Final report

1. Project details

Project title	OES Task 10 WEC Modelling, Verification and Validation of Wave Energy Converters, Part II
File no.	64020-1105
Name of the funding scheme	EUDP
Project managing company / institution	Ramboll
CVR number (central business register)	35128417
Project partners	AAU, DTU, FPP
Submission date	31 March 2023

2. Summary

OES Task 10 is a permanent Tasks initiated in 2016 under Ocean Energy Systems (OES) a Technology Collaboration Programme (TPC) under The International Energy Agency (IEA) with focus on Modelling, Verification and Validation of numerical models used for Wave Energy Converters.

The objective is to improve confidence in the numerical tools of different fidelity used in the design of Wave Energy Converters and prediction of their power production. Calculations based on linear and weakly-nonlinear potential flow theory provide fast and reliable results which are suitable for the design process. High-fidelity, fully nonlinear potential flow or CFD models can provide more accurate and detailed results in cases with steep waves and/or large-amplitude responses, but they require careful and diligent set-up and validation to be reliable.

The development of Wave Energy Converters relies on numerical simulations to optimize and evaluate their designs and provide power performance estimates that feed into calculations of the Levelized Cost of Energy (LCoE). The reliability and accuracy of the numerical tools used is therefore of paramount importance.

Within the scope of the current phase of the project and based on the selected testcases, answers have been obtained to the original problem statement. Specifically, confidence has been gained in the numerical models and a first step made towards quantitative identification of model accuracy.

Summary in Danish

OES Task 10 er en permanent Task som blev startet i 2016 under Ocean Energy Systems (OES), et Technology Collaboration Program (TPC) under Det Internationale Energiagentur (IEA) med fokus på modellering, verifikation og validering af numeriske modeller for bølgeenergi maskiner.

Målet er at øge tilliden til de numeriske værktøjer, der anvendes til design af bølgeenergikonvertere og beregning af deres elproduktion. Beregninger baseret på lineær og svagt ikke-lineær potentialestrømningsteori giver hurtige og pålidelige resultater, der passer til designprocessen. High-Fidelity, fuldt ikke-lineært potentielt flow eller CFD-modeller kan give mere nøjagtige og detaljerede resultater hvis der er tale om stejle bølger, men det kræver omhu mht. opsætning og validering for at være pålidelige.

Udviklingen af bølgeenergikonvertere er afhængig af numeriske simuleringer for at optimere og evaluere deres design og give estimater for energiproduktion, der indgår i beregning af energipriser (LCoE). Pålideligheden og nøjagtigheden af de anvendte numeriske værktøjer er derfor af afgørende betydning.

Inden for rammerne af denne projektfase har projektet, med de valgte test eksempler, givet svar på den oprindelige problemformulering. Specifikt er der opnået tillid til de numeriske modeller og et første skridt mod kvantitativ identifikation af modelnøjagtighed.

3. Project objectives

The objective is to improve confidence in the numerical tools used in the design and prediction of power production from Wave Energy Converters. The development of Wave Energy Converters relies on numerical simulations to optimize and evaluate their designs and provide power performance estimates that feed into calculations of the Levelized Cost of Energy (LCoE).

The long-term objectives of the OES task 10 are:

1. To assess the accuracy and establish confidence in the use of numerical WEC models

2. To validate a range of validity of existing computational modelling tools

3. To identify uncertainty related to simulation methodologies to:

- Reduce risk in technology development
- Improve WEC energy capture estimates
- Improve loading estimates
- Reduce uncertainty in LCOE models

4. Define future research and develop methods of verifying and validating the different types of numerical models required depending on the conditions:

- Operational conditions significant wave height Hs<5 meters: Validation of energy production and power take-off (PTO) optimization
- Survival conditions significant wave height Hs > 12 meters: Validation of structural and mooring system loads, and operation of the PTO and structural motion in extreme conditions

The OES Task 10 on WEC modelling verification and validation was identified in 2016 as a task that was very suitable for international co-operation, with the overall goal to assess the accuracy of the numerical models used, and to improve confidence in these codes. The task is like offshore wind validation/verification projects (OC3-OC5 conducted within IEA Wind Task 30).

