VERY LARGE SCALE WAVE ENERGY CONVERTERS

ANALYSIS OF THE INNOVATION LANDSCAPE

WES_LS07_ER_Very_Large_Scale

Revision	Date	Purpose of issue
1.0	28.11.2018	First WES release

Job number 260796-00

Ove Arup & Partners Ltd
13 Fitzroy Street
London
W1T 4BQ
United Kingdom
www.arup.com

ARUP

Document Verification

ARUP

Job title	Very Large Scale Wave Energy Generation	Job number 260796-00
Document title	Analysis of the Innovation Landscape	File reference
Document ref		

Contents

List of Acronyms

AHTS	Anchor Handling Tug Supply
EMEC	European Marine Energy Centre
FOWT	Floating Offshore Wind Turbines
LCoE	Levelised Cost of Energy
MAEP	Mean Annual Energy Production
NumWEC	Numerical benchmarking study of a selection of Wave Energy Converters [2]
OWC	Oscillating Water Column
PCC	Power Conversion Chain
PTO	Power Take-Off
RCW	Relative Capture Width
TLP	Tension-Legged Platform
TRL	Technology Readiness Level
WEC	Wave Energy Converter
WES	Wave Energy Scotland
WTGs	Wind Turbine Generators

Executive Summary

This report describes a study commissioned by Wave Energy Scotland (WES) into the potential of very large scale (10MW+) Wave Energy Converters (WECs). The study aims to quantify opportunities associated with very large scale wave energy generation and provide recommendations for the future approach to its realisation.

For the purposes of the study, large scale wave energy generation was defined as a WEC with an energy rating of 10MW in line with established offshore wind capacity. Three possible large scale WEC configurations were considered:

1. Scaling existing individual WEC types;
2. Grouping normal scale devices on a shared structure; and,
3. Development of a novel large scale WEC.

The project was undertaken in three stages. Stage I considered the entire WEC landscape through a developer survey and literature review. Stage II quantified the potential opportunity and limits associated with scaling the most common WEC geometry types. Stage III comprised a more detailed opportunities assessment, focused on cost-effective and practical large scale WEC configurations identified in the previous stages.

The Stage I literature review highlighted the main large scale cost reduction drivers in offshore wind as installation costs and O&M costs. Limited existing research into novel WEC concepts, which specifically target large individual devices, was found. The majority of large scale WEC research and development involved concepts comprising multiple devices installed on a shared platform. The results of the survey mirrored this finding; none of the respondents believed that scaled-up versions of their current concept represents the ideal way forward and grouping of multiple units on a single platform is seen as the most feasible option.

Stage II included scaling existing device geometries to quantify energy performance & CAPEX and assess construction & installation feasibility. Existing geometries were taken from the NumWEC project [2], including individual and grouped concepts. An energy performance scaling assessment highlighted that the gains in energy yield with device size diminish at a certain size for individual large scale WECs and therefore an optimum exists. The optimum size depends on the device in question and the site resource but was found to be <10MW for the devices investigated across a range of sites. Structural scaling revealed the significant cost associated with shared structures, highlighting the need for an optimised arrangement to make grouped configurations cost effective. A number of suitable sites in Scotland were identified with sufficient physical capacity for construction of large scale WECs considering the global dimensions and masses estimated in this study. The structural CAPEX/MW was calculated for the concepts investigated. This indicated a number of configurations with potential for maintained or reduced CAPEX/MW at a 10MW scale.

Stage III comprised a quantitative comparison between a baseline array of 100 x 1MW individual devices, an array of 10 x 10MW individual devices and an array

of 100 x 1MW devices on a shared structure. The Stage II assessment was expanded to include a more detailed energy performance estimate, an OPEX study and assessment of electrical infrastructure and installation campaign CAPEX. This enabled estimation of the Levelised Cost of Energy (LCoE) for the large scale configurations relative to a baseline array of 1MW devices. The energy performance assessment was performed for three sites to assess the sensitivity of large scale WECs to the available wave resource. The sites covered the range of theoretically available global wave energy resource.

10 x 1MW devices grouped on a shared structure were found to realise CAPEX per MW reductions whilst maintaining similar energy performance to the baseline. However, this type of configuration has significant technical risks and a complex installation campaign. If these could be overcome, it would represent a promising option for large scale WEC deployment.

A high LCoE was predicted for the large scale individual device array (10 x 10MW devices) compared to the baseline. This was due to the difficulty in ensuring the power performance of 10MW individual concepts. The LCoE difference was reduced at more energetic sites, but it seems unlikely that the 10MW+ individual devices investigated in this study could achieve the required energy performance at sites suitable for actual installation due to the proximity to shore and depth.

The feasibility of novel individual large scale WEC configurations was investigated through the Stage I literature review, however few examples were found. In light of this, generic criteria for an idealised large scale WEC were developed based on the findings of the study. These criteria aim to detail the limitations, areas of most opportunity and key drivers to enable large scale WECs and provide guidance for future development of novel large scale devices.

