User Organisation: Carnegie Clean Energy

User Project: High fidelity surface measurements to validate wave prediction schemes

Project Acronym: Wave PS

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Infrastructure Accessed Cantabria - Coastal & Ocean Basin

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MaRINET2

ABOUT MARINET

The MaRINET2 project is the second iteration of the successful EU funded MaRINET Infrastructures Network, both of which are coordinated and managed by Irish research centre MaREI in University College Cork and avail of the Lir National Ocean Test Facilities.

MaRINET2 is a €10.5 million project which includes **39 organisations** representing some of the top offshore renewable energy testing facilities in Europe and globally. The project depends on strong international ties across Europe and draws on the expertise and participation of **13 countries**. Over 80 experts from these distinguished centres across Europe will be descending on Dublin for the launch and kick-off meeting on the 2nd of February.

The original MaRINET project has been described as a *"model of success that demonstrates what the EU can achieve in terms of collaboration and sharing knowledge transnationally".* Máire Geoghegan-Quinn, European Commissioner for Research, Innovation and Science, November 2013

MARINET2 expands on the success of its predecessor with an even greater number and variety of testing facilities across offshore wind, wave, tidal current, electrical and environmental/cross-cutting sectors. The project not only aims to provide greater access to testing infrastructures across Europe, but also is driven to improve the quality of testing internationally through standardisation of testing and staff exchange programmes.

The MaRINET2 project will run in parallel to the MaREI, UCC coordinated EU marinerg-i project which aims to develop a business plan to put this international network of infrastructures on the European Strategy Forum for Research Infrastructures (ESFRI) roadmap.

The project will include at least 5 trans-national access calls where applicants can submit proposals for testing in the online portal. Details of and links to the call submission system are available on the project website www.marinet2.eu

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Table of Contents

1 Introduction & Background

1.1 Introduction

CCE is developing an advanced controller for its CETO technology enabling enhanced power production and survivability over standard controllers. This campaign was the first physical test dedicated to the development of this new controller.

Optimised controllers require accurate prediction of waves and hydrodynamic forces in real time. Contrasting with traditional CFD tools, recent advances in mooring and sensing technologies (allowing cheap distributed sensing of surface waves) and in sophisticated algorithms for wave prediction (e.g machine learning (ML)) put real-time accurate wave prediction within reach. CETO's smart controller therefore includes a wave predictor (WP), predicting surface elevation in space and time.

The aim of this campaign was to provide data to validate a Machine Learning WP (MLWP) and a physics based (deterministic) WP developed by The University of Western Australia.

1.2 Development So Far

1.2.1 Stage Gate Progress

Previously completed: ✓

Planned for this project: ➲

STAGE GATE CRITERIA	Status
Stage 1 – Concept Validation	
• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)	Choose an item.
• Finite monochromatic waves to include higher order effects (25 –100 waves)	
• Hull(s) sea worthiness in real seas (scaled duration at 3 hours)	
• Restricted degrees of freedom (DofF) if required by the early mathematical models	
• Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)	
• Investigate physical process governing device response. May not be well defined theoretically or numerically solvable	
• Real seaway productivity (scaled duration at 20-30 minutes)	
• Initially 2-D (flume) test programme	
• Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them	
• Evidence of the device seaworthiness	
• Initial indication of the full system load regimes	
Stage 2 – Design Validation	
• Accurately simulated PTO characteristics	
• Performance in real seaways (long and short crested)	➲
• Survival loading and extreme motion behaviour.	
• Active damping control (may be deferred to Stage 3)	
• Device design changes and modifications	
• Mooring arrangements and effects on motion	
• Data for proposed PTO design and bench testing (Stage 3)	
• Engineering Design (Prototype), feasibility and costing	
• Site Review for Stage 3 and Stage 4 deployments	

