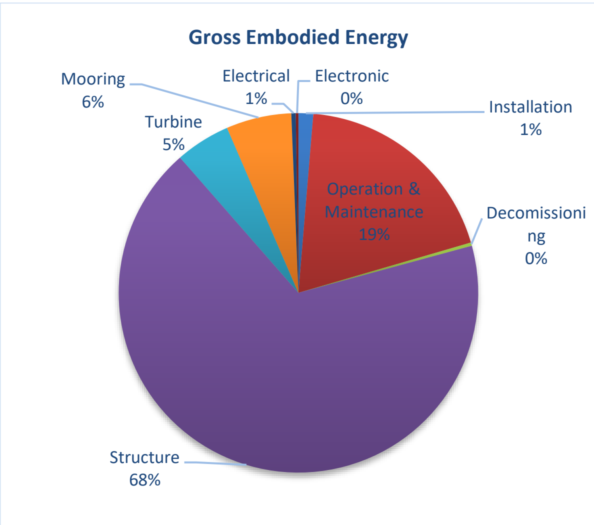
It needs to be stated that NPV and IRR metrics assume a specific sale price of electricity, which is variable. In 2019, in the UK, the Department for Business, Energy & Industrial Strategy [3] defined a new CfD administrative strike price for wave energy of between 268-291 £/MWh. In Spain, in 2007, the Agencia Estatal - Boletin Oficial del Estado [4] defined an electricity price of 306 €/MWh, whereas in 2017 the Boletin Oficial del Estado [5] reduced the support for renewables to 40 €/MWh or 150 €/MW.

9.2.2.2 LCA MODEL

This section presents updates on the LCA metrics presented in D7.3 (Embodied carbon emission and energy; Global Warming Potential – GWP; Energy Pay Back Time – EPBT; and Energy Return of Investment - EROI) due to the final OPERA experience. When comparing the final OPERA experience with the initial OPERA experience, fuel consumption was observed to be less than initially through. This update directly influences the LCA results.

EMBODIED CARBON EMISSION AND ENERGY

Embodied carbon emission and energy results for the life cycle of the OPERA 18 MW array deployed at EMEC are updated with final OPERA experience and shown in Figure 9.9. The embodied carbon emission and energy figures indicate that the most significant stage is manufacturing of the structure, which is followed by O&M. Calculations completed based on the final OPERA experience resulted a reduction in the O&M share of the embodied values.



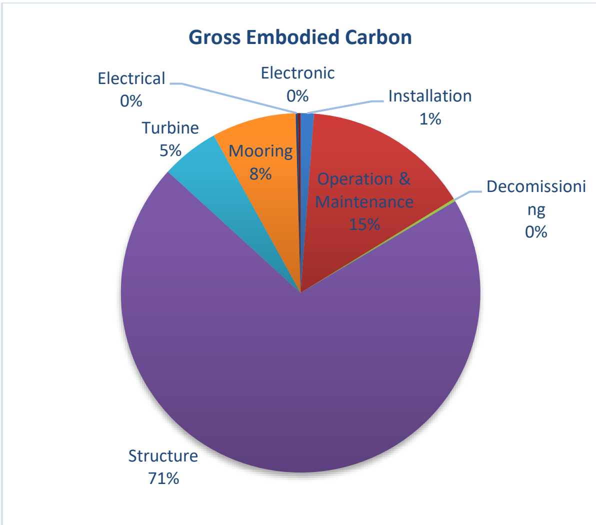


FIGURE 9.9: GROSS EMBODIED ENERGY (LEFT) AND CARBON (RIGHT) BREAKDOWN OVER THE LIFE-CYCLE, CONSIDERING FINAL OPERA EXPERIENCE.

GWP, EPBT and EROI

Table 9.3 presents the LCA results calculated for the *With Innovation* array 2 scenario when deployed at EMEC (the reference case in the LCA modelling). Table 9.3 presents results calculated using both initial and final OPERA experience data.

TABLE 9.3: GWP, EPBT AND EROI FIGURES CALCULATED FOR THE WITH INNOVATION ARRAY 2 SCENARIO DEPLOYED AT EMEC. CALCULATIONS PERFORMED BASED ON INITIAL AND FINAL OPERA EXPERIENCE.