The study considered a range of existing device types but as-yet unknown alternatives may exist with greater energy performance at a large scale. Future research into individual devices with more energy scaling potential is recommended. The study highlighted that an optimum device size exists based on a CAPEX/MW metric. This was found to be in the range 2 - 5MW for the WEC devices investigated. Research to identify the optimum size of other existing devices, which is likely to be above 1MW but less than 10MW, would also be of value. The benefit of grouped devices would be enhanced by further development to reduce technical risk. The study also revealed evidence of grouped devices being commercially unfeasible at demonstrator stage due to high costs associated with early deployment. Development of a roadmap for funding, commercial and logistical deployment of large scale WECs is therefore recommended.

1 Introduction

1.1 Background

This report describes a study commissioned by Wave Energy Scotland (WES) into the potential of very large scale (10MW+) Wave Energy Converters (WECs). The study aimed to quantify opportunities associated with very large scale wave energy generation and provide recommendations for the future approach to its realisation.

Significant cost reduction associated with increased device size has been seen in other offshore renewable industries, most notably in offshore wind. Offshore wind turbine size is predicted to continue to increase rapidly, with 13-15 MW wind turbine generators (WTGs) expected to be on the market by 2025. A number of factors have contributed to this cost reduction and large scale wave energy devices may also be able to make similar strides in competitiveness.

In light of this, WES have commissioned this ‘analysis of the innovation landscape’ study to quantify the opportunity and limitations associated with very large scale wave energy generations. These landscaping studies aim to provide sector wide information and to inform WES on promising innovation opportunities on which to focus future research projects. WES have commissioned a number of ‘innovation calls’; significant research projects which aim to develop commercial subsystems with potential for enabling step change cost reductions in WEC devices. The focus of these calls is in part guided by these landscaping studies.

1.2 Study Objectives

In support of WES’s aim, the objectives of the study include;

- Estimation of the Levelised Cost of Energy (LCoE) benefit of potential large scale WEC configurations relative to a common baseline and confirmation of the practical feasibility;
- Identification of sector wide limitations, dependencies and risks associated with large scale WECs;
- Recommendations for further research to realise the opportunities identified, e.g. future WES innovation calls.

1.3 Scope and Definitions

The project considered scaling existing WEC device types, grouping devices on a shared structure and development of novel large scale device types. In line with this, the following definitions have been assumed for this study:

- **Large Scale WEC:** Considered to be those with a rated generation capacity >10MW, commensurate with offshore wind.

- **Scaled Existing Devices:** Increasing the size of current state-of-the-art WEC concepts.
- **Grouped Devices:** Combination of WEC devices onto a single platform with shared infrastructure e.g. PTO, moorings, foundation.
- **Novel Devices:** WEC concepts not currently in development which would be enabled by large scale deployment. This was primarily addressed through development of a design criteria for an idealised large scale WEC (Section 7.2).

1.4 Report Structure

The project was undertaken in a three-stage tiered approach to consider the entire technology landscape and then the most promising large scale configurations in more detail. The report is presented in these stages as follows:

- An overview of the methodology is provided in Section 3.
- Stage I considered the entire WEC landscape through a sector wide survey and literature review and is reported in Section 4.
- Stage II comprised quantitative assessment into the potential opportunity and limitations based on scaling the main existing WEC types. Stage II is reported in Section 5.
- Stage III comprised a more detailed opportunities assessment, focused on cost-effective and practical large scale WEC configurations as identified in the previous stages. Stage III is reported in Section 6.
- The main conclusions are summarised in Section 7.

2 References

2.1 Technical References

[1] Wave Energy Scotland (2016). Structural Forces and Stresses for Wave Energy Devices - Landscaping Study. Report prepared by Ove Arup & Partners (Scotland) Ltd and Cruz Atcheson Consulting Engineers Lda.

[2] Babarit, A., et al. (2012). Numerical benchmarking study of a selection of wave energy converters. Renewable Energy, 41, 44-63.

[3] Tolman, H.L., 2009. User Manual and System Documentation of WAVEWATCH III Version 3.14. Tech. Note 276, NOAA/NWS/NCEP/MMAB, 220 pp.

[4] IEC/TS 62600-100 (2013) Marine Energy – Part 100: Electricity Producing WEC – Power Performance Assessment

[5] Budal K., Falnes J., 1975. A resonant point absorber of ocean waves. Nature 256 478–479. with Corrigendum in vol. 257, p.626.

[6] Evans D.V., 1976. A theory for wave-power absorption by oscillating bodies. Journal of Fluid Mechanics 77 1–25.

[7] Newman J.N., 1976. The interaction of stationary vessels with regular waves. Proceedings of the 11th Symposium on Naval Hydrodynamics, London, pp. 491–501.

[8] Falnes J., 2007. A review of wave-energy extraction, Marine Structures 20 (4) 185–201.