STAGE GATE CRITERIA	Status
• Over topping rates	
Stage 3 – Sub-Systems Validation	
• To investigate physical properties not well scaled & validate performance figures	
• To employ a realistic/actual PTO and generating system & develop control strategies	
• To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag	
• To validate electrical supply quality and power electronic requirements.	
• To quantify survival conditions, mooring behaviour and hull seaworthiness	
• Manufacturing, deployment, recovery and O&M (component reliability)	
• Project planning and management, including licensing, certification, insurance etc.	
Stage 4 – Solo Device Validation	
• Hull seaworthiness and survival strategies	
• Mooring and cable connection issues, including failure modes	
• PTO performance and reliability	
• Component and assembly longevity	
• Electricity supply quality (absorbed/pneumatic power-converted/electrical power)	
• Application in local wave climate conditions	
• Project management, manufacturing, deployment, recovery, etc	
• Service, maintenance and operational experience [O&M]	
• Accepted EIA	
Stage 5 – Multi-Device Demonstration	
• Economic Feasibility/Profitability	
• Multiple units performance	
• Device array interactions	
• Power supply interaction & quality	
• Environmental impact issues	
• Full technical and economic due diligence	
• Compliance of all operations with existing legal requirements	

1.2.2 Plan For This Access

The above table is oriented towards device testing, which makes it challenging to match stage gate criteria with what was achieved during this campaign, which was a wave-only campaign aimed at validating wave-prediction algorithms. The plan for this campaign is outlined in the below sections:

1.2.2.1 Irregular sea states

Irregular waves were generated, with the aim to obtain data for the training and validation of the ML wave predictor and the validation of the physics-based wave predictor. The tests covered over 22 sea states (Hs / Tp combinations), and 3 different wave spreads (one long crested and two short crested sets). With regards to the ML wave predictor, these tests were separated into 2 categories:

- Training runs: long runs aiming to generate enough training data for the ML wave predictor
- Validation runs: shorter runs, not used during training, on which the accuracy of the wave predictor is evaluated

1.2.2.2 Focused wave group tests

Focused wave groups are short duration deterministic simulations/runs, whereby the phase of each component is specifically chosen (as opposed to randomly assigned, as is the case in irregular random wave runs). The phases are chosen such that all the components come into phase at one point in time and space. Such wave group runs are therefore compact (in time and space) and allow for uncontaminated measurements/analysis in the absence of wave reflection (from the far end of the basin). These short and precise tests were run in short and long crested conditions, and are useful for validation of the physics-based predictor.

1.2.2.3 Inverse phase tests

The inverse phase runs allowed us to isolate the linear (main harmonic) components and higher harmonics. These runs were mainly aimed at validating the treatment of higher harmonics in the physics-based wave predictor. The inverse phase runs were carried out for both irregular sea states and focused wave group cases.

2 Outline of Work Carried Out

2.1 Setup

The Cantabria Coastal and Ocean Basin (CCOB) is 44 m wide and 30 m long, with a variable depth (depth adjustment is made through emptying / filling up the tank). A segmented piston-typewave maker is located along the width of the tank, generating waves propagating towards the absorbing wall. The side walls can be chosen to be either reflective or absorbing. It was decided to have reflective walls for the following reasons:

- There were concerns that absorbing walls would cause a diffraction pattern in the wave field, which could not be quantified.
- The spreading factor of short-crested runs was such that reflected waves seen at the prediction point would necessarily have been measured by the sensor array.

A full 1 day (10 July 2020) was spent installing the 19 wave gauges and 6 Acoustic Doppler Velocimeters (ADV) in the tank. The tank was filled up on the following day. The layout of the sensors is not disclosed in this report for IP protection reasons.

2.2 Tests

The tests started on 13 July, and ran over 6.5 days, until 21 July. Due to COVID19 measures, the tank operators were running two shifts per day (12 hours of testing per day), each shift running with half the usual staff count.

2.2.1 Test Plan

Test category		Duration
A	Operational long crested waves	8h
B	Operational medium spread	19h
C	Operational high spread	19h
D	Extreme long crested waves	2.5h
E	Extreme medium spread	5.5h
F	Extreme high spread	3.5h
G	Long-crested focused wave groups	1.5h
H	Medium-spread focused wave groups	5h
I	High-spread focused wave groups	2.5h
J	Inverse-phase runs	11.5h

Table 2.1 Test plan

2.3 Results

The test campaign has generated useful dataset across various sea states and wave conditions, which are valuable for comprehensively validating the two wave predictors.

1.1.1 ML wave predictor

The ML wave predictor was trained and tested on a dataset combining surface elevation measurements form tests A, B, C, D, E, and G (see Table 2.1). The results are presented in Figure 1, Figure 2 and Figure 3. In both these figures, the error is defined as the RMSE error normalised by the measured significant wave height. In Figure 1, it can be seen that the prediction error is constant over the prediction horizon, and increases with the directional spread.

