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Programme Area: Marine

Project: PerAWAT

Title: Final Summary Report

Abstract:

This Final Summary Report is the final publishable report of the Performance Assessment of Wave and Tidal Array Systems Project (PerAWaT). It provides an overview of the background and structure of the project, and summarises its results, conclusions and the environmental impact.

Context:

The Performance Assessment of Wave and Tidal Array Systems (PerAWaT) project, launched in October 2009 with £8m of ETI investment. The project delivered validated, commercial software tools capable of significantly reducing the levels of uncertainty associated with predicting the energy yield of major wave and tidal stream energy arrays. It also produced information that will help reduce commercial risk of future large scale wave and tidal array developments.

PERAWAT

Final Summary Report

Energy Technologies Institute LLP

Report No.: 104325-BR-R-04, Rev. A
Date: 26/02/14

Project name:	PerAWaT	DNV GL Energy
Report title:	Final Summary Report	Engineering Support/Wave & Tidal
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Date of issue:	26/02/14	Bristol
Project No.:	104325	BS2 0QD
Organisation unit:	Renewables Advisory	Tel: +44 (0)117 972 9900
Report No.:	104325-BR-R-04, Rev. A	
Document No.:		

Task and objective:
Production of Final Summary Report for the PerAWaT project.

Prepared by:	Verified by:	Approved by:
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Keywords:
[Keywords]

Reference to part of this report which may lead to misinterpretation is not permissible.

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
A	2014-02-26	First issue			

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1 INTRODUCTION

This Final Summary Report is the final publishable report of the Performance Assessment of Wave and Tidal Array Systems Project (PerAWaT). It provides an overview of the background and structure of the project, and summarises its results, conclusions and the environmental impact. The report's acceptance criteria are as follows.

> The project end summary report will provide a brief summary of all the key project deliverables and briefly describe how the underlying models and data identified in WGO D1 and D2 have been used in the ultimate Beta software tools. The report will then refer back to original project objectives and comment on progress against those, along with an up to date description and timeline for the production of the commercial software tool.

2 BACKGROUND

PerAWaT was commissioned and funded by the Energy Technologies Institute (ETI) with the aim of establishing and validating numerical models to predict the hydrodynamic performance of wave & tidal energy converters (WECs and TECs) when operating in arrays. The primary focus PerAWaT was the development of hydrodynamic models of array performance that were validated and verified through a combination of benchmarking against different modelling approaches, and comparison with model scale and full scale measurements. The key project deliverables were the WaveFarmer and TidalFarmer engineering models.

PerAWaT started on 27th October 2009, with the final deliverable, WaveFarmer Beta 2 release, being delivered on 12th December 2013. The project was undertaken by a consortium consisting of the following organisations (the Participants):

- DNV GL {formally Garrad Hassan & Partners Ltd} who was the Lead Co-ordinator;
- E.ON Engineering Ltd (EON);
- Electricité de France SA (EDF);
- The University of Edinburgh (UoE);
- Queen's University Belfast (QUB);
- The University of Oxford (UoO);
- The University of Manchester (UoM).

3 PROJECT MANAGEMENT ARRANGEMENTS

At the outset of PerAWaT, all the Participants signed a consortium agreement which, amongst other things, set out the following arrangements for the management of the project.

The Lead Co-ordinator (DNV GL) was given the following rights and responsibilities, which were exercised through the Project Manager:

- to be the primary contact for the participants and the ETI Programme Manager, for the day to day running of the project;
- to be responsible for the co-ordination and day to day management of the project;
- to be responsible for implementing decisions taken by the Steering Committee;
- to monitor the progress of the project with respect to Milestones and deliverables;
- to invite the Programme Manager to attend all meetings of the Steering Committee;
- to convene all meetings of the Steering Committee;
- to review and endorse all project deliverables prior to submission the ETI for approval;
- to approve all project deliverables denoted as an INTRA deliverable;
- to countersign all cost reports prior to their submission to the ETI for approval;
- to prepare monthly reports for submission to the ETI Programme Manager.

Robert Rawlinson-Smith of DNV GL was appointed as the Project Manager. He retained this role until the end of the project.

The Participants formed a Steering Committee, which was responsible for making decisions on all day to day matters relating to the project that did not affect its overall scope, structure and timing; or the material rights or obligations of a Participant.

Each Participant appointed one individual to the Steering Committee (the Nominated Representative). In addition, each Participant was entitled to appoint an additional individual to the Steering Committee to act as an observer. This observer was entitled to attend meetings of the Steering Committee, but not vote. The Project Manager was the Nominated Representative of the Lead Co-ordinator.

The quorum for a meeting of the Steering Committee was the Nominated Representatives of at least four of the Participants, one of whom had to be the Nominated Representative of the Lead Coordinator. The Project Manager chaired the meetings.

The Steering Committee met every 3 months. Decisions were taken by a majority vote of the Steering Committee. In the event of a tied vote, the Nominated Representative of the Lead Co-ordinator had the casting vote.

The PerAWaT Technical Contract was put in place between the ETI and each of the Participants on 27th October 2009. During the course of the project, a range of issues resulted in 42 variation requests being raised. These variations requests resulted in the release of six amendments to the contract.

A summary of the variation requests is at Appendix 1.

4 WORK BREAKDOWN STRUCTURE

PerAWaT was separted into two workstreams, Wave and Tidal. Each workstreams was then divided into two work groups, one covering numerical modelling, and the other covering experimental work. These work groups were then further divided into work packages covering specific elements of the numerical modelling and experimental work. Each work package was then implemented through a series of deliverables.

The work breakdown structure for the Wave Workstream is shown in Figure 1, and the work breakdown structure for the Tidal Workstream is shown in Figure 2. Note that WG4 WP5 was cancelled by Contract Amendment 4 due to storm damage to the test equipment.

