WEETICS:
Wave Energy Enhancement Through Innovative Control System

WES Control Systems Stage 1 Public Report

TECNALIA

This project has been supported by Wave Energy Scotland

1 Project Introduction

Despite the significant achievements in the last decades, wave energy devices are at an earlier stage of development than other offshore renewable energy technologies.

Unfortunately, an issue normally relegated to the last phases of development is the design of global control architectures and supervisory systems. This is a common mistake that can cause serious consequences when the Wave Energy Converter (WEC) is deployed, such as instability, poor efficiency and low availability. Hence, integrating the development of the control system in early development phases is a key element of project success as it can bring coherence between all WEC components and take care for its safe operation.

The main aim of WEETICS-Stage 1 is to assess the **feasibility** of a novel control system methodology, and its **applicability** to different WECs and Power Take-Off (PTO) typologies.

1.1 Control system methodology

The proposed control system considers the device as a whole system and is structured in three layers, each one with a clearly defined goal. This solution is inspired by the last developments and experience gained after WEC sea trials, and foresees technology transfer from other mature sectors such as the wind industry, robotics and aeronautics.

WEETICS proposes a multilayer control architecture aiming at evaluating the best control action according to both internal and external criteria:

- **Layer 1 (L1)** – Integrated Control System is the main control program implemented in the Wave Energy Converter (WEC) Programmable Logic Controller (PLC). It centralises every monitored data from all WEC sub-systems. This layer is also responsible of guaranteeing the output data stream containing data and status of sensors that will enable both system monitoring in a local station, but most importantly, to an external database processed in the 3rd Layer.
- **Layer 2 (L2)** – Real Time Controller is exclusively dedicated to the WEC power production. In fact, there are three real time core controllers and an algorithm that enables power smoothing assuming the WEC is equipped with an energy storage system.
- **Layer 3 (L3)** – Data Fusion and Machine Learning represents an organised collection of physic-based models and methods of data integration and advanced analytics hosted in a cloud-base service. It is used to feedback information into lower levels of the WEC control. The PLC should support high-level communication protocols for data exchange with Layer 3, a robust Information and Communication Technology (ICT) infrastructure should guarantee network performance and availability.

The Control System (CS) framework is a global solution applicable to different WECs since it considers the device as a whole system where each block encapsulates specific control functions.

1.2 Project team

This project phase has been executed by TECNALIA, a research and technology organisation; OCEANTEC, a dynamic Wave Energy Technology developer; and the University of Edinburgh, one of the largest and most successful universities in the UK. TECNALIA acted as project manager and led the technical activities. OCEANTEC contributed to the technical activities and provided strong collaboration for all the technical development thanks to experience learnt in the offshore deployment of the MARMOK-A5; whereas the University of Edinburgh main focus was on the applicability of the CS to other WEC and performed a thorough WEC/PTO technologies literature review.

TECNALIA is the leading private and independent research and technology organisation in Spain and one of one of the largest in Europe, employing 1,400 people (230 PhDs), a turnover of €102m in 2016. Tecnalia is committed to generate major impacts in economic terms, by means of innovation and technological development, addressed by 6 business divisions, covering economic sectors of Energy, Industry, Transportation, Construction, Health and ICT. The current project has been carried out by the Offshore Energy Department of the Energy and Environment Division. This Department, with a staff or 20 experienced researchers, is mainly focused on modelling and analysis of offshore structures (including mooring systems, foundations, hydrodynamic characterisation, structural analysis and optimisation); electric transmission (grid connection solutions, power quality and grid code compliance); materials (testing and failure analysis, corrosion monitoring, fatigue, bio-fouling…); O&M strategies definition, installation, commissioning and decommissioning simulations. The Offshore Energy Department applies this knowledge using a coordinated and holistic approach, focusing on the deployment of cost-effective offshore wind and ocean energy farms throughout their life cycle.