[9] Hals Todalshaug J., 2013. Practical limits to the power that can be captured from ocean waves by oscillating bodies. International Journal of Marine Energy 3–4 (2013) e70–e81

[10] S. Salter. Looking back. In J. Cruz, editor, Ocean Wave Energy, pages 7-38. Springer, 2008

[11] Wave Energy Scotland, LCoE Calculation Tool WES-NWNN-ER01-v.2.5.xlsx, Wave Energy Scotland, 2017

[12] WES_ARP_MC11_D07 WES CREATE Manufacturing Report, Arup, 2017

[13] WES_ARP_MC11_D05_CREATE Interim Report, Arup, 2017

[14] Quoceant, 2016. Power Take-off: Non-confidential summary report

[15] Internal Arup data on offshore wind cable procurement

[16] Marine Energy Challenge, Oscillating Water Column WEC Evaluation Report, Carbon Trust, 2005

[17] Sharkey, F., 2014. Offshore Electrical Networks and Grid Integration of Wave Energy Converter Arrays

[18] Wave Energy Scotland (2018). Electrical Architecture Landscaping Study

[19] ORE Catapult (2015) Marine Energy Electrical Architecture, Report 3: Optimum Electrical Array Architectures

[20] IEA Wind Task 26 (2016), Offshore Wind Farm Baseline Documentation

[21] Internal Arup data

[22] Quoceant, 2016. Economics: Non-confidential summary report

[23] Wave Energy Scotland, O&M Simulation Tool, wes_om-model-empty.xlsm

[24] Wave Energy Scotland, O&M Model - Pelamis P2 Case Study, wes_om-model-p2-v20.xlsm

[25] World Energy Council, 2016. World Energy Resources: Marine Energy

[26] Leask Marine, MV C-Odyssey Specification, 2015

[27] Marine Towage Services, MTS Vanquish

[28] Eidesvik, M/V Acergy Viking, 2017

[29] DTI (2007) "Preliminary Wave Energy Device Performance Protocol ANNEX II - Task 3.1 Assessment of the performance of Wave energy systems"

[30] The European Marine Energy Centre (2009) "Assessment of Performance of Wave Energy Conversion Systems

[31] EquiMar D4.2 (2010) "Data Analysis & Presentation to Quantify Uncertainty

[32] IEC/TS 62600-100 (2013) Marine Energy – Part 100: Electricity Producing WEC – Power Performance Assessment

[33] Babarit, A. 2015. Power Take-Off (PTO modelling) – From floating body to WEC. (Presentation, August 2015)

[34] Cargo, Christopher J., et al. 2012. Determination of optimal parameters for a hydraulic power take-off unit of a wave energy converter in regular waves. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 226.1: 98-111

[35] Danielsson, Oskar, et al. 2003. Permanent magnet fixation concepts for linear generator. Proceedings of the 5th European Wave Energy Conference

[36] TECO Westinghouse. Wind Turbine Generators. http://www.tecowestinghouse.com/site/DefaultSite/filesystem

/documents/wind_turbine_generators.pdf (accessed Sept. 2017)

[37] Hals J., Falnes J., Moan T., 2011. A Comparison of Selected Strategies for Adaptive Control of Wave Energy Converters. Journal of Offshore Mechanics and Arctic Engineering, March 2011

[38] Wave Energy Converter SIMulator, an open-source WEC simulation tool developed in MATLAB / Simulink using the multi-body dynamics solver SimMechanics. http://wec-sim.github.io/WEC-Sim/

[39] Michelen, C., and Coe, R., 2015. "Comparison of methods for estimating short-term extreme response of wave energy converters". In OCEANS2015, IEEE

[40] Cruz J. et. al (2010) "Estimating the loads and energy yield of arrays of wave energy converters under realistic seas". In IET Renewable Power Generation, 2010, Vol.4, Iss.6, pp. 488-497

[41] Babarit, A. et. al. (2010) "Assessment of the influence of the distance between two wave energy converters on energy production". In IET Renewable Power Generation, 2010, Vol.4, Iss.6, pp. 592-601

[42] Nebel, P. (1992) "Optimal control of a Duck". The University of Edinburgh, Department of Mechanical Engineering, [Online] Available at https://www.era.lib.ed.ac.uk/handle/1842/23540 [Last accessed 11/07/2018]

2.2 Literature Review

2.2.1 Trends in Offshore Wind

[43] Fichaux, N., Beurskens, J., Jensen, P.H., Wilkes, J., Frandsen, S., Sorensen, J. and Eecen, P., 2011. Upwind: Design limits and solutions for very large wind turbines. Sixth Framework Programme.

[44] Marsh, G., 2005. Wind turbines: How big can they get?. Refocus, 6(2), pp.22-28.

[45] Dismukes, D.E. and Upton Jr, G.B., 2015. Economies of scale, learning effects and offshore wind development costs. Renewable Energy, 83, pp.61-66.

[46] Matha, D., Brons-Illig, C., Mitzlaff, A. and Scheffler, R., 2017. Fabrication and installation constraints for floating wind and implications on current infrastructure and design. Energy Procedia, 137, pp.299-306.

[47] Scottish Development International, 2011. Scottish Offshore Renewables Development Sites. West Coast Cluster. London: Scottish Development International.