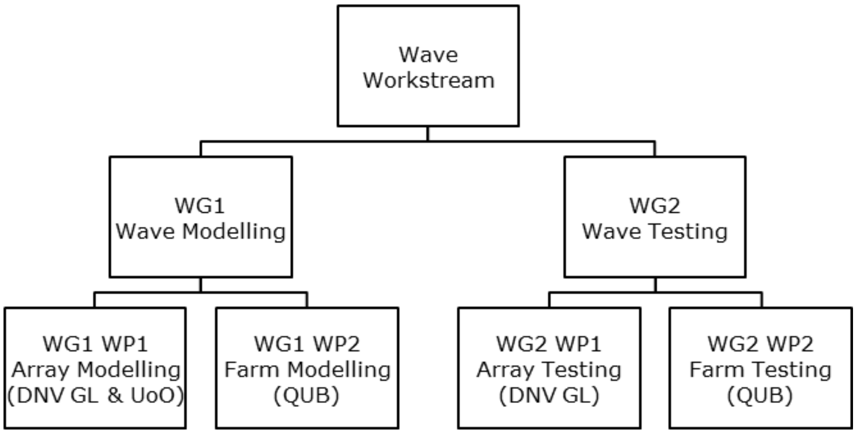

Figure 1: Wave Workstream Work Breakdown Structure

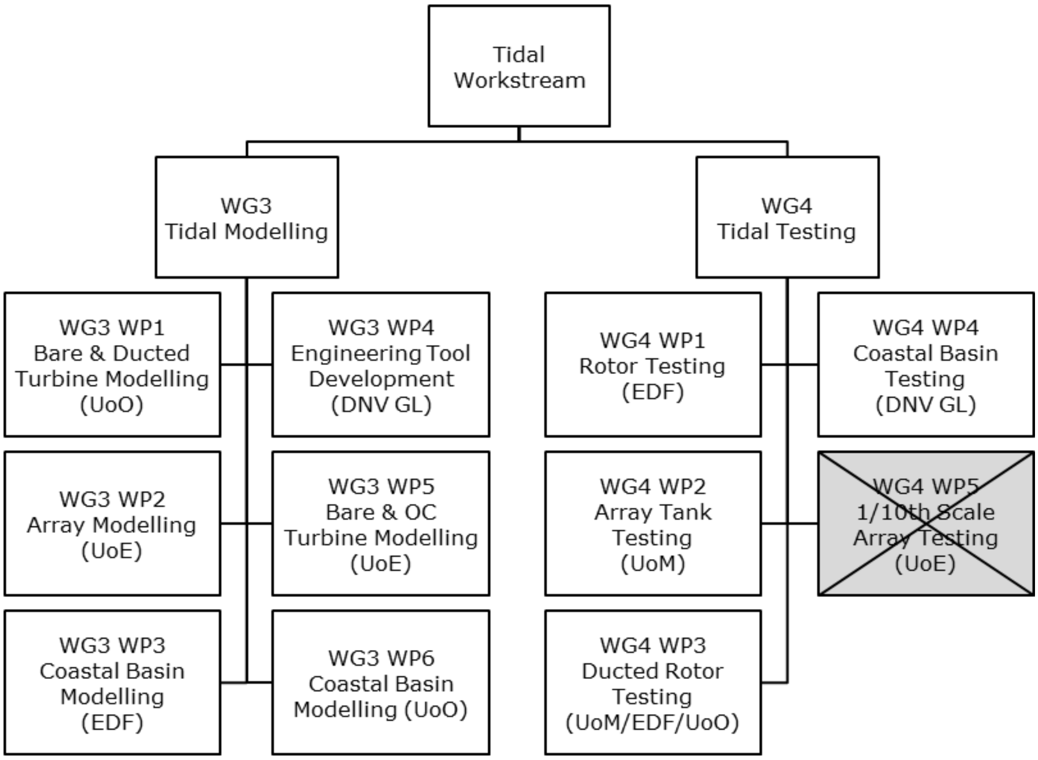

Figure 2: Tidal Workstream Work Brreakdown Structure

The product flow diagram for the Wave Worstream is shown in Figure 3, and the product flow diagram for the Tidal Workstream is shown in Figure 4.

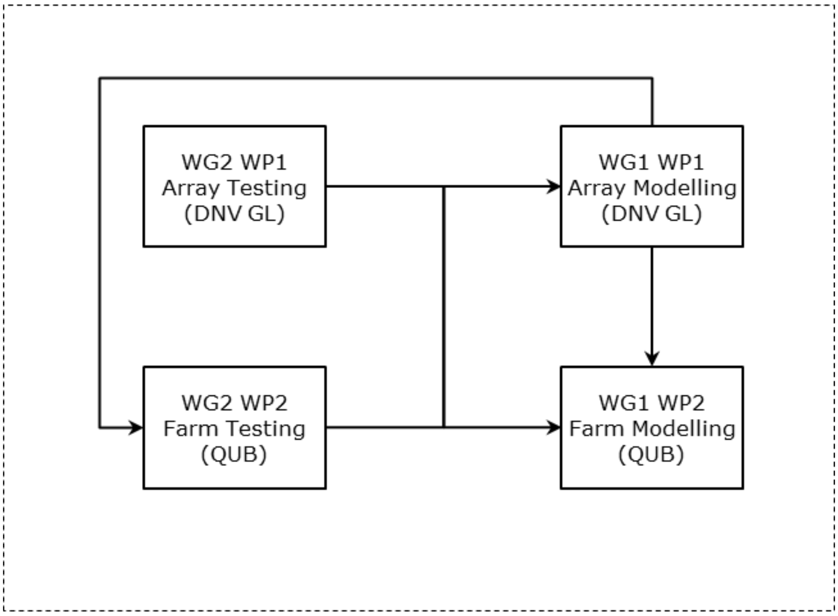

Figure 3: Wave Workstream Product Flow Diagram

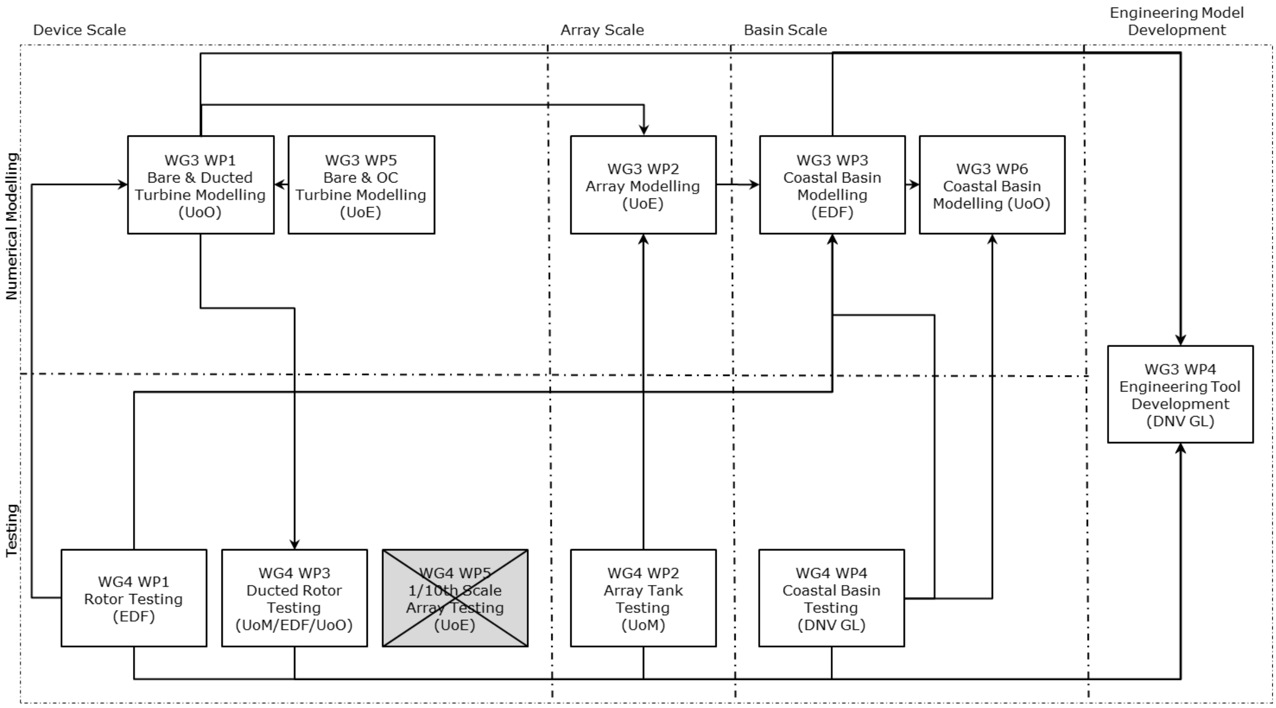

Figure 4:Tidal Workstream Product Flow Diagram

A list of the deliverables associated with each work package is included in Appendix 2.