OCEANTEC is a private SME, founded in 2008 by TECNALIA and IBERDROLA as main partners, committed to generate major impacts in economic terms, by means of innovation and technological development focused on the wave energy sector. OCEANTEC's skills and experience include: Technological development; Site selection and resource energy analysis; design, construction and installation of prototypes; Project Management; Testing, control and technical evaluation of on-site tests; Optimisation of energy costs; Commissioning and operations. Experience of Oceantec in the wave energy industry is confirmed by the following milestones:

- Focused in Offshore OWC based wave energy converter development (since 2013);
- Grid-connected 30 kW prototype (MARMOK-A5) deployed in BIMEP since October 2016;
- Looking ahead to exploit & operate the WEC for at least 2 years more, including mooring and turbine changeover as part of OPERA H2020 Project;
- Currently working in the design of full scale device, actively incorporating experience being gathered from the operation/scientific exploitation of the reduced-power MARMOKA-A5 WEC prototype.

The University of Edinburgh is one of the largest and most successful universities in the UK with an international reputation as a centre of academic excellence. It is home to over 30,000 students and attracts students and staff from 140 countries. The University of Edinburgh is regarded as one of the world's top universities, consistently ranked in the world top 50 and placed 19th in the 2016/17 QS World University Rankings. The Institute for Energy Systems (IES) at the University of Edinburgh, with 23 staff, 20 RAs and 50 PhDs, is one of six multi-disciplinary research institutes within the School of Engineering. The institute delivers world leading research in low carbon energy systems, technology and policy with areas of expertise including: ocean energy; innovation; life-cycle analysis; resource modelling and measurement; hydrodynamics; thermodynamics; and power systems. In the most-recent Research Excellence Framework assessment in 2014, 94% of the overall research activity within the School of Engineering was deemed to be world-leading or internationally excellent, making Edinburgh the UK powerhouse in Engineering.

2 Description of Project Technology

2.1 Key features of the control system methodology

The proposed control framework is global as it sees the WEC and PTO as a whole system and where each layer encapsulates specific functions as can be seen in Figure 1.