[48] Perveen, R., Kishor, N. and Mohanty, S.R., 2014. Off-shore wind farm development: Present status and challenges. Renewable and Sustainable Energy Reviews, 29, pp.780-792.

[49] Rodrigues, S., Restrepo, C., Kontos, E., Pinto, R.T. and Bauer, P., 2015. Trends of offshore wind projects. Renewable and Sustainable Energy Reviews, 49, pp.1114-1135.

[50] World Energy Council, World Energy Resources: Wind 2016

[51] Jamieson, P. and Branney, M. 2014. Structural Considerations of a 20MW Multi-Rotor Wind Energy System. J. Phys.: Conf. Ser., 555, 012013

[52] Jamieson, P. and Branney, M., 2012. Multi-rotors; a solution to 20 MW and beyond?. Energy Procedia, 24, pp.52-59.

2.2.2 Large Scale WEC Devices

[53] Yemm, R., Pizer, D., Retzler, C. and Henderson, R., 2012. Pelamis: experience from concept to connection. Phil. Trans. R. Soc. A, 370(1959), pp.365-380.

[54] Stansby, P., Moreno, E.C. and Stallard, T., 2017. Large capacity multi-float configurations for the wave energy converter M4 using a time-domain linear diffraction model. Applied Ocean Research, 68, pp.53.

[55] Drew, B., Plummer, A.R. and Sahinkaya, M.N., 2009. A review of wave energy converter technology. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 223(8): p. 887-902.

[56] De Andres, A., Maillet, J., Hals Todalshaug, J., Möller, P., Bould, D. and Jeffrey, H., 2016. Techno-economic related metrics for a wave energy converters feasibility assessment. *Sustainability*, *8*(11), p.1109.

[57] Carnegie Clean Energy, 2018. CETO commercial scale unit, accessed 31 May 2018, www.carnegiece.com/wave/ceto-commercial-scale-unit/.

[58] Carnegie Clean Energy, 2018. Development pathway, accessed 31 May 2018, www.carnegiece.com/wave/development-pathway/.

[59] reNEWS, n.d. Wavestar future on knife edge, accessed 28 May 2018, http://renews.biz/102918/wavestar-future-on-knife-edge/

[60] Pontoon Power, 2012. First model test completed, accessed 15 May 2018, www.pontoon.no/News.html

[61] Weller, S.D., Stallard, T.J. and Stansby, P.K., 2010. Experimental measurements of irregular wave interaction factors in closely spaced arrays. IET renewable power generation, 4(6), pp.628-637.

[62] Gao, Z. and Moan, T., 2009, September. Mooring system analysis of multiple wave energy converters in a farm configuration. In 8th European Wave and Tidal Energy Conference (EWTEC), Uppsala, Sweden (pp. 509-518).

[63] Leirbukt, A. and Tubaas, P., 2006. A wave of renewable energy. ABB Review, (3), p.29.

[64] Garnaud, X. and Mei, C.C., 2010. Comparison of wave power extraction by a compact array of small buoys and by a large buoy. IET renewable power generation, 4(6), pp.519-530.

[65] Garnaud, X. Mei, C.C., 2009. Wave-power extraction by a compact array of buoys. Journal of Fluid Mechanics, Cambridge University Press (CUP), 635, pp 389-413.

[66] Lee, H., Poguluri, S.K. and Bae, Y.H., 2018. Performance Analysis of Multiple Wave Energy Converters Placed on a Floating Platform in the Frequency Domain. Energies, 11(2), p.406.

[67] Wilkinson, L., T.J.T. Whittaker, P.R. Thies, S. Day, and D. Ingram, The power-capture of a nearshore, modular, flap-type wave energy converter in regular waves. Ocean Engineering, 2017. 137: p. 394-403.

[68] Folley, M., T. Whittaker, and J. Van't Hoff. The Design of Small Seabed Mounted Bottom Hinged Wave Energy Converters. 2007.

[69] Cameron, L., R. Doherty, A. Henry, K. Doherty, J.v.t. Hoff, D. Kaye, D. Naylor, S. Bourdier, and T. Whittaker, Design of the next generation of the Oyster wave energy converter, in 3rd International Conference on Ocean Energy. 2010: Bilbao, Spain.

[70] Mäki, T., M. Vuroinen, and T. Mucha, WaveRoller - One of the Leading Technologies for Wave Energy Conversion, in 5th International Conference on Ocean Energy. 2014: Halifax, Canada.

[71] Wilson, J.C., 2012. *A history of the UK renewable energy programme, 1974-88: some social, political, and economic aspects* (Doctoral dissertation, University of Glasgow).

[72] Pecher, A., J.P. Kofoed, J. Espedal, and S. Hagberg. Results of an Experimental Study of the Langlee Wave Energy Converter. in 20th International Offshore and Polar Engineering Conference. 2010. Beijing, China.

[73] Arup. "Oscillating water column wave energy converter evaluation report." The Carbon Trust, Marine Energy Challenge (2005).