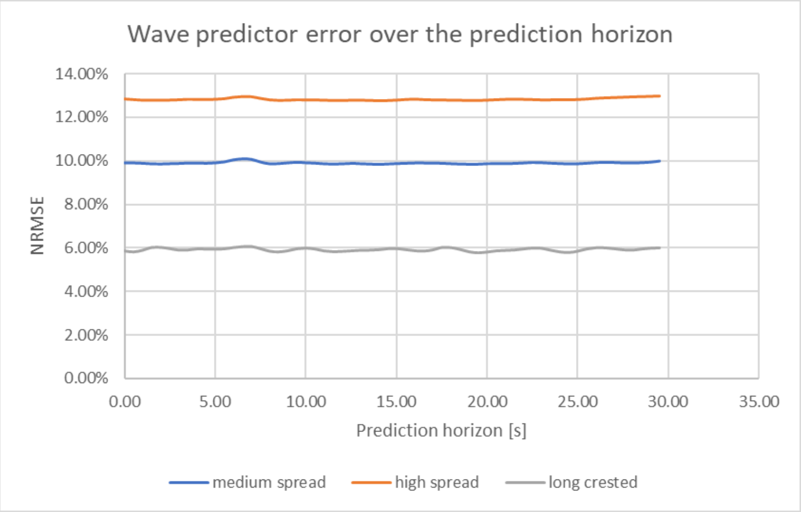


Figure 1: Wave prediction error (averaged across sea states)

In addition, it can be seen that the prediction error increases as the wave period decreases (Figure 2). The cause of this effect are still being investigated.

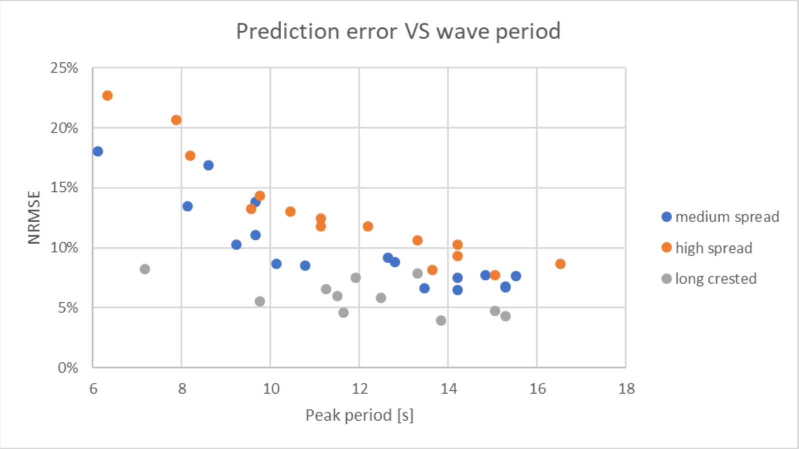


Figure 2: Influence of wave period on prediction error (averaged across prediction horizon)

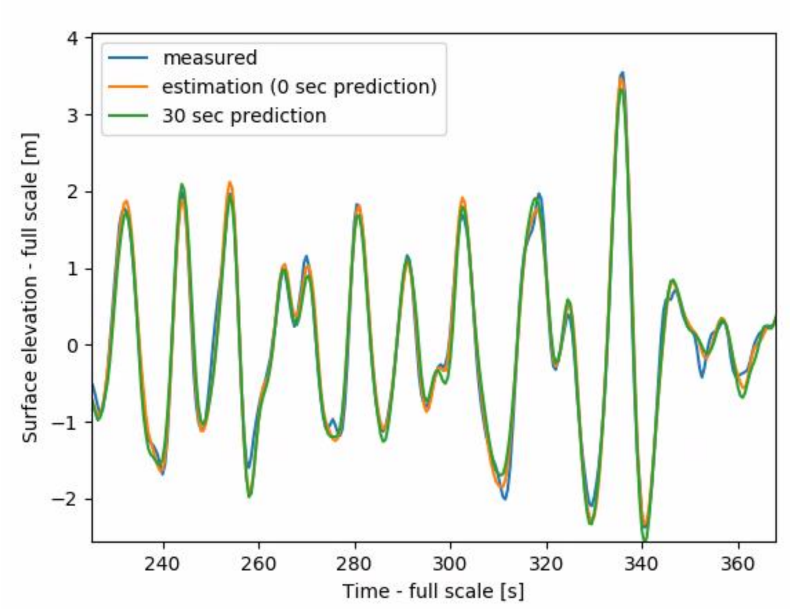


Figure 3: Prediction of unidirectional irregular waves, Hs = 5 m, Tp = 16 s

One of the objectives of this campaign was to prove that the number of required wave sensors for the wave predictor could be reduced, by using surface elevation and orbital velocity as an input. The ADV measurements proved to be problematic during the campaign, as the 1:40 scale of the tests meant that the wave generated were not energetic enough the keep the reflective particles in suspension. Though the measurements improved slightly through the campaign, the amount of useable data was not sufficient to generate a large enough dataset.