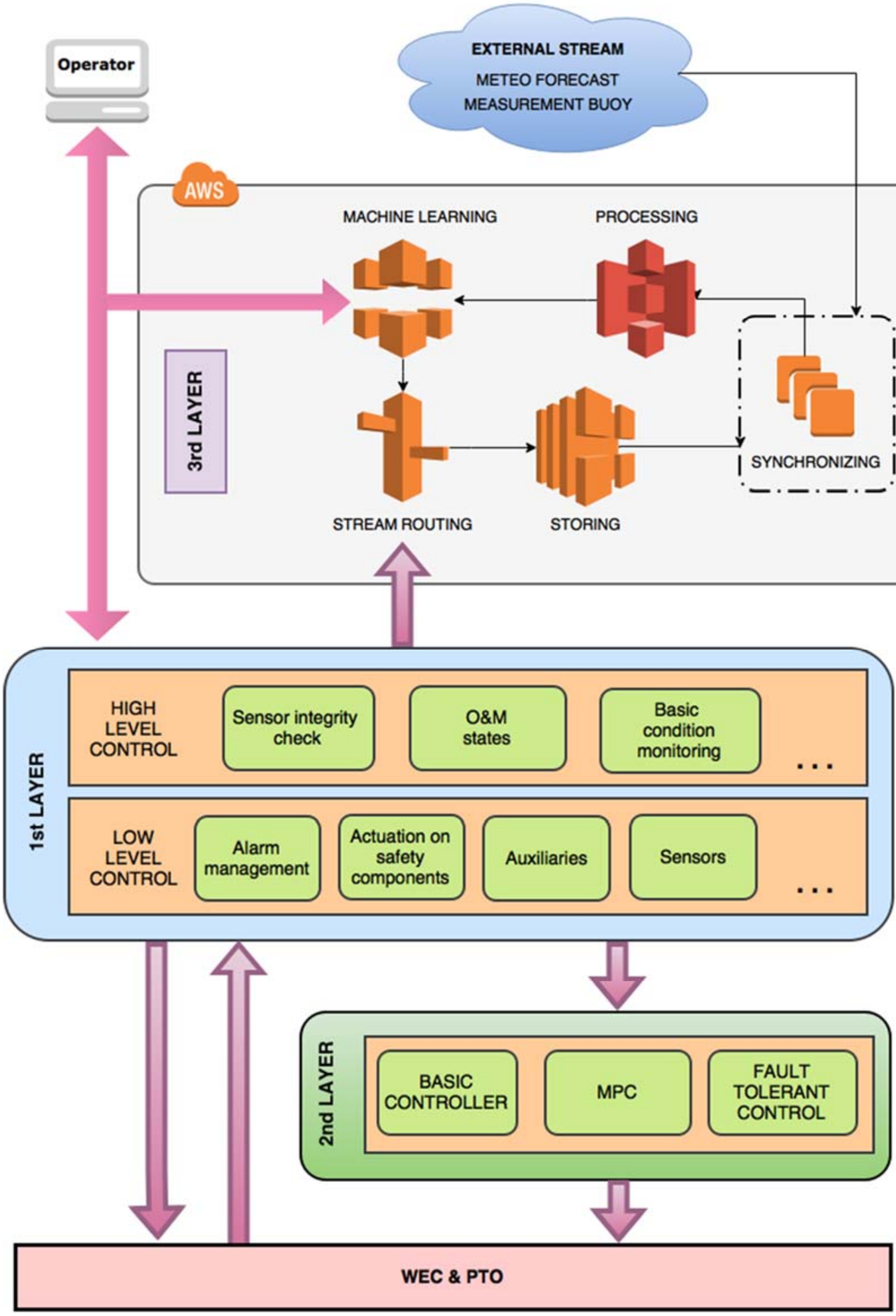

Figure 1 - Global control system framework

Layer 1 – Integrated Control System is determined by its fast response against an error from the detection and diagnostic of a fault, till the physical application of safety procedures in response to this fault. At this level of control, safety of personnel and equipment is the main concern. The integrity of the WEC and its components is assured by various means covered by the integrated control system. It is also in charge of the safe operation and selects the most appropriate control strategy embedded in the 2nd Layer.

Functionality	Measurements, signals and sensors	Process & control commands
Protect staff safety, integrity of plant assets and the environment	• Heat and fire presence • Gas and fume spreading • Water intrusion and fluid leakage • Device amplitude and accelerations • WEC position monitoring • Staff presence	• Default in sensor or communication • Fault detection and diagnostic • Assign the operational state (Ready, O&M, Storm protection)
Safe power production of plant	• Pressure, temperature and humidity • Temperature of critical components • Generator rotational speed • Vibration monitoring of the PTO • Position of safety components • Over-voltage/current	• Safe WEC operation • Real time controller decision for Layer 2
Basic condition monitoring	• Pressure sensors • Temperature sensors • Humidity and dew-point sensor • Speed/position encoder • Position switches • Current and voltage sensors	• Ageing • Automated maintenance • Sensor integrity check

Layer 2 – Real Time Controller is exclusively dedicated to the optimisation of WEC power production. There are 3 real time core controllers and common to these three control strategies, an algorithm enables power smoothing assuming the WEC is equipped with an energy storage system. The objective is to optimise the overall WEC performance depending on the decision of Layer 1.

Functionality	Modelling and prediction	
Basic controller	• Accurate Wave-to-Wire (W2W) model • Sea state dependent resistive control • Adaptive resistive control	• Management of the Energy Storage System
Model Predictive Control (MPC)	• Accurate wave excitation force prediction • MPC model including W2W • Latching and PTO damping control • Synchronisation of the control action	
Fault Tolerant Control (FTC)	• Reconfiguration of operational bounds • Use of redundant PTO parts • Watch fault recovery	

Layer 3 – Data Fusion and Machine Learning represents an organized collection of physic-based models and methods of data integration and advanced analytics used to feedback information into lower levels of the WEC control. The models in conjunction with the sensor data give the ability to predict the device's performance, evaluate different scenarios, and enhance power production through model correlation and integrate smart component prognostics.

<table>
<tr><th>Functionality</th><th colspan="2">Modelling and prediction</th></tr>
<tr><td>Integrity check</td><td>• Detects malfunction of sensor
• Detects anomaly in auxiliary system</td><td rowspan="3">• Data routing and synchronization
• Integration with external data streams (WMI, meteo forecast, onshore substation, O&M planner)</td></tr>
<tr><td>Power performance improvement</td><td>• Digital WEC model: performance simulation and modelling actualization
• Machine learning</td></tr>
<tr><td>Advanced condition monitoring</td><td>• Ability to compute long term effects
• Machine learning</td></tr>
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2.2 Anticipated benefits

Performance is mainly dealt with by the second layer, responsible for the efficient power production. The proposed CS has potential to significantly improve performance in terms of Peak to average power ratio, Annual Energy Capture (AEC), and the Annual Energy Production (AEP). In addition, because it is aware of past operation data, the 3rd layer can send back to Layer 2 optimally adjusted control parameters to further optimise the AEP.