[74] Torre-Enciso, Y., Ortubia, I., de Aguileta, L.L. and Marqués, J., 2009, September. Mutriku wave power plant: from the thinking out to the reality. In Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden (Vol. 710).

[75] Washio Y, Osawa H, Nagata Y, Fujii F, Furuyama H, Fujita T. The offshore floating type wave power device ‘‘Mighty Whale’’: open sea tests. In: Proceedings of 10th International Offshore Polar Engineering Conference, Seattle; 2000, vol.1, p. 373–80.

[76] Leancon, n.d. Leancon Wave Energy, accessed 18 May 2018, http://leancon.dk/hjem.html

[77] Leybourne, M., W.M.J. Batten, A.S. Bahaj, N. Minns, and J. O'Nians, Preliminary design of the OWEL wave energy converter pre-commercial demonstrator. Renewable Energy, 2014. 61: p. 51-56.

[78] Joubert, J.R., van Niekerk, J.L., Reinecke, J., Meyer, I., 2013. Wave Energy Converters – Centre for Renewable and Sustainable Energy Studies, accessed 25 May 2018, www.crses.sun.ac.za/files/technologies/ocean/WECs_2013_list.pdf

[79] European Union, 2012, Final Report Summary - WAVE DRAGON MW (Development and validation of technical and economic feasibility of a multi MW Wave Dragon offshore wave energy converter), available https://cordis.europa.eu/result/rcn/47003_en.html

[80] Wave Dragon, n.d., Technology Specifications, assessed 1 June 2018, www.wavedragon.net/specifications/.

[81] Thorpe, T.W., 1999. A brief review of wave energy. London: Harwell Laboratory, Energy Technology Support Unit.

[82] Salter, S.H., Wave power. Nature, 1974. 249: p. 720.

[83] Crowley, S., Porter, R. and Evans, D.V., 2012. The New Bristol Cylinder: A submerged cylinder wave energy converter. In Twenty-seventh Int. Workshop on Water Waves and Floating Bodies,

[84] Pecher, A., J.P. Kofoed, and T. Larsen, Design Specifications for the Hanstholm WEPTOS Wave Energy Converter. Energies, 2012. 5(4): p. 1001.

[85] AWS, n.d. AWS-III Multi-Cell Wave Power Generator, assessed 1 June 2018 www.awsocean.com/multi-cell-wave-power.html

[86] Manasseh, R., K.L. McInnes, and M.A. Hemer, Pioneering developments of marine renewable energy in Australia. The International Journal of Ocean and Climate Systems, 2017. 8(1): p. 50-67.

[87] Bombora Wave Power, Cost of energy study, in P003-REP-G-002, 2016

[88] de Sousa Prado, M.G., Gardner, F., Damen, M. and Polinder, H. Modelling and test results of the Archimedes wave swing. Proceedings of the

Institution of mechanical Engineering, Part A: Journal of Power and Energy, 2006. 220(8), pp. 855-868

[89] AWS, n.d. Archimedes Waveswing submerged wave power buoy, assessed 20 Aug 2018 www.awsocean.com/archimedes-waveswing.html

[90] Farley, F.J.M., Rainey, R.C.T. and Chaplin, J.R., 2012. Rubber tubes in the sea. Phil. Trans. R. Soc. A, 370(1959), pp.381-402.

[91] Rainey, R.C.T. and Chaplin, J.R., 2013. Demonstrating the Feasibility of a Distensible WEC with a Distributed Power Take-Off. In Twenty-eighth Int. Workshop on Water Waves and Floating Bodies, Marseille, France, 7-10 April. see www.iwwwfb.org/Abstracts/iwwwfb28/iwwwfb28_47.pdf

[92] Babarit, A., Gendron, B., Singh, J., Mélis, C. and Jean, P., 2013, June. Hydro-elastic modelling of an electro-active wave energy converter. In ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering (pp. V009T12A033-V009T12A033). American Society of Mechanical Engineers.

[93] Currents Issue 11, 2015. SBM Offshore Group Communications Department, accessed 10 June 2018, www.sbmoffshore.com/wp-content/uploads/2015/10/Currents11_OCT_15_17-low-res.pdf

[94] Marine Energy, 2017, Interview: Power vessel navigates to wave energy cost-effectiveness, assessed 19 May 2018 https://marineenergy.biz/2017/02/16/interview-power-vessel-navigates-to-wave-energy-cost-effectiveness/

[95] Kinetic Wavepower, 2012, The PowerGin Operational Description, accessed 25 May 2018, www.kineticwavepower.com/tech.html

[96] Wave & Tidal Power, 2013, Magnetic technology, accessed 25 Mar 2018, http://swel.eu/wp-content/uploads/2013/06/Magnetic-technology.pdf

2.2.3 PTO Limitations

[97] Plummer, A.R., Hill, A.J., Perez-Collazo, C. (2018) ‘Power Systems’, in Greaves, D. and Iglesias, G. (eds.) Wave and Tidal Energy. Wiley, pp. 191-232.

[98] Babarit, A., Guglielmi, M. and Clément, A.H., 2009. Declutching control of a wave energy converter. *Ocean Engineering*, *36*(12-13), pp.1015-1024.