4. Project implementation

The OES task 10 started without financial support, a period in which the teams conducted numerical coding and calculations, included two webinars in which the preliminary results were discussed. At the Workshop held in March 2017 it was agreed to prepare a reference paper based on these results for the EWTEC conference 2017. To bring the work further the US, Sweden and the Danish participants had received national funding, and all other partners agreed to try find their own financial support.

Participation is open to all interested partners, and initially a total of 29 organizations from 13 countries joined the project. The participants include universities, research laboratories, commercial software developers, consultants and WEC developers. The numerical models range from linear and weakly nonlinear potential flow models, to fully nonlinear potential-flow models, and fluid dynamics (CFD) solvers.

The work in the OES Task 10 WEC modelling task is, so far, mainly focused on operational conditions, concentrating on a range of regular wave cases and a few irregular sea states, so there was a risk that the focus was too narrow and leaves out extreme loading cases. During the project, complimentary work is being undertaken in the Collaborative Computational Project in Wave Structure Interaction, in which members from the wider wave structure interaction community have been participating in blind comparative studies involving the interaction of focused wave events with various surface-piercing structures. Also, the network WECANET has emerged under which simulations and experiments are undertaken. The OES Task 10 has chosen the strategy to cooperate with these emerging groups of similar interest and benefit from these additional efforts undertaken – and so far, this strategy has been successful.

The project has developed according to the scheduled plan. The detailed description and choice of the test cases were selected along the way by the participating experts of the OES Task 10 group and based on their actual interests and needs. This approach has been successful and necessary as many of the participating partners carried out the work without funding.

Problems that were not expected have been related to the quality of experimental data selected for verification. The participants found even selecting high quality test data at relatively large scale – imposed a challenge when it came to detail. This could be simple issues such as calibration errors, synchronisation of time series of different measured quantities etc. Surprisingly, there were also more fundamental problems in obtaining an accurate description of the undisturbed incident wave in some experiments. Such problems could lead to delays in deliverables, but at the same time comfort could be found in the fact that the simulated results compared well between the partners – which lead us to challenge to accuracy of the experimental measurements.

5. Project results

Within the scope of the current phase of the project, confidence has been gained in the numerical models and a first step towards quantitative identification of model accuracy has been made. The main unexpected result of the project was the level of difficulty that exists in obtaining high-quality experimental data which is suitable for distinguishing the accuracy of the different numerical models.

This international collaboration under the OES project builds on results obtained by experts from different member states. The principles for simulation and analysis were developed as part of the project. The Specification of output data format for Post-processing and Analysis was provided in the writeup, in connection with each numerical testcase.

All participants submitted their results from simulating the response of the WEC over each experimental condition. This included: their model of the incident wave forcing; the motion response of the device; forces on the device, including Power Take Off (PTO) forces; and the absorbed power. All simulated data was then analysed and compared the experimental data both directly (as time-series) and statistically.

The results of the OES Task 10 participants show in general good agreement between the different numerical models. Although the comparison with experiments in was general reasonable, it was not possible to draw firm conclusions about the relative accuracy of the different models, due to the uncertainties in the experimental measurements.

As part of the DTU fixed OWC test case, the OWC chamber was fitted with “one way” valves. This provided an opportunity to validate simulation of even more nonlinear PTO damping models, compared to orifice damping only. One-way absorption has the potential to significantly improve the efficiency of energy generation.

The calculation of annual energy production from waves depends on both the distribution of the wave conditions and the WEC, and the importance of which will be integrated in future phases of the project.