5 PROJECT AIM, OBJECTIVE & OUTCOMES

The following aim, objective and outcomes of PerAWaT were set out in the Technical Contract.

Project Aim

The aim of PerAWaT was:

> To establish and validate numerical models to predict the hydrodynamic performance of wave & tidal energy converters (WECs and TECs) when operating in arrays.

This aim was achieved by the completion of Work Group 1, Work Package 2; Work Group 3, Work Package 1; Work Group 3, Work Package 5; and Work Group 3, Work Package 6.

Project Objective

The objective of PerAWaT was as follows:

> The primary focus of PerAWaT is the development of hydrodynamic models of array performance, the models will be validated and verified through a combination of benchmarking with different modelling approaches and comparison with model scale and (where available) full scale measurements.

This objective was achieved by the release of the WaveFarmer and TidalFarmer Beta 2 Software .

Project Outcomes

The two outcomes of the project were as follows:

> Once established, the numerical models will enhance levels of confidence in the design of WEC and TEC arrays and therefore accelerate their large scale deployment.
>
> By accelerating deployment rates PerAWaT will directly address the ETI Marine Programme outcome goal of increasing deployment to 2GW by 2020 and 30GW by 2050.

It is not possible to determine whether these outcomes have been achieved at this time. Therefore, the ETI will need to carry out an assessment after a suitable period.

Work Package Objectives

In addition to the project objective, each work package had a series of objectives, and contributed to the achievement of various ETI Marine Sector objectives. Details of these objectives are set out in Appendix 3.

In summary, of the 48 Work Package Objectives, 42 were achieved, one was partially achieved and 5 were not achieved. Of the 22 Marine Sector Objectives, 19 were achieved and 3 were not achieved.

The work package objectives that were partially or not achieved relate to the tidal array modelling undertaken by UoE in Work Group 3, Work Package 2; the coastal basin modelling undertaken by EDF in Work Group 3, Work Package 3; and the tidal array testing undertaken by UoE in Work Group 4, Work Package 5.

In the case of Work Group 3, Work Package 2, UoE encountered software issues with Code_Saturne that could not be resolved and meant that this work could not be used to verify other models developed by the project. In the case of Work Group 3, Work Package 3, EDF encountered technical issues with Telemac that prevented the provision of suitable data to cross-compare with other models developed by the project. In the case of Work Group 4, Work Package 5, storm damage to the tidal array resulted in the cancellation of this work package and meant that test data was not available for model verification.

However, as alternative data was available for model validation, cross-comparisn and verification none of these events had a significant impact on the project outcome.

6 RESULTS

The key deliverables from PerAWaT were the WaveFarmer and TidalFarmer engineering models. These are briefly described below, together with how the underlying models and data were used to verify and validate in the final Beta2 software tools.

WaveFarmer

WaveFarmer is a software tool that enables technology developers, project developers, utilities and investors to assess the potential energy yield from a wave farm. The design aim was to produce a tool that would run on a PC or laptop, and which included suitable methodologies and mechanisms to optimise the design of a wave farm. The tool is divided into three components:

- **Wave Climate Module**, which creates parameterisations of site-specific wave climates, and provides inputs describing sea states to the other software components;
- **WaveDyn**, which is a performance and loads calculation tool that operates in the time-domain, and provides a detailed model of a wave energy convertor (WEC) or array of WECs, taking into account nonlinearities in power take-off mechanisms, moorings and structural constraints;
- **WaveFarmer**, which is a tool that enables the planning and optimisation of arrays of WECs, and incorporates the functionality of WaveDyn as well as frequency and spectral domain solvers for assessing arrays in a given configuration.

The core software structure of WaveFarmer is modular, and suitable for coupling with frequency, time and spectral domain solvers. It allows the detailed modelling of various fundamental design concepts (FDC) over a wide range of power take off and mooring configurations, and sea states. It also allows the user to determine the optimal layout and control settings for an array of WECs through detailed site specific simulations under realistic constraints.

The three components support the detailed evaluation of a site-specific wave climate (Wave Climate Module), a WEC (WaveDyn) or an array of WECs (WaveFarmer). While WaveDyn is a time-domain solver, WaveFarmer can utilise either time, frequency or spectral domain solvers. In a time-domain formulation the description of the mooring and power take off forces and the kinematics of the structural constraints in response to these, can be non-linear. This results in a more computationally intensive model that is suitable for the detailed assessment of the loads that affect a WEC or a small array of WECs, and enables the estimation of its performance.

During the course of the project, the algorithms and outputs of WaveFarmer were verified against non-linear models developed by UoO in Work Group 1, Work Package 1; and spectral wave models developed by both QUB and DNV GL in Work Group 1, Work Package 2. The model outputs were then validated against data from intermediate scale tests of point absorbers and attenuators operating in isolation and in small arrays, carried out by DNV GL in Work Group 2, Work Package 1; and small scale tests of large arrays carried out by QUB in Work Group 2, Work Package 2.

Tidal Farmer

TidalFarmer is a software tool that enables technology developers, project developers, utilities and investors to assess the potential energy yield from a tidal array. The design aim was to produce a tool that would run on a PC or laptop, which allowed the user to design a tidal array to achieve the maximum energy production within the geometric and environmental constraints of the site. In order to obtain a prediction of energy yield of a tidal array, TidalFarmer requires a description of the tidal energy convertors (TEC) that make up the array, the resource at the site in terms of a temporal and spatial flow field, and other site characteristics which may impact on device interactions. TidalFarmer uses mathematical models to predict the flow in and around a tidal turbine array, allowing the evaluation of array energy capture.

In order to provide a design tool that allows for numerous iterations, the approach to energy yield prediction is to use an efficient means of evaluating array scale interactions and the potential effect which the array layout has on energy yield. This is achieved through the development of rationalised modelling methods, which involves reducing the extremely complex interactions between tidal turbines and the surrounding flow field into a series of distinct physical processes at the coastal basin, array scale and device scale that can be simplified and modelled. Coupling these rationalised models together enables the strength of different modelling methods to be used in a computationally efficient way.