Metrics	Initial OPERA experience	Final OPERA experience	Difference
GWP (gCO2/kWh)	69.4	44.2	- 36%
EPBT (years)	6.6	4.1	- 38%
EROI	3.2	5.1	+ 59%

Using final OPERA experience data resulted in a reduction in the GWP of 36%, resulting in a final carbon intensity of 44.2 gCO2/kWh. Final OPERA learnings also resulted in a reduction of EPBT by 38%, resulting in a value of 4.1 years. EROI improved by 59% when using the final OPERA inputs, showing a value of 5.1. Note, these improvements aren't based on improvements made in the technologies, just that they performed better than expected.

COMPARISON WITH OTHER SOURCES OF ELECTRICITY

- **Ocean energy technologies**

When comparing the WEC array 2 analysed through OPERA with a range of other ocean energy devices [6], the OPERA array's carbon intensity result is positioned in the lower middle of all concepts (15) considered, and is lower (about 60%) than the generic point absorber technology, which is the most comparable device with the WEC tested in OPERA.

The WEC array analysed through OPERA achieves the UK target for renewable energy technologies. The array 2 analysed in OPERA showed a GWP of 44.2 gCO2/kWh, which is smaller than the UK target of 50 gCO_2/kWh by 2030 [7].

- **Overall technologies**

The OPERA array 2 was shown to compare well with more traditional electricity generation alternatives such as fossil fuels, see Figure 9.10. The OPERA array (2) was shown to have a similar carbon intensity to better-established renewable technologies such as solar [8].

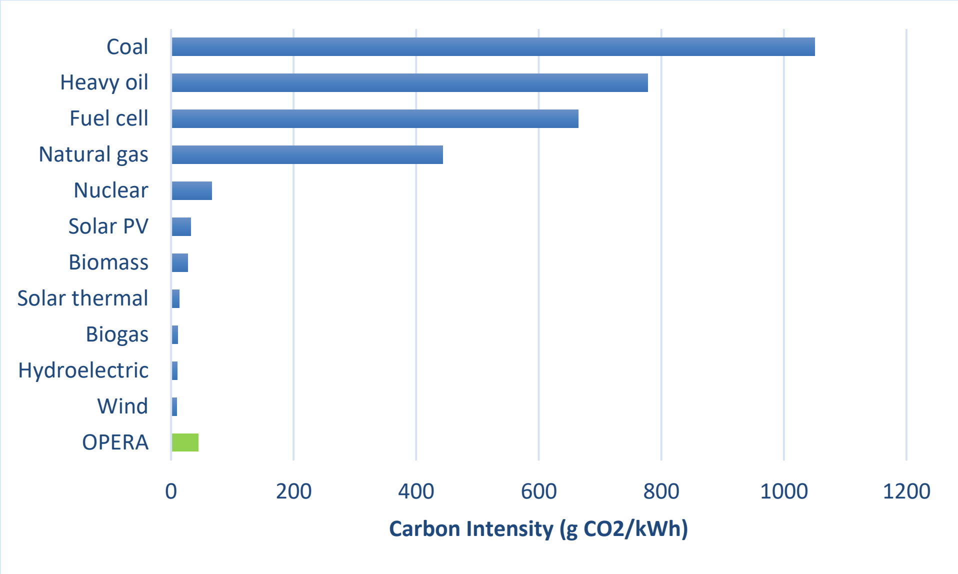


FIGURE 9.10: LIFE CYCLE CARBON INTENSITIES OF OPERA AND ALTERNATIVE ENERGY GENERATION TECHNOLOGIES [8].

Every kWh of energy generated by OPERA device saves 1,006 g CO_2 when compared to the same energy from coal, 734 g CO_2 when compared to heavy oil and 399g CO2 when compared to gas. This is relevant considering that the energy industry is required to be almost completely decarbonized by 2030 [9]. In the UK, electrification is the focus for emissions' reduction. The government is dedicated to eliminating coal power by 2025 [9]. This transition to renewables will assist on carbon savings. The OPERA device has the potential to contribute to the reduction in carbon emissions.