As a first step towards the goal of high-quality benchmark experimental data with well-defined uncertainties, a dedicated experimental program was initiated as part of this EUDP project. An aluminium sphere of 300mm in diameter was constructed to extremely high tolerances, both in terms of its geometry and its mass properties. A dedicated drop-test mechanism was also built and confirmed to produce a high-accuracy impulsive release of the body to produce decay test data at various initial drop heights. Measurement of the motion was confirmed to be accurate to well below 1mm. This data made it possible to characterize the accuracy of numerical simulations carried out in the first phase of the project. Since the original calculations were made at a much larger scale than the experiments, the CFD simulations were re-run at the correct scale to finalize the comparison. This work was presented in a *Highly Accurate Experimental Heave Decay Tests with a Floating Sphere A Public Benchmark Dataset for Model Validation of Fluid–Structure Interaction:* https://www.mdpi.com/1996-1073/14/2/269

The project results and progress has been presented with short PowerPoint presentations form for the ExCo meetings, by the co-ordinator.

OES EXCO 39 Webinar_Task 10 Wave 04-11-2020

OES EXCO 41 Webinar Task 10 Wave 19-05-2021

OES EXCO 43 Webinar Task 10 Wave 08-12-2021

OES EXCO 47 Webinar Task 10 Wave 20-03-2023

Annual progress reports on the OES Task 10 Phase II have been submitted to the OES annual report 2020, 2021 and 2022. These reports include a status report on the Danish Wave Energy sector – and the reports have been submitted to the Danish Partnership for Wave Power: www.wavepartnership.dk. The annual reports can be found at the links below:

https://www.ocean-energy-systems.org/publications/oes-annual-reports/document/oes-annual-report-2020/

https://www.ocean-energy-systems.org/publications/oes-annual-reports/document/oes-annual-report-2021/

https://www.ocean-energy-systems.org/publications/oes-annual-reports/document/oes-annual-report-2022/

The project has in addition been disseminated via the following webinars

26-01-2021 WEBINAR OES TASK 10 KRISO OWC

- Agenda:
- Introduction and overview (KIN)
- Review of the KRISO OWC simulations and results case (Hi-shiang)
- Special Journal Paper - content and conclusions (Harry Bingham) -
- Next step –
  - Annual Energy Production from Kriso OWC scaled up by 4 to a at selected wave climate. (i.e. the Port of Hanstholm DanWEC)
  - New OWC test case and selected experiments

The results are presented in the paper:

Ocean Energy Systems Wave Energy Modelling Task 10.4: Numerical Modelling Of A Fixed Oscillating water Column https://www.mdpi.com/1996-1073/14/6/1718

28-01-2021 SPHERE FULL WEBINAR

Highly Accurate Experimental Heave Decay Tests with a Floating Sphere:

A Public Benchmark Dataset for Model Validation of Fluid Structure Interaction

1. Presentation and discussion of the methodology and results (Morten Kramer and Jacob Andersen AAU)

2. Next step Suggestions and discussion of new experimental validation tasks using the sphere (Kim Nielsen / Morten Kramer)

- Diffraction and radiation force experiments.
- Sphere connected to pulley at seabed via PTO

The results are presented in the paper:

Highly Accurate Experimental Heave Decay Tests with a Floating Sphere A Public Benchmark Dataset for Model Validation of Fluid–Structure Interaction: https://www.mdpi.com/1996-1073/14/2/269

2021-06-23 DTU Fixed OWC test case

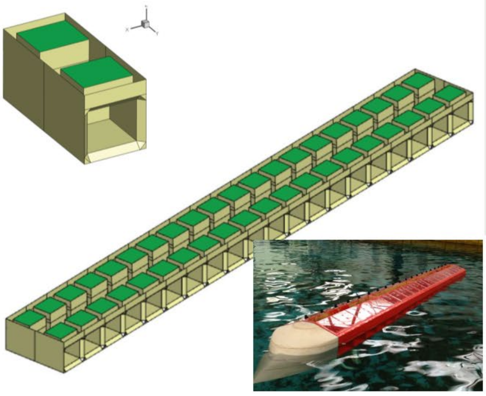
- The test case general description and plan (Kim Nielsen, Ramboll)
- Available test data and numerical data (Harry Bingham, DTU)
- Data sharing and filing system (Yi Hsiang, NREL)