[99] Hansen, R. H. (2013). Design and Control of the PowerTake-Off System for a Wave Energy Converter with Multiple Absorbers. Department of Energy Technology, Aalborg University.

[100] Vladimir Kalinin. A wave energy conversion system. Patent WO2009153329, 2008.

[101] Artemis Intelligent Power (2017). Hydraulic Digital Displacement hydraulic PTO for wave energy – WES Power Take Off Stage 2 Project Public Report.

[102] Stephen Salter and Matthew Rea. Hydraulics for wind. In In proc. of the European Wind Energy Conference in Hamburg in October, 1984.

[103] N. Hodgins, O. Keysan, A. S. McDonald and M. A. Mueller, "Design and Testing of a Linear Generator for Wave-Energy Applications," in *IEEE Transactions on Industrial Electronics*, vol. 59, no. 5, pp. 2094-2103, May 2012.

[104] Polinder, H., Damen, M.E. and Gardner, F., 2004. Linear PM generator system for wave energy conversion in the AWS. *IEEE transactions on energy conversion*, *19*(3), pp.583-589.

[105] University of Edinburgh (2017). C-GEN Direct Drive PTO – WES Power Take Off Stage 2 Project Public Report.

[106] Liserre, M., Cardenas, R., Molinas, M. and Rodriguez, J., 2011. Overview of multi-MW wind turbines and wind parks. *IEEE Transactions on Industrial Electronics*, *58*(4), pp.1081-1095.

[107] Wang, J., Qu, R., Tang, Y., Liu, Y., Zhang, B., He, J., Zhu, Z., Fang, H. and Su, L., 2016. Design of a superconducting synchronous generator with LTS field windings for 12 MW offshore direct-drive wind turbines. *IEEE Transactions on Industrial Electronics*, *63*(3), pp.1618-1628.

[108] Abrahamsen, A.B., Mijatovic, N., Seiler, E., Zirngibl, T., Træholt, C., Nørgård, P.B., Pedersen, N.F., Andersen, N.H. and Østergaard, J., 2010. Superconducting wind turbine generators. *Superconductor Science and Technology*, *23*(3), p.034019.

[109] Kurniawan, A., Chaplin, J.R., Hann, M.R., Greaves, D.M. and Farley, F.J.M., 2017. Wave energy absorption by a submerged air bag connected to a rigid float. *Proc. R. Soc. A*, *473*(2200), pp. 20160861.

[110] Takao, M. and Setoguchi, T., 2012. Air turbines for wave energy conversion. *International Journal of Rotating Machinery*, *2012*.

[111] Bard, J. and Kracht, P., 2012. “Rotating Generators”. Deliverable D3.3 SDWED Structural Design of Wave Energy Devices. Available: www.sdwed.civil.aau.dk/digitalAssets/97/97526_d3.3.pdf

[112] Arup. "Oscillating water column wave energy converter evaluation report." *The Carbon Trust, Marine Energy Challenge* (2005).

[113] Torre-Enciso, Y., Ortubia, I., de Aguileta, L.L. and Marqués, J., 2009, September. Mutriku wave power plant: from the thinking out to the reality. In *Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden* (Vol. 710).

[114] Moretti, G., Fontana, M. and Vertechy, R., 2015. Model-based design and optimization of a dielectric elastomer power take-off for oscillating wave surge energy converters. *Meccanica*, *50*(11), pp.2797-2813.

[115] Scuola Superiore Sant’Anna (2017). Direct Contact Dielectric Elastomer PTO for Submerged Wave Energy Converters – WES Power Take Off Stage 1 Project Public Report.

[116] Martinelli, L., Zanuttigh, B. and Kofoed, J.P., 2009, September. Statistical analysis of power production from OWC type wave energy converters. In *Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden* (Vol. 710).

[117] Hudson, J., Phillips, D. & Wilkins, N. (1980), `Materials aspects of wave energy converters', Journal of Materials Science 15, 1337.

[118] Platts, M. (1981), Engineering development of the Lancaster flexible bag, in H. Stephens & C. Stapleton, eds, `Papers presented at the Second International Symposium on Wave and Tidal Energy: held at Cambridge, England, September 23-25 1981', pp. 283.

[119] Evans, D. V. & Thomas, G. P. (1981), A hydrodynamical model of the lancaster flexible bag wave energy device, in H. Stephens & C. Stapleton, eds, `Papers presented at the Second International Symposium on Wave and Tidal Energy: held at Cambridge, England, September 23-25 1981', pp. 129-141.

[120] Huang, M. and Aggidis, G.A., 2008. Developments, expectations of wave energy converters and mooring anchors in the UK. *Journal of Ocean University of China*, *7*(1), pp.10-16.

[121] Duckers, L. J. (1999), Reinforced rubber membranes for the clam wave energy converter, in `The Proceedings of the Ninth (1999) International Offshore and Polar Engineering Conference', pp. 174-179.