In the context of the four key aspects of an energy yield and optimisation tool, TidalFarmer undertakes analysis at each step:

- Site specific temporal tidal flow prediction, using results from a standard tidal forcing model based on tidal harmonic constituents; and spatial flow variation, incorporating the effect of bathymetry on flow field model data to give localised speed-ups and downs coupled with boundary layer models to give the variation in flow velocity through the water column;
- Array influenced flow field prediction incorporating the hydrodynamic interaction between adjacent devices and the bounding surfaces of the channel (blockage modelling); and the wake effect upon the downstream flow (wake modelling);
- Energy calculation over a project life time using the device-specific performance characteristics to evaluate the energy capture of each turbine, and summing these to give an overall energy yield;
- Energy optimisation by altering array layout.

During the course of the project, the algorithms and outputs of TidalFarmer were verified against:

- computational fluid dynamics models developed by UoO using Ansys Fluent in Work Group 3, Work Package 1;
- computational fluid dynamics models developed by EDF using Code_Saturne in Work Group 3, Work Package 1;
- computational fluid dynamics models developed by UoE using Code_Saturne in Work Group 3, Work Package 5;
- coastal basin models developed by EDF using Telemac in Work Group 3, Work Package 3;
- and coastal basin models developed by UoO using Adcirc in Work Group 3, Work Package 6.

The model outputs were then validated against data from:

- 1/30th scale tests of individual devices carried out by EDF in Work Group 4, Work Package 1;
- 1/70th scale tests of arrays carried out by UoM in Work Group 4, Work Package 2;
- 1/70th scale tests of ducted and unducted rotors carried out by UoM and EDF in Work Group 4, Work Package 3;
- and coastal basin testing carried out by HR Wallingford under sub-contract to DNV GL in Work Group 4, Work Package 4.

7 CONCLUSIONS

The following conclusions have been drawn from the project.

Overall Conclusions

- Project Aim of establishing and validating numerical models to predict the hydrodynamic performance of wave & tidal energy converters when operating in arrays was achieved.
- Project Objective of developing hydrodynamic models of array performance, and validating and verifying them through a combination of benchmarking with different modelling approaches and comparison with model scale and (where available) full scale measurements, was achieved
- Of the 48 Work Package Objectives, 42 were achieved, one was partially achieved and 5 were not achieved.
- Of the 22 Marine Sector Objectives, 19 were achieves and 3 were not achieved.
- Achievement of Project Outcomes will need to be assessed by the ETI after a suitable period.

Technical Conclusions

- Hydrodynamic interactions between WECs and TECs operating in arrays can be significant therefore modelling of array effects is essential when estimating the energy yield of potential project.
- Wave tank testing of WEC arrays is extremely demanding and needs to be carefully planned and analysed. In particular the effects of reflections can be of the same order as effects of the interactions you are trying to measure. Despite the challenges, it is possible to measure significant interactions in the tank.
- Linear potential flow theory (used in WaveDyn) is sufficient to accurately model device interactions. Weakly non-linear wave kinematics (non-breaking) do not have a significant influence on device response and performance for operational conditions.
- The spectral approach in WaveFarmer is capable of accurately predicting energy yield for a large wave farm.
- Model-scale & full-scale validation of WaveDyn has been invaluable as has model scale validation of WaveFarmer. However, full-scale validation of WaveFarmer will be essential when data becomes available.
- The mean performance of a tidal device can be predicted using a Reynolds Averaged Navier Stokes (RANS) model, however, more work is required in order to `correct’ this type of model so as to accurately capture wake recovery.
- Basin scale modelling using linear momentum actuator disc theory (LMADT) for one row of devices was successful. The limitations of the model are well understood, and the upper limit of energy extraction compares well to analytical methods. However, 3D models such as TidalFarmer are required for detailed assessment of annual energy production.
- Whilst progress has been made on the analysis of blockage effects of arrays and devices, further work is required to fully understand and model the flow reduction through the array.

Project Management Conclusions

- The approach of bringing together a consortium of universities, utilities and an engineering consultancy to develop a range of hydrodynamic models, and validate and verify them through a combination of benchmarking with different modelling approaches and comparison with model scale and full scale measurements has been successful.
- The establishment of the PerAWaT Consortium has accelerated the development of commercially viable modelling tools that predict the hydrodynamic performance of WECs and TECs operating in arrays.

Commercial Conclusions

- The launch of WaveFarmer & TidalFarmer is only the first step in increasing project developers' confidence in their return on investment in WEC & TEC arrays.
- Effective commercial exploitation will be required to stimulate use of the tools.
- The resulting data generated by full scale deployments will enable further development of the tools and the reduction of uncertainty.
- The reduction of uncertainty could be accelerated by investment in trials to generate full scale data for validation.

8 ENVIRONMENTAL IMPACT

The uncertainty surrounding estimates of energy capture is one of the major obstacles to the large scale deployment of wave and tidal energy arrays, as it affects the confidence of project developers and investors that they will receive an acceptable the return on their investment. As WaveFarmer and TidalFarmer can reliably assess the potential energy yield from a wave or tidal farm, they will significantly increase levels of confidence.

Consequently, the environmental impact if PerAWaT is that it will reduce carbon emissions by accelerating the large scale deployment of the emerging wave and tidal energy technologies.

However, the uncertainty surrounding estimates of energy capture is only one of many factors that can influence investment decisions, and it remains to be seen what the relative importance of these various factors to project developers and investors will be. Therefore, an objective assessment of how much the large scale deployment of the emerging wave and tidal energy technologies accelerates, and how much of this acceleration can be attributed to PerAWaT must await an assessment of the project outcomes discussed at Section 5 of this report.

APPENDIX 1: VARIATION REQUESTS

Variation ID	Contract Amendment	Variation Title	Owner	Affected work packages	Comment	Status
VR 001	1	Schedule adjustment to reflect start date	GH	N/A		Accepted
VR 002	2	Recruitment Delays in Year 1	GH, UoE, QUB, UoO, EDF	WG1 WP1, WG1 WP2, WG3 WP2, WG3 WP5		Accepted
VR 003	2	Wave tank test facilities and device developer input	GH	WG2 WP1		Accepted
VR 004	2	User group seminar	GH	WG0		Accepted
VR 005	2	Consortium integration event	GH	WG0		Accepted
VR 006	N/A		ETI	None		Withdrawn
VR 007	3	Abandonment of WG4 WP3	GH	WG4 WP3		Accepted
VR 008	N/A	Changes to WG3 WP5	GH, UoE	WG3 WP5	Superseded by Var011	Accepted
VR 009	3	Tests modification in WG4 WP1 D4	EDF	WG4 WP1		Accepted
VR 010	3	Changes to WG4WP4	GH/UoM/UoO	WG4 WP4		Accepted
VR 011	3	Changes to WG3 WP5	UoE	WG3 WP5		Accepted
VR 012	3	WG2 sub-Contracts	GH	WG2 WP1		Accepted
VR 013	5	Modifications to WG3 WP3 D1	EDF	WG3 WP3		Accepted
VR 014	3	Purchase of WAMIT for use in Beta Testing of WaveFarmer	EON	WG3 WP4		Accepted
VR 015	3	Deliverable review process	ETI	All		Accepted
VR 016	4	Basin modelling outputs; removal of Bathymetry data from deliverables	UoO/EDF	WG3 WP6		Accepted
VR 017	5	Modifications to WG3 WP1 D8	EDF	WG3 WP1		Accepted
VR 018	N/A	Changes to schedule of WG4 WP5	UoE	WG4 WP5	Work Package abandoned.	Withdrawn
VR 019	3	Rescheduling of WG3 WP4 D10	GH	WG3 WP4		Accepted