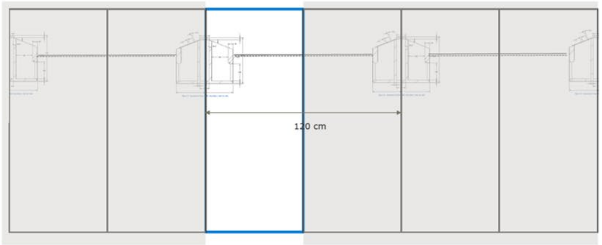
	Structure dimensions	
	Real	Scale
Length	150 m	3 m
Width	17.25 m	0.345 m
Height	13.5 m	0.27 m
Thickness	0.23 m	0.0046 m

Table2 : Dimensions of the full structure

	Chamber dimensions	
	Real	Scale
Length	7.5 m	0.15 m
Depth	5 m	0.10 m
Wall thickness	1.5 m	0.03 m

Table1 : Dimension of one OWC chamber



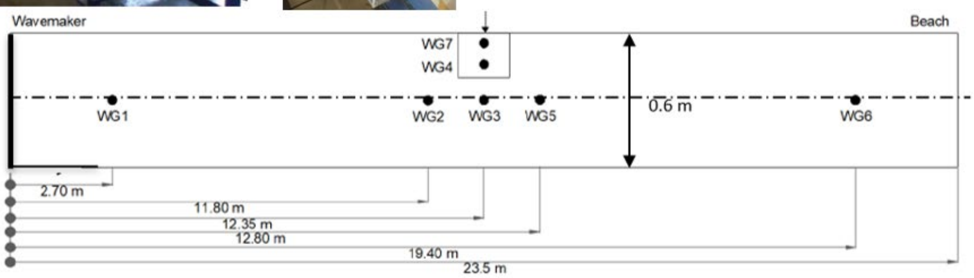


- Consider mirror effect of half model in flume → Half model in CFD simulation

Figure 1 Illustration of the experimental setup of the half sections of a section of the KNSwing attenuator WEC

2022-01-20 DTU Fixed OWC test case, review status 1

EXPERIMENTAL SETUP OF SINGLE CHAMBER IN FLUME



RAMBØLL

2022-01-20 DTU Fixed OWC test case, review status 2

Discussion on which metrics to compare? The amplitudes of response, (flow through orifice), phase relations compared to wave elevation, the pressures (if not open chamber), power – amplitude and average.

2022-06-23 DTU Fixed OWC test case, review status 3

$$Q(t) = C_d A_o \sqrt{\frac{2|\Delta P(t)|}{\rho_a}} sign(\Delta P) \quad (1)$$

$$x_7(t) = \frac{a_1(t) + a_2(t)}{2} \quad (2)$$

$$Q(t) = \frac{dx_7(t)}{dt} S_i \quad (3)$$

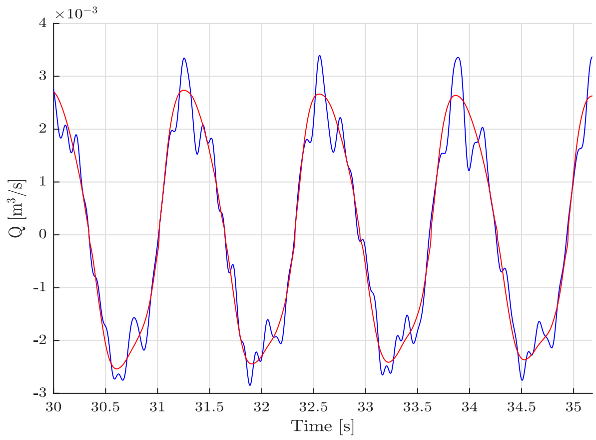


Figure 1 Comparison of the air-volume flux computed from the pressure measurement Eq. 1 (red curve) and the air-volume flux computed from the 2 wave probes Eq. 3 (blue curve). H=0.099m T=1.31s. Cd=0.64.