3 Methodology

The project was undertaken using a tiered approach comprising three stages as summarised in Figure 1 and the sections below. A detailed assessment basis and assumptions for each stage are reported in the relevant sections of the report.

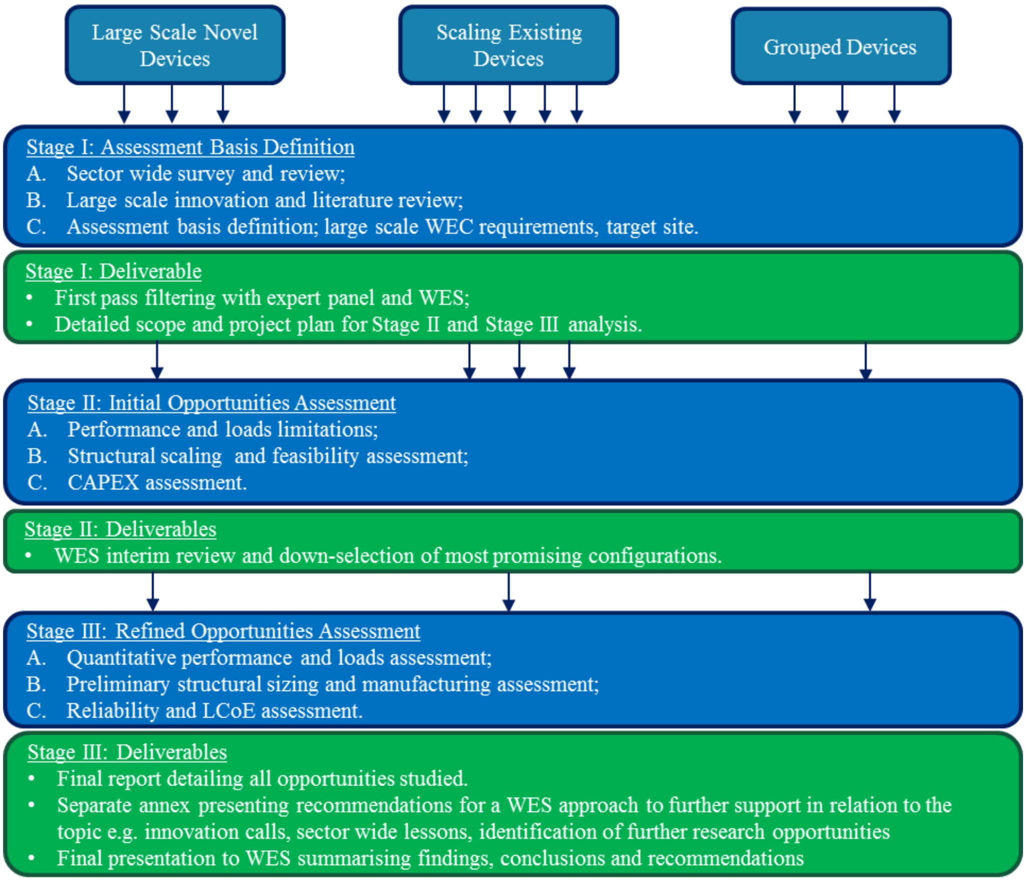


Figure 1. Summary of the methodology

3.1 Stage I: Literature Review and Survey

Stage I considered the entire WEC landscape to identify large scale WEC opportunities through a sector wide survey and literature review. The literature review covered trends in offshore wind to highlight opportunities and challenges applicable to the wave sector and a review of specific large scale WEC devices. The sector wide survey targeted 34 leading WEC technology developers to assess their current plans and ambitions regarding large scale wave energy generation.

3.2 Stage II: Initial Assessment

Stage II comprised quantitative assessment into the potential opportunity and limitations based on scaling the main existing state-of-the-art WEC types. Scaling calculations included energy performance, structural and moorings size, construction and feasibility limits and PTO arrangements. High level metrics, for example CAPEX/MW, were used to compare the scaling potential of these devices.

3.3 Stage III: Refined Assessment

Stage III comprised a more detailed quantitative assessment of a generic large scale device and devices grouped on a shared structure. These large scale configurations were both considered to have potential following the Stage I and II assessments. A more refined assessment was undertaken and expanded to include OPEX and feasibility of the offshore campaign during installation. Detailed metrics, including LCoE, were calculated and compared to a common baseline array of 1MW devices to quantify the opportunity compared to the scale of the current state-of-the-art.

Stage III also included development of a list of generic requirements and guidance for a large scale WEC based on the findings of the study. These requirements aim to guide future development of a novel large scale device.

4 Stage I: Literature Review and Survey

4.1 Literature Review: Trends in Offshore Wind

4.1.1 Background and Approach

It has been estimated that since 2001 the installed European offshore wind capacity grew on average by 36.1% [49]. The wind industry has seen significant success in the scaling of horizontal axis turbines over the last 30 years; developing from 0.05MW, 15m diameter blades in the mid-1980s, to 5MW 126m diameter blades in 2005 [1] with 12MW capacity designs now being pursued. The first offshore windfarm was completed in 1991 in Ravnsborg, Denmark and had a total capacity of 5MW from 11 turbines [3].