1.1.2 Physics-based wave predictor

The physics-based wave predictor works by taking the surface elevation measured at an up-wave location and propagating it down-wave to the desired prediction location according to the linear dispersion equation. For steep waves, higher harmonics are first removed from the signal before propagating the linearised signal to the desired location and adding back the bound higher harmonics. The predictor does not require any training data and runs orders of magnitude faster than real time.

The physics-based wave predictor has so far been well-validated using synthetic numerical data for waves of varying steepness. The use of tank data for validation presents new challenges, such as the presence of reflected waves due to the finite size of the basin, which affects the accuracy of prediction to varying degrees. To deal with this, reflection analysis was first carried out on the measured surface elevations to separate the reflected waves from the incident waves.

An example of wave prediction result using the physics-based wave predictor is shown in Figures Figure 4 and Figure 5.

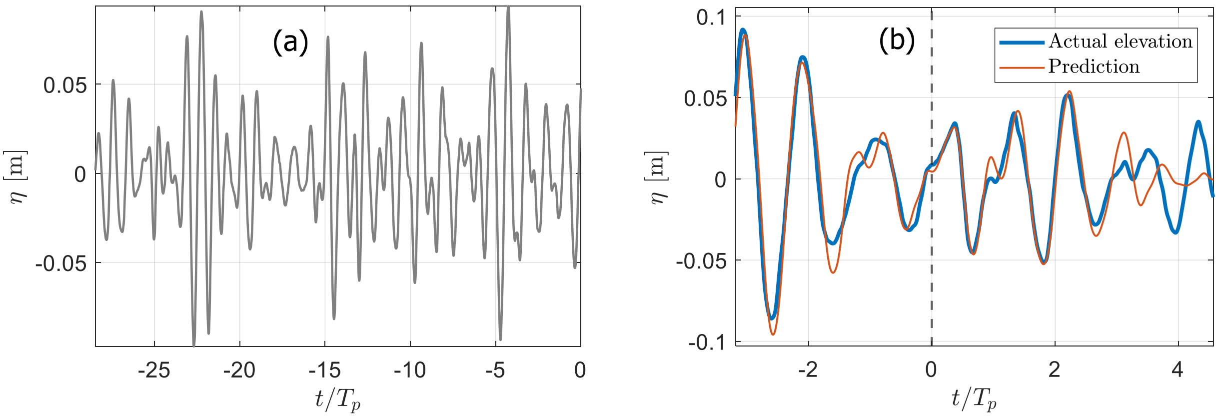


Figure 4: Prediction of unidirectional irregular waves at a point that is 4.2 m (1.1λ_p) down-wave. (a) Input record for the predictor, and (b) wave-fields at prediction point.