Besides, several control functionalities in WEETICS are thought to assure WEC operation in the best condition. The CS is aware of the components' operation bounds and life expectancy and aims at reducing the downtimes, thus contributing to maximise device **availability**.

Although the term survivability recalls the potentiality of a catastrophic hazard and should be tackled during the design phase of the different subsystems (e.g. structure, moorings, PTO, …), the CS plays an important role in monitoring loads and extending the operational range in which the WEC can operate without entering survival mode. In storm protection mode, the device is not producing any power but still specific measures are taken in order to change the response of the device and reduce the loads generated by extreme waves.

The ultimate goal of all these control functionalities is to **lower the cost of energy**. Apart from the impact on performance and availability, the CS is expected to have a net positive effect on the OPEX by reducing the O&M at sea, thanks to selecting the correct operation mode according to internal and external conditions.

The analysis has found **mature applications** of Layer 1 and 2 functionalities in other sectors. However, real-time predictive control, conditioning monitoring and data fusion/machine learning functionalities still need **further development efforts** for the wave energy sector since they are at applied research and small-scale testing stages.

Finally, WEETICS control methodology has provided evidence that it is well suited regardless the technology type. Not only can this CS open up the opportunities in the most mature concepts, but also it is **compatible with WES novel PTO and WEC projects developments**, thus increasing their commercial attractiveness.

3 Scope of Work

As it has been already mentioned, the objective of the project is to assess the requirements of this novel control system methodology, its applicability to different WECs and PTOs typologies and readiness of the project to proceed to Stage 2. In order to achieve this objective, a work plan structured in three work packages was followed. The work plan involved the following types of activities:

WP1: Definition of the control system methodology

The main objective of this work package was to define in a comprehensive and detailed manner the control system methodology, its structure, the dependencies between layers and the integration in a global solution.

It consisted of the following tasks and activities for each of the 3 layers:

- Define the proposed control system methodology, describing at low level of detail the layers in which it is structured;
- Perform the literature review of the current development status of the proposed control system methodology;
- Specific requirements regarding each functionality to be developed focusing on the following items: implementation, measuring and sensing, modelling and prediction, processes and algorithms, control commands and actions;
- Detail the flow of data internal to each layer and the interlayer connection. Example is given for the 1st layer in the following figure.