9.2.2.3 SCOE MODEL

Based on the updated OPEX model figures, obtained using the final OPERA experience, the SCOE metrics presented in D7.3, Gross Value Added (GVA) and job years supported, were observed to reduce marginally from those presented in Deliverable D7.3. GVA to the Scottish economy, arising from the deployment of an 18 MW array of MARMOK-A-5 devices at EMEC, was observed to reduce from £92 M to £89 M. The job years supported reduced from 1,309 to 1,264. Note, these reductions in society benefits demonstrate the weakness of basing an evaluation of the socio-economic benefits of a technology on a single project. To obtain a more realistic picture of how technology improvements, or cost reductions, would result in positive social impacts, it is necessary to model at an industry level. It is envisaged that, as technologies improve, become cheaper, the more units that would be sold, therefore more investment in economies and the more positive the social impacts.

It must be stressed that the differences in the GVA and job years supported figures, between those obtained with the final OPERA experience and those presented in OPERA D7.3, is negligible when compared to the uncertainty contained in the figures. As outlined in D7.3, there are numerous sources of uncertainty in the calculations of GVA and job years supported. The figures presented are most useful for highlighting that investment in WEC array projects can provide positive economic impacts to deployment regions and support jobs. As discussed, a more meaningful analysis would require the modelling of an industry.

9.2.3 RISK ASSESSMENT

OPERA also focused on the risks arising from the innovative technologies tested in the project and the risks relating to the different phases of and activities performed during the life cycle of the OPERA technologies. Risks have been evaluated for the following technologies (also shown in the list is the relevant OPERA partner):

- Floating WEC – Idom-Oceantec,
- Advanced elastomeric mooring lines – University of Exeter, and
- Bi-radial air turbine – Kymaner.

Following the Technology Qualification methodology defined by DNV-OSS-312 [10], each technology developer (Idom, UNEXE and Kymaner) performed an initial risk assessment at the beginning of the Project, applying Certification Basis, TA and FMEA spreadsheets to identify the risks to be monitored along the project. Technology developers identified any required risk treatments and undertook continual risk monitoring, throughout the length of the project, constantly updating the FMEA spreadsheet. Risks identified over the initial risk assessments, or at any stage through the project, were treated until their levels were As Low As Reasonably Practicable (ALARP).

Technology developers made use of a number of collection protocols to update their respective risk assessments and to inform the WP leader (UEDIN) and task leader (DNV GL). The risk assessments were formally reviewed by developers every 3 months.

During the OPERA operational phases, most of the high and medium risks were treated until their level was ALARP, by reducing the severity of consequence and/or the probability of failure. The operational experience also revealed new risks which were added to the FMEA. Risks can be unexpected (due the difference between design and execution, insufficient level of detail in the risk investigation or design, handling of interfaces or unpredictable responses due to novelty) or assume a different nature than the one anticipated. The OPERA project showed that even with the effort of reducing risks there are still a few remaining risks and uncertainties. The probability of encountering unexpected risks does not yield the risk management process redundant as the process itself reduces the number of new significant risks encountered. The final FMEA spreadsheets show that the majority of risks identified by the end of the OPERA project were classified as low. However, it is likely that that new risks may be identified during further longer sea testing considering that other elements such as degradation may play a more prominent part on failure mechanisms.

Figure 9.11 presents a summary of the OPERA risk categories and their levels before (top) and after the OPERA deployment phases (bottom).