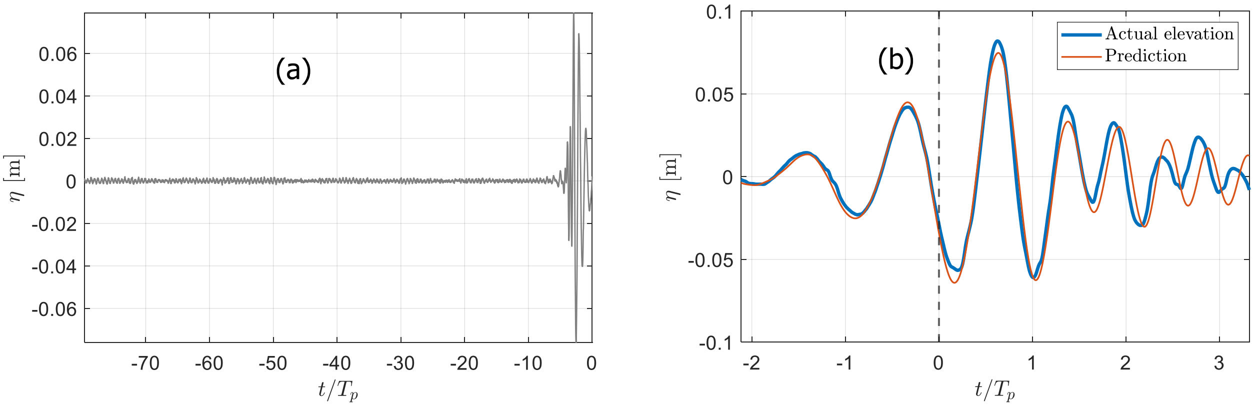


Figure 5: Prediction of unidirectional focused-wave groups at a point that is 7.8 m (1.6λ_p) down-wave. (a) Input record for the predictor, and (b) wave-fields at prediction point.

The spread focused wave tests were the first to be carried out in this basin. Some inaccuracies in the way these waves were generated were identified and were quickly rectified.

2.4 Analysis & Conclusions

The ML wave predictor has shown good accuracy in sea states expected at potential deployment locations. ADV measurements issues prevented sufficient data to be gathered to validate the orbital velocity prediction, although this is not expected to be a serious issue as the concept has already been proven with numerical data.

Good agreement is also obtained with the physics-based predictor, both for the irregular wave and the focused wave cases. The predictor currently assumes unidirectional wave propagation and work is underway to extend the method to spread seas. The spread wave data will be used for validation of the extended method.

3 Main Learning Outcomes

3.1 Progress Made

3.1.1 Progress Made: For This User-Group or Technology

We have validated the ML and physics-based wave predictors on a range of sea states which is representative of potential deployment locations for the CETO technology. Based on the above results, we are expecting to move to the next phase of which is the development of the controller. The campaign also highlighted the decrease in accuracy at lower periods

3.1.2 Progress Made: For Marine Renewable Energy Industry

This campaign has demonstrated the feasibility of real-time wave prediction, using physics and ML based algorithms. Wave prediction is a key element of all advanced WEC control algorithms. The results from this campaign put advanced control within reach of WEC developers.

3.2 Key Lessons Learned

- Accurate planning: detailed test plan (down to the minute) was very useful throughout the campaign as it allowed for changes to be made on the fly
- Ensure all instruments have been used/tested in similar wave conditions as those of the campaign would have avoided issues with ADV measurements
- Testing functions of the wave maker which are new to the tank operators, prior to the campaign, is beneficial in order to avoid delays.
- Checking measured data files throughout the campaign to spot any issues and allow for a re-run of any tests which had been corrupted.
- Keeping a detailed log of all tests and any issues and/or modifications. Together with video footage and photographs, these can be invaluable a few months down the line.

4 Further Information

4.1 Scientific Publications

List of any scientific publications made (already or planned) as a result of this work:

- The data analysis forms part of the PhD thesis work being undertaken by Thobani Hlophe and is expected to be used in subsequent publications (in planning).

4.2 Website & Social Media

Website:

https://www.carnegiece.com/

https://www.uwa.edu.au/

YouTube Link(s):

https://www.youtube.com/watch?v=OUX1yfcEX58

LinkedIn/Twitter/Facebook Links:

https://twitter.com/carnegieclean?lang=en

https://www.linkedin.com/company/carnegie-wave-energy/?originalSubdomain=au

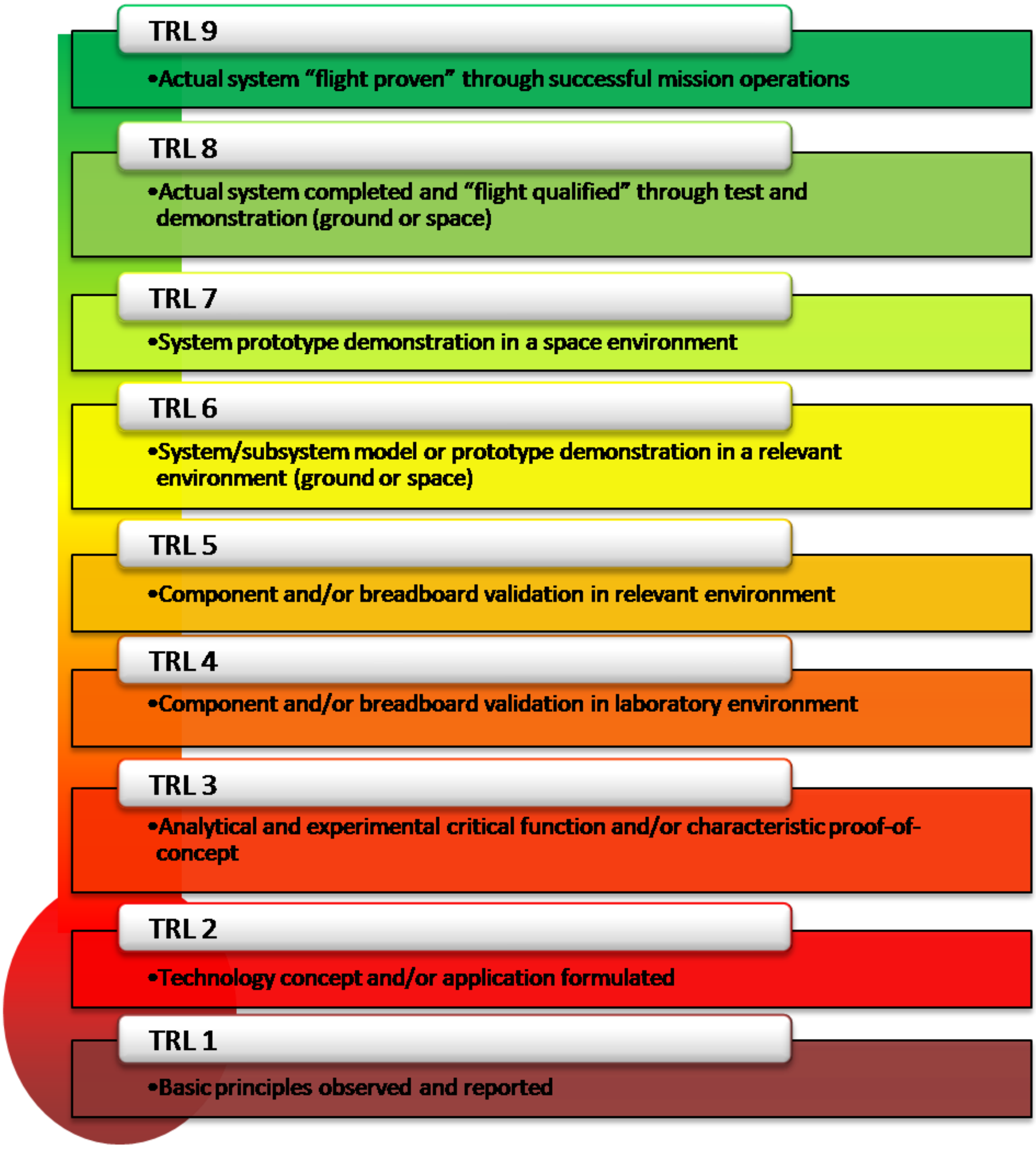
5 References

N/A

6 Appendices

6.1 Stage Development Summary Table

The table following offers an overview of the test programmes recommended by IEA-OES for each Technology Readiness Level. This is only offered as a guide and is in no way extensive of the full test programme that should be committed to at each TRL.



NASA Technology Readiness Levels[1]

[1] https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

NASA TRL Definition Hardware Description Software Description Exit Criteria

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modelling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test Performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in an operational environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test Performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results