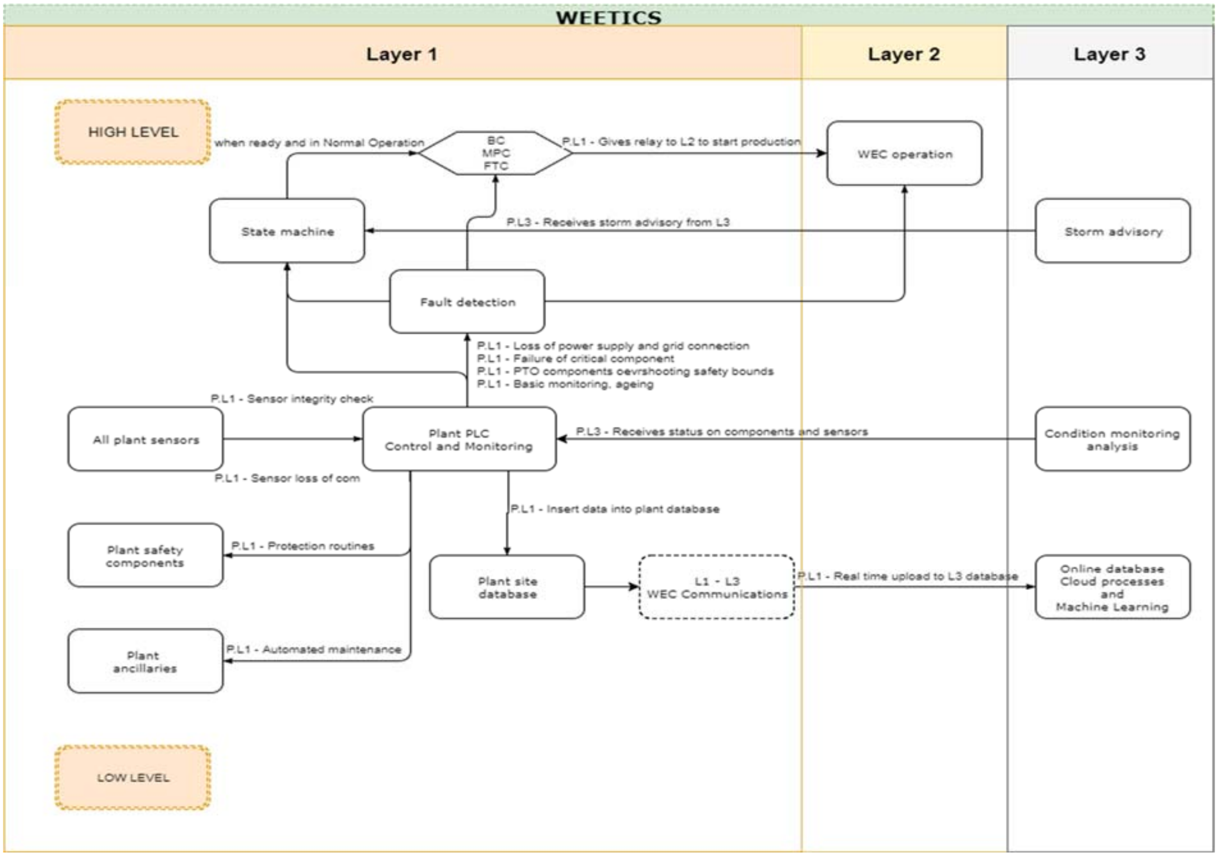

Figure 2 - Data flow diagram of Layer 1

WP2: Demonstration of the feasibility of the proposed control system methodology

The main purpose of this work package was to demonstrate the overall feasibility of the proposed control system methodology and readiness of the project to proceed to Stage 2, starting from all technical results of WP1.

It consisted of the following tasks and activities:

- Detail the benefits on such a control methodology and propose a methodology to estimate the improvements in line with the main WES outcome metrics which are: performance, availability, survivability and affordability;
- Present the proper feasibility study where the Technology Readiness Level (TRL) is assessed and the suitability of each functionality for the wave energy sector is analysed;
- Develop the applicability study of the CS to a variety of WEC. Next table reflects the ease of implementing the control methodology based upon publically available information.

Table 1 - Suitability of the CS for WECs

Device Name	Lead Developer	Classification	Status	Suitability ranking
ACER	4C Engineering	Attenuator	WES NWEC Stage 2; TRL5; 1/4th testing @Galway Bay	~ ~ ~
Laminaria	Laminaria	Attenuator	TRL4, 1/30th scale wave tank tested	~ ~
CorPower	CorPower	Point Absorber	TRL6; 1/2th scale testing @EMEC	~ ~ ~
CETO	Carnegie Clean Energy	Point Absorber	TRL6, large scale testing @PWEP	~ ~ ~
CCell Mark 3	Zyba Ltd.	OWSC	TRL3; small scale tank tested	~ ~
WaveRoller	AW-Energy Oy	OWSC	TRL 7, full scale tested @Peniche (3* 100kW)	~ ~ ~
MARMOK-A	Oceantec	OWC	TRL 7; large scale prototype @BiMEP	~ ~ ~
OBREC	Dimemo	Overtopping	TRL 5; small scale test in relevant environment	N/A
Anaconda	Checkmate Sea Energy	Bulge Wave	NWEC stage 2, TRL3; 1/25th tank testing	N/A
Penguin	Wello Oy	Rotating mass	TRL7; Large scale demonstrator @EMEC (500kW)	~ ~
GEL	Seapower SCRL and Umbra Group	OWSC	TRL 5; 1/5th scale tested in wave tank	~
C-GEN	The University of Edinburgh	Various Types	WES PTO Stage 3 in progress; TRL4	~
			N/A Lack of information	

WP3: Project management

The project management dealt with the role and responsibilities of the various actors and the contract with the contractor and included the following tasks:

- Organise the overall management, communication and coordination between the different partners. Monitor the technical progress of the project, by means of the supervision of the achieved milestones and application of LEAN management techniques. Management of the risks and establish of contingency plans, as well as IPR issues;

- Plan and detail of the activities to be taken on next stages accordingly to the outcomes of WP1 and WP2. It describes the main Stage 2 activities on the design and development of the control system. The definition of the test campaign for Stage 3 is specified regarding the practical control system demonstration;
- All contractual requirements, risk management register and dissemination of lessons learned from the project. This risk assessment will be updated with the project findings.