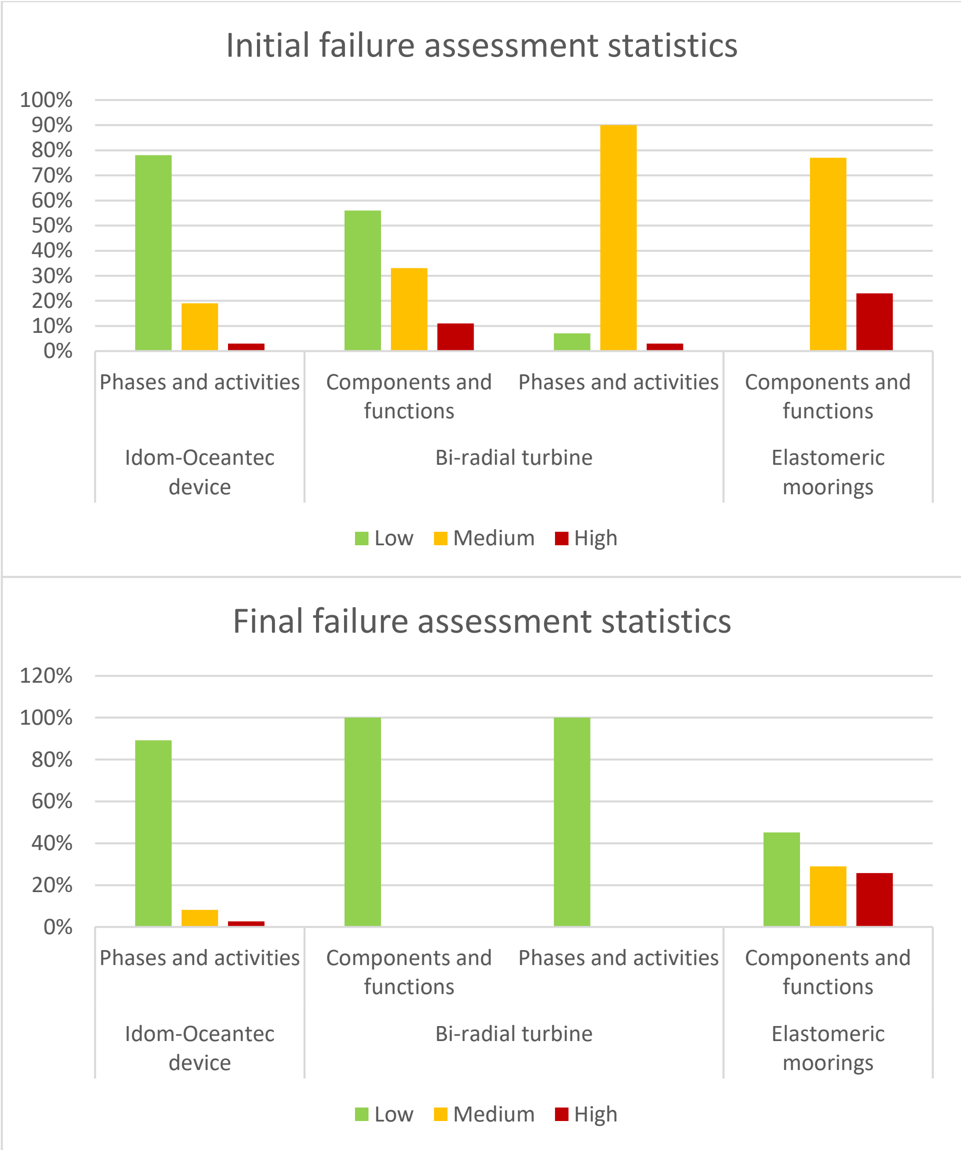


FIGURE 9.11: SUMMARY OF INITIAL (TOP) AND FINAL (BOTTOM) OPERA FMEA DATA

The risk management work also involved the gathering the lessons learned from each innovation owner during the OPERA project. This included their experience of working with their technologies and their experience of monitoring the risks. Further to this D7.4 also presents lessons learned by UEDIN and DNV-GL in the gathering of risk management information from multiple project partners.

10. POLICY RECOMMENDATIONS FOR THE WAVE ENERGY SECTOR

10.1 OVERVIEW OF THE SECTOR

This section presents a brief overview of the ocean energy sector before presenting recommendations deemed necessary for the sector's, and specifically the Idom-Oceantec WEC's, commercialisation. Recommendations are based on [10] and on the Idom-Oceantec WEC's stage of development.

Depending on their level of development, ocean energy technologies require different types and levels of support, to achieve competitive costs and to progress. Figure 10.1 presents five stages of device development in terms of Technology Readiness Level (TRL). This figure illustrates a road that the ocean energy sector could follow to reach market.