DEVELOPMENT PROTOCOL	STAGE 1 CONCEPT VALIDATION			STAGE 2 DESIGN VALIDATION	STAGE 3 SYSTEMS VALIDATION		STAGE 4 DEVICE VALIDATION		STAGE 5 ECONOMICS VALIDATION
	TRL 1: Confirmation of Operation	**TRL 2: Performance Convergence**	**TRL 3: Device Optimisation**	**TRL 4: Sub-Systems Assessment**	**TRL5: Sub-Assembly Bench Tests**	**TRL 6: Full System Sea Trials**	**TRL 7: Solo, Sheltered, Grid Emulator**	**TRL 8: Solo, Exposed, Grid Connected**	**TRL 9: Multi-device Array (3-5)**
Objectives/ Investigations	Op. Verification Design Variables Physical Process Validate/Calibrate Maths Model Damping Effect Signal Phase	Real Generic Seas Design variables Damping PTO Natural Periods Power Absorption Wave to Devise Response Phase	Hull Geometry Components Configurations Power Take-Off Characteristics Design Eng. (Naval Architects)	Final Design Accurate PTO [Active Control] Mooring system Survival Options Power Production Added mass	PTO Method Options & Control Inst. Power Absorption Electricity Production & Quality	Scale effects of Overall Performance Characteristics Mooring & Anchorage Security Environmental Influences & Factors	Oper & Mains Procedures Electrical Output Quality Grid Supply, Stability & Security PTO Performance at all phases Control Strategy Seaworthiness, Survival & Lifecycle Analysis Device Array Interaction (Stages 1 & 2)		Grid Connection Array Interaction Maintenance Service Schedules Component Life Economics
Output/ Measurement	Vessel Motion Response Amplitude Operators & Stability Pressure / Force, Velocity RAOs with Phase Diagrams Power Conversion Characteristic Time Histories Hull Seaworthiness; Excessive Rotations or Submergence Water Surface Elevation Abeam of Devices			Motion RAOs Phase Diagrams Power v Time Wave Climates @ *head, beam, follow*	PTO Forces & Power Conversion Control Strategies	Incident Wave Field 6 D of F Body Motion & Phase Seaworthiness of Hull & Mooring [Survival Strategies]	Full On-Board Monitoring Kit for Extended Physical Parameters Power Matrix Supply forecasting	Array Interaction Annual Power Prod. Elec. Power Perfrm. Failure Rates Grid EIA reviews	Service, Maintenance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	λ = 1 : 25 - 100 (∴ λ_t = 1 : 5 - 10)			λ = 1 : 10 - 25	λ = 1 : 2 - 10		λ = 1 : 1 - 2		λ = 1:1, Full size
Facility	2D Flume or 3D Basin			3D Basin	Power Electronics Lab	Benign Site	Sheltered Full Scale Site	Exposed Full Scale Site	Open Location
Duration –*inc Analysis*	1-3months	1-3months	1 3 months	6 – 12 months	6 – 18 months		12 – 36 months		1 – 5 years
Typical No. Tests	250 - 750	250 - 500	100 - 250	100 - 250	50 - 250		Continuous		Statistical Sample
Budget (€,000)	1 – 5	25-75	25-50	50 - 250	1,000 – 2,500		10,000 – 20,000		2,500 – 7,500
Device	Idealised with Quick Change Options Simulated PTO (0-∞ Damping Range) Std Mooring & Mass Distribution		Distributed Mass Minimal Drag Design Dynamics	Final design (internal view) Mooring Layout	Advanced PTO Simulation Special Materials	Full Fabrication True PTO & Elec Generator	Grid Control Electronics or Emulator Emergency Response Strategies Pre-Production Pre-Commercial		Operational Multi-Device
Excitation / Waves	Monochromatic Linear (10-25Δ*f*) (25-100 waves)	Panchromatic Waves (20min scale) +ve 15 Classical Seaways Spectra Long crested Head Seas		Deployment -Pilot Site Sea Spectra Long, Short Crested Classical Seas Select Mean wave Approach Angle		Extended Test Period to Ensure all Seaways inc.	Full Scatter Diagram for initial Evaluation Continuous Thereafter Time & Frequency Domain Analysis		
Specials	DofF (heave only) 2-Dimentional Solo & Multi Hull	Short Crest Seas Angled Waves As Required	Storm Seas (3hr) Finite Regular As required	Power Take-Off Bench Test PTO & Generator	Device Output Repeatability Survival Forces	Salt Corrosion Marine Growth Permissions	Grid Emulator Quick Release Cable Service Ops	Stakeholder Consult. Health & Safety Issues	Small Array (Up-grade to Generating Station)?
Maths Methods (Computer)	Hydrodynamic, Numerical Frequency Domain to Solve the Model Undamped Linear Equations of Motion		Finite Waves Applied Damping Multi Freq Inputs	Time Domain Response Model & Control Strategy Naval Architects Design Codes for Hull, Mooring & Anchorage System. Economic & Business Plan			Economic Model Electrical Stab. Array Interaction	Grid Simulation Wave forecasting	Array Interaction Market Projection for Devise Sales
	EVALUATION [Stage Gates]								
Absorbed Power [kW]									
Converted Power [kW]									
Weight, [tonnes]									
Manufacturing Cost [€]									
Capture [kW/tonne] or [kW/m^3]	[200-50 m^3]								
Production [c/kW]	< 25 €c / kW			≤ 15 €c / kW			≤ 10 €c / kW		≤ 5 €c / kW