Variation ID	Contract Amendment	Variation Title	Owner	Affected work packages	Comment	Status
VR 020	5	Ducted Rotor Tests	UoM	WG4 WP3		Accepted
VR 021	N/A	Additional work package	UoM/EDF	N/A	Incorporated into Var020.	Withdrawn
VR 022	5	Extension for WG1 WP1 D9 delivery date	UoO	WG1 WP1		Accepted
VR 023	6	Rescheduling of WG3 WP3 D2 & D3	EDF	WG3 WP3		Accepted
VR 024	4	Reorganization and rescheduling of deliverable content in WG3 WP1 D3 & D4 (device scale modelling)	UoO	WG3 WP1		Accepted
VR 025	5	Changes to WG3 WP2	UoE	WG3 WP2		Accepted
VR 026	3	Re-scoping of WG2 WP1 D5	GH	WG2 WP1		Accepted
VR 027	4	WG2 Sub-contract deliverables	GH	WG2 WP1		Accepted
VR 028	4	Change to WG4 WP4	GH	WG4 WP4		Accepted
VR 029	4	Consortium Integration Event 2012	All Partners	WG0		Accepted
VR 030	5	WG4 WP1 D4 delay	EDF	WG4 WP1		Accepted
VR 031	4	Delays to Tidal Tool Beta Testing	GH	WG3 WP4		Accepted
VR 032	N/A	Delays to WG2 WP2 D4	QUB	WG2 WP2		Withdrawn
VR 033	5	Change to Tidal Farmer Deliverable Dates	GH	WG3 WG4		Accepted
VR 034	6	WG3 WP5 D3 and D4 re-Scoping	UoE	WG3 WP5		Accepted
VR 035	5	Amendment to Wave Array Testing Final Report	GH	WG2 WP1		Accepted
VR 036	5	Additional Budget for Tidal Work Stream Project Management	GH	WG3 & WG4		Accepted
VR 037	6	2nd and 3rd User Group Seminars and 3rd Consortium Integration Meeting	GH	WG0		Accepted
VR 038	6	Validation of WaveDyn against Pelamis P2-001 Full Scale Data	EON	WG1 WP1		Accepted
VR 039	6	Delay to WG3 WP1 D5 – Wave model	UoO	WG3 WP1		Accepted

Variation ID	Contract Amendment	Variation Title	Owner	Affected work packages	Comment	Status
VR 040	6	Additional Budget for Tidal Work Stream Project Management – 2003	GH	WG0		Accepted
VR 041	N/A	Explicit use of URANS in WG3 WP2	UoE	WG3 WP2		Withdrawn
VR 042	6	WG3 WP2 D6 Delay, and WG3 WP2 D7 & D8 Cancellation	UoE	WG3 WP2		Accepted

APPENDIX 2: TECHNICAL DELIVERABLES

Deliverable Number	Work Package Title	Deliverable Title	Owner	Notes
WG1 WP1 D1a	Array Modelling	WaveFarmer Methodology Development (Initial)	DNV GL	
WG1 WP1 D1b	Array Modelling	WaveFarmer Methodology Development (Final)	DNV GL	
WG1 WP1 D2	Array Modelling	Frequency Domain Linear Modelling	DNV GL	
WG1 WP1 D3	Array Modelling	Time Domain Linear Modelling	DNV GL	
WG1 WP1 D4a1	Array Modelling	WaveFarmer Beta 1 Draft Test Specification	DNV GL	Not for publication
WG1 WP1 D4a2	Array Modelling	WaveFarmer Beta 1 Draft Theory Manual	DNV GL	Not for publication
WG1 WP1 D4a3	Array Modelling	WaveFarmer Beta 1 Draft User Manual	DNV GL	Not for publication
WG1 WP1 D4b1	Array Modelling	WaveFarmer Beta 1 Test Specification (Final)	DNV GL	Not for publication
WG1 WP1 D4b2	Array Modelling	WaveFarmer Beta 1 Theory Manual (Final)	DNV GL	Not for publication
WG1 WP1 D4b3	Array Modelling	WaveFarmer Beta 1 User Manual (Final)	DNV GL	Not for publication
WG1 WP1 D4b4	Array Modelling	WaveFarmer Beta 1 Source Code (Final)	DNV GL	Not for publication
WG1 WP1 D4c	Array Modelling	WaveFarmer Beta 1 Training	DNV GL	Not for publication
WG1 WP1 D5a	Array Modelling	WaveFarmer Beta Testing - EON	EON	Not for publication
WG1 WP1 D5b	Array Modelling	WaveFarmer Beta Testing - EMEC	DNV GL	Not for publication
WG1 WP1 D6	Array Modelling	WaveFarmer Validation against Array & Farm Tests	DNV GL	Not for publication
WG1 WP1 D7	Array Modelling	Non-Linear Model Methodology Development	UoO	
WG1 WP1 D8	Array Modelling	Non-Linear Modelling of Free Floating Device	DNV GL	
WG1 WP1 D9	Array Modelling	Non-Linear Modelling of Free Floating Array	DNV GL	
WG1 WP1 D10	Array Modelling	Non-Linear Array Modelling with PTO in Regular Waves	UoO	
WG1 WP1 D11	Array Modelling	Non-Linear Device Modelling with PTO in Irregular Waves	UoO	
WG1 WP1 D12	Array Modelling	Non-Linear Array Modelling with PTO in Irregular Waves	UoO	
WG1 WP1 D13	Array Modelling	Non-Linear Model Validation against Array Tests	UoO	
WG1 WP1 D14	Array Modelling	Non-Linear Model Validation against Linear Modelling	UoO	Not for publication
WG1 WP1 D15a	Array Modelling	WaveFarmer User & Theory Manuals	DNV GL	Not for publication
WG1 WP1 D15b	Array Modelling	WaveFarmer (Beta 2)	DNV GL	Not for publication
WG1 WP1 D15c	Array Modelling	WaveFarmer Beta 2 Training	DNV GL	Not for publication