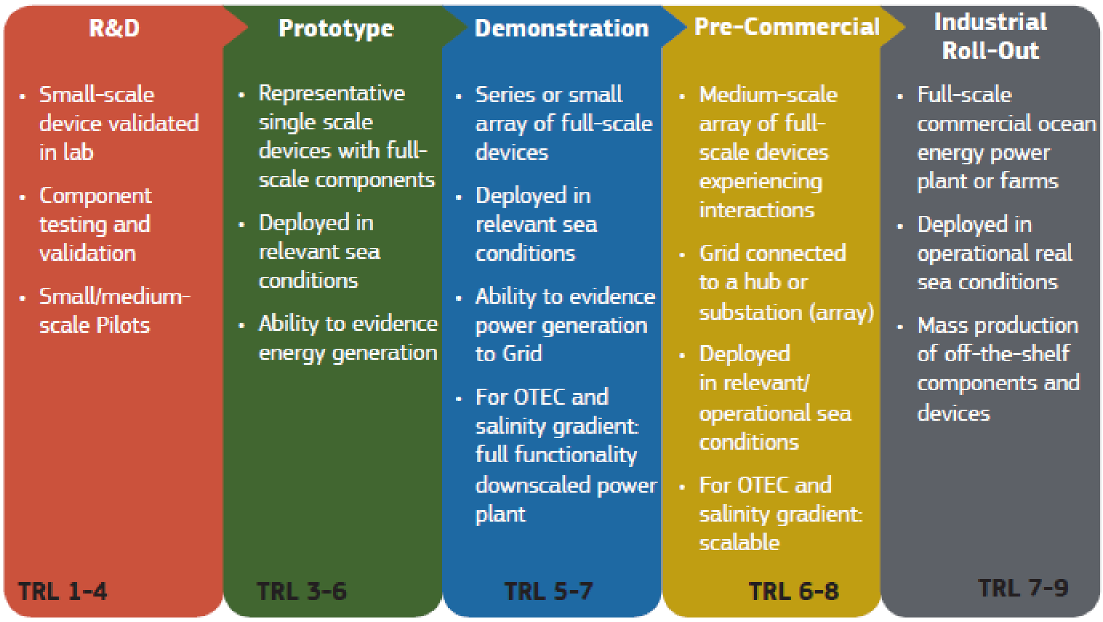


FIGURE 10.1: STAGES OF DEVELOPMENT OF OCEAN ENERGY TECHNOLOGIES [10].

Wave energy is going through the earlier stages of development. The Idom-Oceantec WEC deployed through the OPERA project is an example of a single device, deployed in relevant sea conditions (TRL 3-6). The sector needs Technology Push and Market Pull mechanisms in place. Technology push, with inclusion of subsidies, are required to invest in future demonstration projects, devices and subsystem. Market pull mechanisms should be introduced, in the medium/long-term, in a form of Feed in Tariff (FiT) by member states and European Commission.

10.2 RECOMMENDATIONS FOR COMMERCIALITY

This section outlines actions required for the sector, and specifically the Idom-Oceantec WEC, to achieve commerciality.

Action 1: R&D and Prototype

At this stage of development, ocean energy projects do not make a return. Therefore, grants, with public funding, are necessary. The main objective at this stage is development of the knowledge base. The focal points are improvements of devices, components and sub-systems (PTOs, Control Systems, Moorings etc.). Programmes such as Horizon 2020 (H2020) created by European Commission and Wave Energy Scotland (WES) 'Stage Gate' Processes are sources of grants that currently exist within the sector.

OPERA is funded by the European Commission H2020 programme and has focussed on improving sub-systems with experiences gained during real sea operation. As seen in this report, the OPERA project has identified means of reducing LCOE, determining areas for improvement in component performance and reducing risks. This has demonstrated the benefits of early stage technology research programs and therefore it is recommended that Member States and European Commission should set up funding programs for early stage technologies. A wider European stage gate programme would avoid duplication of research and would be consequently more cost effective.

OPERA next step: Full Scale Demonstration project

In order for the Idom-Oceantec WEC to reach commercialisation, it is recommended that the next stage of development should see a full-scale demonstration of the device, so that in the following stage it will be ready to move to Pre-Commercial farms. Current work programs that could facilitate that transition are as follows:

- National programmes,
- European work programmes,
- Wave energy Europe-JA3 established.

Action 2: Pre-commercial farms

At the pre-commercial level of development, the objective will not only be learning but also revenue generation. It will be a challenge to obtain funding for this phase of development but it is hoped that demonstration of revenue generation at this stage should be sufficient to convince investors to close the funding gap. There will need to be a blend of financial instruments and private investment.

A combination of grant funding, public-supported equity, public-guaranteed loans, insurance and guaranteed fund, and revenue support, will be required for projects to reach financial closure. The MeyGen project illustrates this need for different mechanisms. During its first phase (installation of 4 devices), 80% of investment came from public sources such as grants, repayable debts and equity.

Currently EU financial instruments available include the InnovFIN EDP facility, NER300 scheme, Horizon 2020, new Scottish Government Energy Investment Fund (EIF) etc. They all require a return from projects. Therefore, to assist wave energy to progress, it would be helpful for the European Commission and National Governments to invest in already existing programmes and propose an insurance and guarantee fund.