2022-11-17 DTU Fixed OWC test case, review status 4

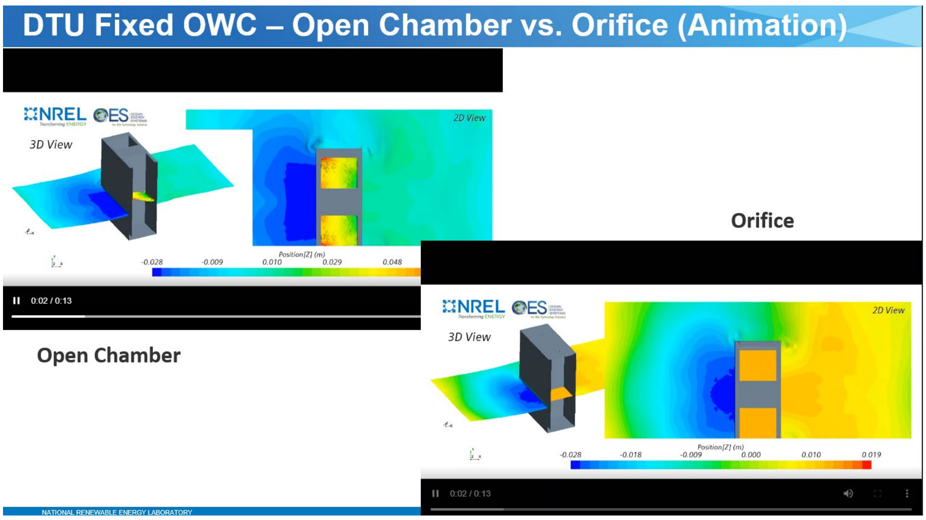


Figure 2 Visualization of CFD simulations of the Double chamber from NREL USA

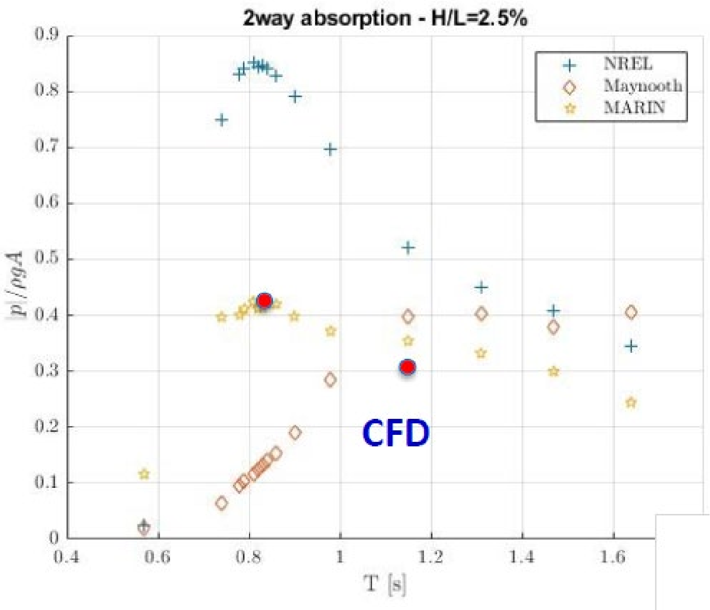


Figure 3 Capture width ration using orifice 2 way absorption (resonance given around 0.82 sec)