Deliverable Number	Work Package Title	Deliverable Title	Owner	Notes
WG1 WP1 D16	Array Modelling	WaveDyn Pelamis P2-001 FSD Validation Specification	EON	Not for publication
WG1 WP1 D17	Array Modelling	WaveDyn Pelamis P2-001 FSD Validation Report	EON	Not for publication
WG1 WP2 D1/D2	Farm Modelling	3GSW Model Development	QUB	
WG1 WP2 D3	Farm Modelling	3GSW Model Development (Beta Version)	QUB	
WG1 WP2 D4-5	Farm Modelling	3GSW Model Validation	QUB	
WG1 WP2 D6-7	Farm Modelling	Application of 3GSW Model to a Specific Site (Orkney)	QUB	
WG1 WP2 D8	Farm Modelling	3GSW Farm Model Development (Final Release)	QUB	
WG2 WP1 D1	Array Testing	Wave Array Test Specification	DNV GL	Not for publication
WG2 WP1 D2&3	Array Testing	WEC Design Specification	DNV GL	Not for publication
WG2 WP1 D4	Array Testing	WEC Prototype Construction	DNV GL	Not for publication
WG2 WP1 D5	Array Testing	WEC Prototype Testing	DNV GL	Not for publication
WG2 WP1 D6	Array Testing	Multiple WEC Construction	DNV GL	Not for publication
WG2 WP1 D7	Array Testing	WEC Array Testing	DNV GL	Not for publication
WG2 WP2 D1	Array Testing	Wave Farm Test Specification	QUB	Not for publication
WG2 WP2 D2&3	Array Testing	WEC Model Design Specification	QUB	Not for publication
WG2 WP2 D4	Array Testing	WEC Model Construction	QUB	Not for publication
WG2 WP2 D5	Array Testing	WEC Farm Testing	QUB	
WG3 WP1 D1	Device Scale Modelling	HA Turbine CFD Model Development	UoO	
WG3 WP1 D2	Device Scale Modelling	Ducted Turbine CFD Model Development	UoO	
WG3 WP1 D3a	Device Scale Modelling	Influence of Turbulence on HA Turbine CFD Model	UoO	
WG3 WP1 D3b	Device Scale Modelling	Influence of Turbulence on HA Turbine CFD Model	UoO	
WG3 WP1 D4	Device Scale Modelling	Influence of Turbulence on Ducted Turbine CFD Model	UoO	
WG3 WP1 D5	Device Scale Modelling	Free Surface Wave HA Turbine Modelling	UoO	
WG3 WP1 D6	Device Scale Modelling	Wave Influence Modelling for HA Turbine	UoO	
WG3 WP1 D7	Device Scale Modelling	Wave Influence Modelling for Ducted Turbine	UoO	
WG3 WP1 D8	Device Scale Modelling	HA Turbine Near Field Modelling & Validation	EDF	
WG3 WP2 D1	Array Scale Modelling	Level Set Free Surface Model Development	UoE	
WG3 WP2 D2	Array Scale Modelling	Zero Tangential Shear Condition Modelling	UoE	

Deliverable Number	Work Package Title	Deliverable Title	Owner	Notes
WG3 WP2 D3	Array Scale Modelling	Validation of Level Set & Zero Shear Models	UoE	
WG3 WP2 D4	Array Scale Modelling	Synthetic Eddy Boundary Modelling	UoE	
WG3 WP2 D5a	Array Scale Modelling	3D CFD Model Development - Steady Flow	UoE	
WG3 WP2 D5b	Array Scale Modelling	3D CFD Model Development - Unsteady Flow	UoE	
WG3 WP3 D1	Coastal Basin Modelling (Telemac)	Coastal Basin Simulation without Farm	EDF	
WG3 WP3 D2	Coastal Basin Modelling (Telemac)	Coastal Basin Simulation with Farm	EDF	
WG3 WP3 D3	Coastal Basin Modelling (Telemac)	Coastal Basin Simulation with Axial Flow Turbine	EDF	
WG3 WP3 D4	Coastal Basin Modelling (Telemac)	Coastal Basin Simulation with Energy Extraction	EDF	
WG3 WP3 D5	Coastal Basin Modelling (Telemac)	Validation of Coastal Basin Simulation	EDF	
WG3 WP4 D1	Engineering Model Development	Tidal Farmer Model Development Methodology	DNV GL	
WG3 WP4 D2	Engineering Model Development	Blockage & Near Wake Modelling	DNV GL	
WG3 WP4 D3	Engineering Model Development	Device Scale Modelling	DNV GL	
WG3 WP4 D4	Engineering Model Development	Regional Scale Modelling	DNV GL	
WG3 WP4 D5	Engineering Model Development	Model Validation	DNV GL	
WG3 WP4 D6	Engineering Model Development	Overall Inter Array Modelling	DNV GL	
WG3 WP4 D7	Engineering Model Development	Tidal Farmer Development (Beta 1)	DNV GL	Not for publication
WG3 WP4 D8a	Engineering Model Development	Tidal Farmer Theory Manual (Beta1)	DNV GL	Not for publication
WG3 WP4 D8b	Engineering Model Development	Tidal Farmer User Manual (Beta1)	DNV GL	Not for publication
WG3 WP4 D8c	Engineering Model Development	Tidal Farmer Training (Beta1)	DNV GL	Not for publication
WG3 WP4 D9a	Engineering Model Development	TidalFarmer Beta Testing - EON	EON	Not for publication
WG3 WP4 D9b	Engineering Model Development	TidalFarmer Beta Testing - EMEC	DNV GL	Not for publication
WG3 WP4 D10	Engineering Model Development	Define Regional Scale Model Plug-in Methodology	DNV GL	
WG3 WP4 D16 & D17	Engineering Model Development	Tidal Farmer Development (Beta2)	DNV GL	Not for publication
WG3 WP4 D17a	Engineering Model Development	Tidal Farmer Training (Beta2)	DNV GL	Not for publication
WG3 WP4 D18	Engineering Model Development	Tidal Farmer Interim Model Validation	DNV GL	
WG3 WP4 D19	Engineering Model Development	Tidal Farmer Final Model Validation & Aggregated Uncertainty Analysis	DNV GL	