Action 3: Industrial Roll-out

Wave energy is not yet mature enough for the industry roll-out phase. Nevertheless, when the time comes, some challenges, currently faced by tidal range sector, will also be observed. At the industrial roll-out stage, the revenue support at a national level will be crucial for the initial deployment projects. After the deployment, cost reductions will occur due to volume. This behaviour was observed in other industries, such as wind energy or solar.

Among the current options available for revenue support, mechanisms are competitive auctions in reserved ‘pots’, Feed-In-Tariffs (FiTs) and tax credits for private Power Purchase Agreements (PPAs). These options have low national support and limited visibility in the market. The challenge at this stage is that the revenue support for wave energy is the same as for other well-established technologies, against which early stage wave technologies cannot compete. In order for wave energy to achieve commerciality; earmarked revenue support must be put in place by national governments.

Overall, when considering that wave energy results in benefits such as jobs supported, previously seen on the SCOE study (section 9.2.2.3), policies should be structured in such a way as to maximize the benefits of deployment regions. The LCA study (section 9.2.2.2) also highlights other benefits of the sector, such as reduction on carbon emissions. Policies could also be structured in a way to benefit wave energy for that positive impact.

11. CONCLUSIONS

Wave energy has seen significant development and deployment achievements in recent years. Most of the research work is focused on reducing wave energy costs, improving overall performance and lowering the risks to attract investors. However, even with these significant achievements in the sector, there has been very limited open-sea experience, which is essential in order to fully understand the challenges in device performance, survivability and reliability.

The OPERA project aimed at removing this roadblock and contributing to reduce the time to market of wave energy by sharing open-sea data and experience to avoid repeating early engineering mistakes and validating and de-risking four cost reducing innovations (i.e. biradial turbine, advanced control algorithms, shared mooring system and elastomeric tethers). Overall, the project ambition was to achieve a long-term cost reduction of 50%.

Project results are quite satisfactory both on the quantitative and qualitative sides. Thanks to the improvements brought about by the cost reducing innovations, the LCOE is reduced by 52-56% when compared to the benchmarking case for an array configuration of 18 MW. The biggest contributor to cost reduction is the novel biradial turbine, followed by advanced controls and the shared mooring configuration. The table below summarises the specific project objectives and the progress achieved.

TABLE 11.1: PROGRESS ACHIEVED TOWARDS TECHNICAL OBJECTIVES

Project objective	Progress achieved
Collect, stream and publish 2 years of open-sea operating data of both a floating WEC and a shoreline wave power plant	2.5 years of resource data at Mutriku and BiMEP; Biradial turbine and power quality data at Mutriku; Online query data tool with BiMEP published data
De-risk innovations that lower mooring cost over 50% and enhance survivability	The tension was found to be reduced by ~50% with the tethers compared to tension measured at similar extreme environmental condition
Increase OWC power production 50% and improve reliability	The turbine exhibited a mean efficiency higher by a factor of 1.55 in comparison with the Wells turbines installed at the Mutriku Power Plant.
Advance predictive and latching control to TRL5 to enable 30% increase in power production	The best in class predictive (CL6) and adaptive (CL2) controls outperformed state-of-the-art speed control power production by 30% and 20% respectively during the Mutriku testing
Advance standards to reduce business risk and give access to lower cost capital	First real application of IEC Technical Specifications: 62600-10 (Mooring), 62600-30 (Power Quality), 62600-100/102 (Power performance), 62600-101 (Resource)
Reduce uncertainty, frequency, risk and cost of offshore operations	Improved OPEX modelling, planning & logging of operations; Health & Safety experience
Improve risk management and cost estimation with real data	Protocol to analyse and manage technical risk and uncertainty arising from the project innovations and activities; Economic, life-cycle and social impact of innovations and technologies tested in the project.

The Idom-Oceantec WEC deployed through the OPERA project is an example of a single device, deployed in relevant sea conditions (TRL 3-6). In order to realise the foreseen cost reductions, and ultimately achieve competitive costs, it will require different types and levels of support. Technology push support, with inclusion of subsidies, is required to invest in future demonstration projects, devices and subsystem. Market pull mechanisms should be introduced, in the medium/long-term, in a form of Feed in Tariff (FiT) by Member States and European Commission.

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