2023-01-26 Sphere Diffraction and radiation force experiments

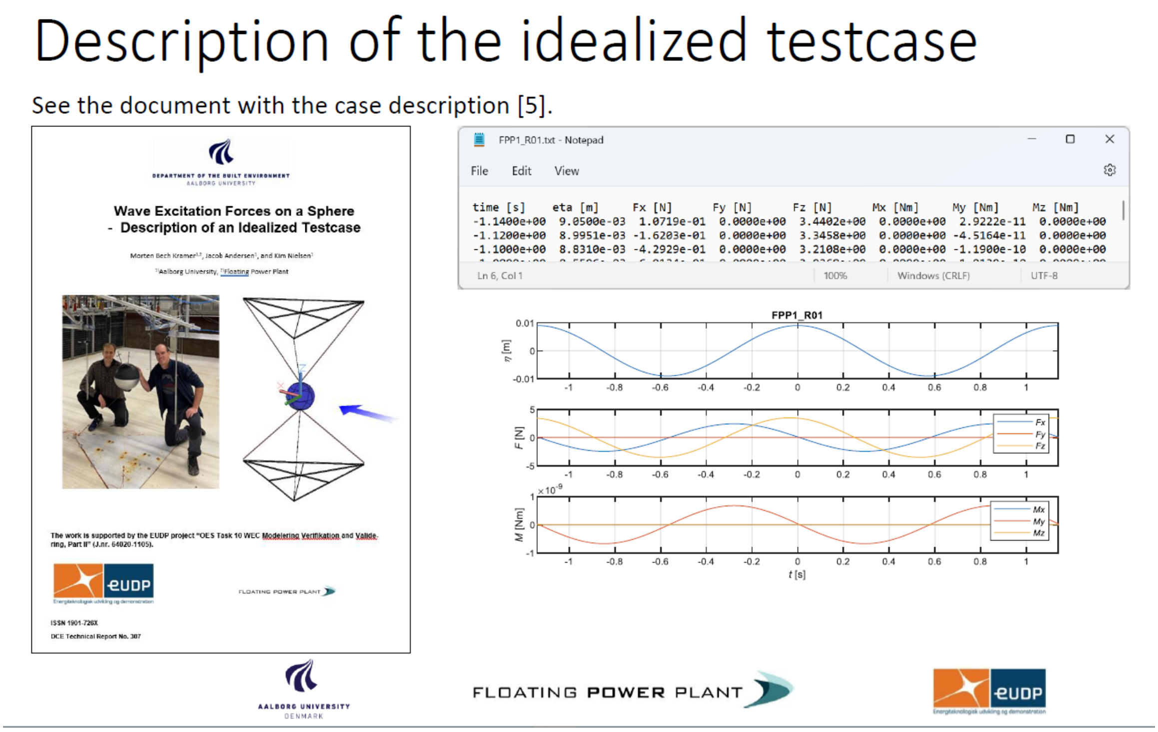


Figure 4 Experimental set-up of the fixed sphere

Paper in progress: “Ocean Energy Systems Wave Energy Modelling Task 10: Benchmark Study of the DTU OWC Chamber with One-Way Absorption".

6. Utilisation of project results

The task on Numerical modelling of WECs is established as a permanent task. That means that the modelling task will continue if there is an interest and motivation among the participating members and as long as they can find the resources to carry out the work.

There are in respect to numerical models no patents involved at this stage, the use of open access simulations is encouraged. As an example, the NEMOH – Open source BEM solver http://openore.org/tag/nemoh/and the WEC Sim software developed by NREL http://wec-sim.github.io/WEC-Sim/, and the DTUMotionSimulator software DTU OceanWave3D / DTUMotionSimulator · GitLab.

This international OES Task 10 project provided the opportunity to collaborate on numerical and experimental results from Wave Energy Conversion systems provided and obtained by experts from different member states. Established as a permanent task under OES-IEA Technology Collaboration Platform it is possible to continue and expand the work into the future. This gives a unique chance for the participants and members to define and find the necessary resources to carry out the work. Within the scope of the current phase of the project, answers have been obtained to the original problem statement. Specifically, confidence has been gained in the numerical models and a first step towards quantitative identification of model accuracy has been made.

In relation to the project two PhD students have been involved – one from DTU assisting in collecting and comparing simulations and results submitted by participants, and one from AAU assisting in developing and testing simulation of highly accurate experimental setups for model validation.

7. Project conclusion and perspective.

The conclusions drawn from this project can be summarized as follows:

1. Calculations based on linear and weakly-nonlinear potential flow theory provide fast and reliable results which are suitable for all phases of the design process.
2. High-fidelity, fully nonlinear potential flow or CFD models can provide more accurate and detailed results in cases with steep waves and/or large-amplitude responses, but they require careful and diligent setup and validation to be reliable.
3. Most existing model test data is not suitable for distinguishing the relative accuracy of different numerical models, due to large uncertainties in the generated incident waves and/or the measured device responses. There is a need for dedicated, high-quality benchmark experimental data with well-defined uncertainties.