Deliverable Number	Work Package Title	Deliverable Title	Owner	Notes
WG3 WP5 D1	HA & OC Turbine Modelling	Horizontal Axis Turbine Modelling	UoE	
WG3 WP5 D2	HA & OC Turbine Modelling	Open Centre Turbine Modelling	UoE	
WG3 WP5 D3	HA & OC Turbine Modelling	HA & OC Turbine Wake Parameterisation	UoE	
WG3 WP5 D4	HA & OC Turbine Modelling	Turbulence Effects on HA & OC Turbine Model	UoE	
WG3 WP6 D1	Coastal Basin Modelling (Adcirc)	Selection of 2D Modelling Code	UoO	
WG3 WP6 D2	Coastal Basin Modelling (Adcirc)	2DModel Development	UoO	
WG3 WP6 D3	Coastal Basin Modelling (Adcirc)	Selection of Sites & Acquisition of Data	UoO	
WG3 WP6 D4	Coastal Basin Modelling (Adcirc)	Application of 2D Model to Selected Sites	UoO	
WG3 WP6 D5	Coastal Basin Modelling (Adcirc)	Incorporation of FDCs into 2D Model	UoO	
WG3 WP6 D6	Coastal Basin Modelling (Adcirc)	2D Model Validation	UoO	
WG3 WP6 D7	Coastal Basin Modelling (Adcirc)	Hydrodynamic Simulation of Sites	UoO	
WG3 WP6 D8	Coastal Basin Modelling (Adcirc)	Assessment of Impact on Tidal Characteristics	UoO	
WG4 WP1 D1	Device Scale Testing	Test Specification & Model Design	EDF	
WG4 WP1 D2	Device Scale Testing	Model Construction	EDF	Not for publication
WG4 WP1 D3	Device Scale Testing	Test Facility Commissioning & Calibration	EDF	Not for publication
WG4 WP1 D4	Device Scale Testing	Testing & Analysis of Results	EDF	Not for publication
WG4 WP2 D1	Array Scale Testing	Test Specification	DNV GL	Not for publication
WG4 WP2 D2	Array Scale Testing	Model Design	UoM	
WG4 WP2 D3	Array Scale Testing	Model Construction	UoM	Not for publication
WG4 WP2 D4	Array Scale Testing	Testing	UoM	
WG4 WP2 D5	Array Scale Testing	Data Analysis	DNV GL	
WG4 WP3 D1	Ducted Rotor Testing	Test Specification & Equipment Delivery	UoM	
WG4 WP3 D2	Ducted Rotor Testing	Testing	EDF	
WG4 WP3 D3	Ducted Rotor Testing	Test Report	UoO	
WG4 WP4 D1	Coastal Basin Testing	Test Specification	DNV GL	
WG4 WP4 D2	Coastal Basin Testing	Model Design	UOM	
WG4 WP4 D3	Coastal Basin Testing	Model Construction, Testing & Data Analysis	DNV GL	Not for publication

APPENDIX 3: WORK PACKAGE OBJECTIVES

WG1 WP1: Wave Array Modelling

Table 1: Work Package Objectives

Objective	Achieved	Deliverable/Implications
Definition of the core modules of a hydrodynamic modelling package able to analyse an array of arbitrary (i.e. a number of leading concepts) wave energy converters (WECs)	Yes	D1
Definition of the critical variables, realistic scenarios and optimisation techniques relevant for wave farm design	Yes	D1
Definition of additional modules to assess real (measured) sea states, non-linear hydrodynamics and non-linear external forces	Yes	D1, D7, D8 D9, D10, D11, D12
Development and implementation of the modelling package in the frequency and time domains	Yes	D2, D3
Validation of the developed package by means of comparison with experimental results (tank test and full-scale data)	Yes	D6, D13, D14, D17
Apply the developed package to representative projects (pre-commercial and commercial scale)	Yes	D15

Table 2: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
Creation of a validated tool that enables stakeholders (project developers, utilities, investors) to assess the energy yield from a wave farm with reduced uncertainty	Yes	D15
Embed in such tool suitable methodologies and mechanisms to optimise the design of a wave farm with regard to device geometry, array geometry, control strategies, wave climate (inc. analysis of wave induced forces) and other relevant variables	Yes	D15
Fill the existing gap between the technology developers and the project developers with regard to project planning	Yes	D15

WG1 WP2: Wave Farm Modelling

Table 3: Work Package Objectives

Objective	Achieved	Deliverable/Implications
To define a flexible representation of wave energy converters (WEC's) as sub-grid elements in third generation spectral wave models (3GSWM)	Yes	D1, D2
To implement a flexible representation of wave energy converters as sub-grid elements in an open-source software code of a third generation spectral wave model	Yes	D3
To validate the flexible representation of wave energy converters as sub-grid elements in third generation spectral wave models using experimental data	Yes	D4, D5
To develop a methodology for the calculation of average annual energy production of a wave farm using the representation of wave energy converters as sub-grid models in a third generation spectral wave model	Yes	D6
To provide a suitable interface to the numerical models developed in WG1 to enable them to be used for complex wave fields where the boundary conditions can be suitably defined	Yes	D8
To calculate the average annual energy production of a wave farm for a representative UK site	Yes	D7

Table 4: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
To provide an estimate of the average annual energy production of a wave farm based on a particular wave energy converter technology and wave farm layout during the wave farm planning stage	Yes	D8
To enable the average annual energy production of alternative wave energy converters and wave farm layouts to be compared at the early stages of a wave farm's development	Yes	D8
To decrease the uncertainty associated with the estimation of income from wave farms	Yes	D8

WG2 WP1: Wave Array Testing

Table 5: Work Package Objectives

Objective	Achieved	Deliverable/Implications
Provision of suitable experimental data for validation of the numerical tools derived in WG1	Yes	D5,D7
Quantification of the wave loading and energy absorption of farm of wave energy converters via experimental modelling at medium scale	Yes	D5,D7
Definition of the limits of validity of the numerical models for performance and survivability scenarios	Yes	D5,D7

Table 6: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
Reduction of the uncertainty associated with the numerical predictions and increase the confidence in the developed software	Yes	D5,D7

WG2 WP2: Wave Farm Testing

Table 7: Work Package Objectives

Objective	Achieved	Deliverable/Implications
To indicate the influence of a variant incident wave field on the power capture of a large wave farm using scale-model experiments	Yes	D5
To provide validation data for the modelling of wave farms in a third generation spectral wave model	Yes	D5
To provide data that helps define the limits of validity of the numerical modelling of wave farms using models based on either potential flow theory or third generation spectral wave models	Yes	D5

Table 8: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
To increase confidence in the ability of numerical models of wave farms to provide accurate predictions	Yes	D5

WG3 WP1: Horizontal axis & Ducted Tidal Device Modelling

Table 9: Work Package Objectives

Objective	Achieved	Deliverable/Implications
To determine, through numerical simulation, the influence of realistic open water flow conditions on the performance and downstream wake structures of generic turbines.	Yes	D1, D2, D3
To provide detailed characterisation of turbine near wake structures in realistic flow conditions to the array and basin scale modelling activities within this work group.	Yes	D4, D5, D6, D7, D8

Table 10: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
Improved understanding of turbine performance in realistic open water flow conditions.	Yes	D3, D4, D5, D6, D7, D8

WG3 WP2: Tidal Array Modelling

Table 11: Work Package Objectives

Objective	Achieved	Deliverable/Implications
To model the interaction of three dimensional unsteady flow and turbine wakes within an array.	Yes	D5b
To verify available numerical models	Partial	D3, D5a. Further verification studies are required to build confidence in the models.
To implement an appropriate free surface model within Code_Saturne.	Yes	D3

Table 12: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
To provide rigorous modelling support for the planning of tidal current arrays	No	D6 & D7 were cancelled so the tools have not been applied to deployment situations. Further work is required to do this. Parallel work in the EPSRC Marine Grand Challenges and NERC EBAO and RESPONSE projects is delivering such models, though more verification is needed.