4 Project Achievements

The main objectives of WEETICS Stage 1 are successfully presented in the first two technical deliverables including the following four main achievements:

- Detail the definition of the overall control architecture to delimit the scope and objectives of each of the 3 layers. All functionalities are now clearly detailed, the requirements stated and the flow of data highlighted.
- Perform a literature review associated to a TRL and feasibility study to conclude on the availability of the technology. The analysis has shown many mature applications of Layers 1 and 2 in existing sectors and a majority yet applicable to the wave energy sector and for most of them yet developed by project partners. Only the predictive control algorithm and online prediction/estimation of the resource lack practical application. In what concerns the 3rd layer, evidence have shown data fusion and machine learning are yet commercial products applied in wind energy farms. However, its development requires further efforts to apply the technology to wave energy control.
- Benefits of the control strategy with respect to the various functionalities will be carried out by the 3 main layers: Integrated control system, Real-time controller, and Data fusion and machine learning. The improvements in line with the main WES outcome metrics are detailed and a methodology presented to evaluate qualitatively those benefits.
- Prove the suitability of each functionality of the control strategy to a variety of the most mature WECs and PTOs.

Globally, some activities could have been more precisely explained if the CS had have been applied to a specific WEC/PTO. Indeed, it is not easy to prove the feasibility of the technology without contextualising/concreting to a technology. It was clear at the beginning that the proposed solution had to be adaptable to variety of devices, but it would have been better to cover and detail even more the functionalities for a specific WEC. In that sense, the quantitative estimation of WES metrics improvements was very tricky. Also, it was proposed to develop a FMECA which would have added useful information in the development of the fault detection and diagnostic functionality of Layer 1. These activities are planned to be done more precisely in Stage 2 Design and Development because the control system will be applied to a floating OWC.

5 Recommendations for Further Work

Future activities will give us the opportunity to pursue the practical technology development and apply the CS to a floating OWC device. This case study will offer a strong base to perform the estimation of metrics improvements. In stage 2, the design & development will take place during 2018. The CS methodology will be developed in a simulated environment and the integration of all the layers into a unique solution will be secured. The quantification of benefits (WES Target Outcome Metrics) will be performed across a methodology presented as part of a Stage 1 activity. Investigate the requirements for physical implementation in existing laboratory testing, or in a demonstrator WEC/PTO for Stage 3. Preliminary practical implementation in a controlled environment.

Once the technology is fully tested and validated, the Stage 3 activities can start, probably starting along 2019. The effort will be focused on the demonstration of control system. The implementation of the CS using production software are to be verified and a physical demonstration in a prototype (NWEC/PTO call, others) or dry test rig can be performed to fully validate the technology and open the path towards commercial implementation.

6 Communications and Publicity Activity

In terms of public communications, two members of the consortium were present during the WES Annual Conference in Edinburgh 2017 and presented a poster during the event. In addition, two articles in LinkedIn were released in the TECNALIA Offshore Renewable Energy page: one at the start of the project and one to advertise the attendance to the WES Conference and promote the CS architecture.

7 Useful References and Additional Data

The confidential contents are the first two project deliverables:

- 'WEETICS. Stage 1: Feasibility Studies - D1: Definition of the Control System Methodology", WES CS Call, 2017.
- 'WEETICS. Stage 1: Feasibility Studies - D2: Overall control system methodology feasibility and benefits", WES CS Call, 2017.

A public content was presented during the WES Annual Conference:

- 'WEETICS. Wave Energy Enhancement Through Innovative Control System. Stage 1 – Feasibility studies", Poster in WES Annual Conference, 2017. Link to the poster.