The main result of this study is the reliability of results of using linear, weakly nonlinear and fully nonlinear models in small and medium wave conditions. This is an important result and shows that linear models can be used instead of computationally costly nonlinear ones for most design purposes.

In this work, numerical modelling tools with different levels of fidelity have been used, in terms of capturing nonlinear hydrodynamic effects, to simulate two different heaving bodies and one OWC chamber. The code-to-code comparison revealed the significant impact of geometric nonlinearities on the simulation results. The weakly nonlinear models that consider the instantaneous wetted surface for hydrostatic and wave forcing forces can capture the impact of geometric nonlinearities on the response of the system. These nonlinear effects eventually impact the power performance predictions.

However, larger differences among the different models was observed in association with strong nonlinearities. Some of these differences can be attributed to the fact that CFD-type models require a lot more input from the user in terms of model definition (e.g., meshing, solver settings, and turbulence models). Some of the differences among the various high-fidelity CFD solutions are also related to the fact that different simplifications were applied to model the flow field (e.g. inviscid and irrotational flow versus URANS-type models). It should also be noted that, for cases including wave breaking, fully nonlinear potential flow methods show divergent behaviour, indicating that the assumption of potential flow is no longer valid.

For the longer simulations that involve waves, especially irregular waves, only very few solutions with strong nonlinearities were supplied by the participants, which highlights the limitations regarding the application of CFD tools to simulate a wide range of wave/design conditions. Simulating many wave conditions eventually yields a significant amount of work in terms of meshing, which adds to the inherently large computational costs of CFD models.

The partners use the results of the OES Task 10 project as follows:

1. To market their services and acquiring new clients or projects.
2. To developing more precise numerical methods and obtaining the insight to select between a portfolio of different numerical tools for certain calculations.
3. To establish a database of benchmark calculations and experimental measurements as a foundation for future projects to build upon.

There is a huge market potential in development, design, building and deployment of Wave Energy Converters which can support the objective of the overall energy policy of a carbon free renewable energy production. In order to tap into this potential, the wide number of competing ideas and WEC concepts must be validated, and the technologies need to converge to a set of competitive designs. In this process the cooperation under OES Task 10 on numerical model validation can play a significant role.

The future development of wave energy converters (WECs) will be increasingly reliant on numerical simulations to optimize and evaluate their designs and provide the power performance estimates that feed into the levelized cost of energy (LCoE) predictions. The reliability and accuracy of the numerical tools is therefore of paramount importance.

The “performance before readiness” path, put forward by Jochen Weber in 2012, argues that it is most economical to make the WEC optimization and major design choices early in the development process (at low TRL). The history of WEC development has shown many cases of over-promising and companies that after the first deployment discovered a poor performance and too costly structure. To achieve a high technology performance and low LCOE, before building and deploying a costly WEC prototype requires several optimization iterations using numerical tools and validations using physical tests, providing confidence in the concept.

There is still a need for solid verification and validation of numerical codes used in wave energy applications, both in terms of how the overall level of fidelity depends on the hydrodynamic model, and how different choices within each sub-category affect the accuracy and reliability of the computed results. Investigation of these questions is the aim of the OES Task 10 on the verification and validation of simulation tools for wave energy systems.

8. Appendices

Link to OES Annual reports that are published in the project period.

https://www.ocean-energy-systems.org/publications/oes-annual-reports/document/oes-annual-report-2020/

https://www.ocean-energy-systems.org/publications/oes-annual-reports/document/oes-annual-report-2021/

https://www.ocean-energy-systems.org/publications/oes-annual-reports/document/oes-annual-report-2022/

OES home page where results and descriptions are stored.

https://www.ocean-energy-systems.org/oes-projects/wave-energy-converters-modelling-verification-and-validation/

Journal Papers:

Ocean Energy Systems Wave Energy Modelling Task 10.4: Numerical Modelling Of A Fixed Oscillating water Column https://www.mdpi.com/1996-1073/14/6/1718

Highly Accurate Experimental Heave Decay Tests with a Floating Sphere A Public Benchmark Dataset for Model Validation of Fluid–Structure Interaction: https://www.mdpi.com/1996-1073/14/2/269