WG3 WP3: Coastal Basin Modelling

Table 13: Work Package Objectives

Objective	Achieved	Deliverable/Implications
Develop a numerical model for the modelling of tidal farms performance and wake at large scale.	Yes	WG3 WP3 D1 - D3
Assess the large scale effects of tidal energy extraction from UK sites.	Yes	WG3 WP3 D4
Provide results for cross-comparison with another model (WG3 WP6 UoO).	No	WG3 WP3 D4. In the end there were too many differences in the flow without TECs for them to be useful.
Provide input data (boundary conditions) to array scale models (WG3 WP2 UoE).	No	
Provide results for validation of the engineering tool (WG3 WP4).	No	WG3 WP3 D4. Not used due to too many differences with WG3 WP6.

Table 14: Marine Sector Objectives

Objective	Achieved	Deliverable
Assess the large scale effects of tidal energy extraction from UK sites.	Yes	WG3 WP3 D4
Validate engineering tools for the tidal performance assessment, with accurate 2D and 3D models.	No	The results exist, but were not used.

WG3 WP4: Engineering Tool Development

Table 15: Work Package Objectives

Objective	Achieved	Deliverable/Implications
To develop, validate and document a modelling tool, allowing a fast assessment of tidal array potentials on non-specialist hardware	Yes	D1, D2, D3, D4, D5, D6, D7, D8, D9, D10, D16, D17, D18, D19
To extend and validate the GH rationalised flow model	Yes	D4
To validate GH blockage modelling	Yes	D18, D19
To extend GH's semi-empirical parametric models characterising the wake, incorporating ambient turbulence intensities (seabed and wave generated) and the bounding effect of the seabed, free surface and other devices.	Yes	D5
To develop the software architect linking the GH models and ensure it complies with international software protocols	Yes	D6
To evaluate the total uncertainties associated with the combined rationalised methods and demonstrate the suitability for use as an array design tool.	Yes	D19

Table 16: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
In order to increase the number of farm deployments to 2GW by 2020 a robust array design and energy yield assessment tool is required. The objective is therefore to provide a tool within the life time of the project and that can be used by project developers without access to expensive computational resource.	Yes	D16, D17
The tool will also incorporate an added turbulence intensity model. Such a model will allow array designers to avoid placing devices in the path of excessive turbulent flow thus avoiding increase device unavailability.	Yes	D16, D17

WG3 WP5: Horizontal Axis & Open Centre Turbine Modelling

Table 17: Work Package Objectives

Objective	Achieved	Deliverable/Implications
Formulate numerical models of 2 (horizontal axis turbine and open centre turbine fundamental design concepts using alternative numerical methodologies to those used elsewhere in the project, thus providing cross methodology verification	Yes	D1, D2, D3, D4. Design tools for Open Centre turbines were developed and simulations of rotor only provided.
To provide this information to extend the numbers of FDCs modelled and to allow cross comparisons between alternative numerical approaches.	Yes	D1, D2, D3, D4.

Table 18: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
To provide rigorous experimental support for the planning of tidal current arrays	Yes	D1, D2, D3, D4. Design of experiments were supported

WG3 WP6: Horizontal Axis & Open Centre Turbine Modelling

Table 19: Work Package Objectives

Objective	Achieved	Deliverable/Implications
Develop a 2D numerical basin model to simulate the hydrodynamic effects of tidal energy extraction in a coastal basin.	Yes	D1, D2, D6
Use this model to (a) assess the large scale effects of tidal energy extraction from example UK sites and (b) to provide cross-verification of other basin scale numerical models.	Yes	D3, D4, D5, D7, D8

Table 20: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
Assessment of the large scale effects of tidal energy extraction from UK sites	Yes	D3, D4, D5, D7, D8

WG4 WP1: Horizontal Axis Turbine Testing

Table 21: Work Package Objectives

Objective	Achieved	Deliverable/Implications
To investigate, through physical testing of a single device (1/20th – 1/30th): • the detailed hydrodynamic performance of rotors in turbulent flows, • the effect of bounding surfaces on the device performance, and • the wake form and structures downstream a tidal device, as a function of flow profile, depth, ambient turbulence and waves.	Yes	D1, D2, D3, D4
Investigation of devices interactions within an array including the influence of turbulent structure and waves using scale model testing in various experimental facilities.	Yes	D1, D2, D3, D4

Table 22: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
To provide rigorous experimental support for tidal farms.	Yes	D1, D2, D3, D4
To enable greater certainty in the modelling tools required to design tidal arrays.	Yes	D1, D2, D3, D4

WG4 WP2: Array Tank Testing

Table 23: Work Package Objectives

Objective	Achieved	Deliverable/Implications
To investigate through physical testing of an array of small up to 15 devices (1/50th to 1/100th scale):	Yes	D1, D2, D3, D4
To evaluate the effect of bounding surfaces (free - surface, seabed and other devices) and device performance characteristics on the device loading	Yes	D5
To evaluate the effect of the bounding surfaces, ambient flow field and device performance characteristics on the far wake form	Yes	D5
To investigate the wake interactions within an array including influence of varying ambient turbulence intensities (seabed, waves and large eddies)	Yes	D5

Table 24: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
Enabling greater certainty in the modelling tools required to design tidal arrays	Yes	D1, D2, D3, D4, D5

WG4 WP3: Ducted Rotor Testing

Table 25: Work Package Objectives

Objective	Achieved	Deliverable/Implications
To provide experimental data quantifying: • the influence of turbine augmentation with duct on turbine performance and on wake structure; • the performance and wake of the UoM rotor in unconstrained flow; • the effect of bounding surface proximity on wake form.	Yes	D1, D2, D3

Table 26: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
To improve confidence in the range of application of wake models.	Yes	D1, D2, D3

WG4 WP4: Coastal Basin Testing

Table 27: Work Package Objectives

Objective	Achieved	Deliverable/Implications
To investigate the impact of arrays on the global flow field (e.g. the change in flow speed and elevation at regional/basin scale) through physical testing (>1/1000th scale). The results of such experiments yields two clear outcomes: • Provided robust validation of the array scale modelling of energy extraction • Will provide critical evidence for stakeholder assessing the viability of large scale energy extraction.	Yes	D1, D2, D3

Table 28: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
Enabling greater certainty of the impact of tidal arrays on the global flow field This piece of research has the potential to demonstrate the impact of large scale energy extraction on the global flow regime.	Yes	D1, D2, D3

WG4 WP5: Array Tank Testing

Table 29: Work Package Objectives

Objective	Achieved	Deliverable/Implications
Establishing through systematic field measurement, the nature of interactions between neighbouring 1/10th scale horizontal axis tidal rotors	No	No field data available to verify numerical models.
To provide this information to support the verification of numerical models	No	Increased uncertainty of numerical models as a result of being unable to verify them against field data.

Table 30: Marine Sector Objectives

Objective	Achieved	Deliverable/Implications
To provide rigorous experimental support for the planning of tidal current arrays	No	Increased uncertainty of numerical models as a result of being unable to verify them against field data.

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