This remarkable rate of scaling of generation capacity is partially due to nature of the wind resource, with greater energy capture being achievable by increasing the capture area. The relationship between potential energy capture and device size is more complex for WECs, as quantified in Stage II and Stage III of this study. There are however potential lessons to be learnt from the wind industry in regards to the sources of cost saving with scale and challenges that have been overcome to achieve this scaling.

In light of this, a literature review was conducted to understand the opportunity and challenge associated with scaling WTGs and to identify parallels in the wave energy sector.

4.1.2 Results

4.1.2.1 Opportunities

The scaling opportunity for individual wind turbines has been partially driven by the fixed costs associated with installation and cabling for offshore sites [43], with [44] reporting that these can account for 40-50% of project costs. Larger rotors also have ‘an averaging effect on wind speed, producing steadier conditions for the blades to operate in’ [44].

Operationally, benefits are also associated with larger offshore WTGs. Although the loss of a single device is more significant, larger devices have a reduced number of system failures for a given array size due to the random nature of unplanned failures. Maintenance cost is insensitive to device size and so arrays of larger machines are associated with reduced OPEX [50]. Experience in offshore wind suggests an OPEX ‘sweet spot’, which is realised for large machines.

The success of large scale wind is in part due to the ability to start small and scale the original design concept. Investor confidence has remained high because onshore has been the proving ground for offshore wind. The nature of the resource allows this scaling, with the same basic 3-blade horizontal axis turbine concept working at 0.1MW, 1MW and 10MW scales. The lack of design convergence in the wave industry may hinder the ability for innovation through progressively scaling up concepts. The success of the wind industry has resulted in several competing companies working on similar technology concepts in the offshore arena, further driving innovation and increased scale.

The wind industry has also had the advantage of being the pioneer of renewable energy, arguably being permitted greater time to reach electricity prices comparable to more traditional generation technology. The wave industry on the other hand is inevitably compared to wind industry, potentially reducing investor's willingness for innovation through progressive scaling up.

4.1.2.2 Challenges

Three main challenges were identified by [44] regarding scaling from 3MW to 10MW WTG capacity; rotor and nacelle weight; device reliability, and scaling of the supply chain capacity. Innovations and improvements have been required in all three areas. The same challenges remain as the wind industry starts to look ahead to larger concepts.

Rotor and Nacelle Weight

Additional weight accentuates both structural and logistical difficulties. Specifically, an increase in rotor weight directly affects the cyclic stresses experienced by the blades and final drives [44]. Such consideration led the wind industry to develop new composite materials and manufacturing techniques to minimise blade weight. The use of prepreg manufacturing with carbon and glass fibres was considered a key enabler for increasing WTG capacity in the mid-2000s. For example, Vestas reported increasing blade length from 39m to 44m without an increase in weight due to the innovative use of new materials [44]. Adoption of new materials and associated manufacturing techniques, especially at scale of the production at which the wind industry is presently operating, can also result in significant supply chain issues.

A significant source of mass within a wind turbine is that of the PTO, particularly the gearbox. Gearbox mass approximately increases with the cube of the volume of air that the wind turbine captures [44]. Innovations in this area were therefore required to allow turbine size to increase. Size reduction has been achieved via various innovations, including the use of variable speed generators and frequency converters or by removing the use of gearboxes through low speed direct drive synchronous generators. These advances were made possible by developments in new permanent magnets synchronous generators and power electronics.

Device Reliability

As turbine systems scale up, faults become increasingly expensive. There is increased lost energy, and therefore revenue, when turbines are not in operation; downtimes are generally longer and the more costly components require higher outlay for operation and maintenance [48]. The financial losses if repairs are not viable are also much greater as scale up occurs. As such, the reliability of wind turbines has increasingly been critical to their scaling success. Gearboxes are a particular source of reliability concern, with the solutions adopted to reduce the mass of these systems also enabling potential reliability improvements.

A key enabler for system reliability has been advancement in sensor integration into all aspects of the turbine and improvements in condition monitoring. Such systems allow the detection of incipient faults, enabling more effective and efficient maintenance scheduling. Structural health monitoring has been found to be one of the most effective methods to improve the availability of turbines [48]. Developments in sensor technology have also helped with the improvement of pitch and generator control techniques to better respond to rapidly detected high wind and gusts, helping to limit extreme loads. For example, [43] has demonstrated the use of LIDAR to measure the wind resource immediately in front of the turbine.

Supply Chain Capacity

The wind industry has had to significantly increase the supply chain capacity to cope with large scale offshore WTGs. As the wind energy industry itself has grown alongside turbine size, companies have been able to use vertical integration to aid growth in the supply chain. This involved developing new works in-house to reduce the dependency on the existing supply chain for critical components.

Logistic and installation issues have also arisen as the turbine size has grown. There is a trade-off between the revenue reward from scaling up the turbine and how much the cost of installation increases. Scaling-up reduces the total cost of achieving an overall target installed capacity wind farm, as fewer expensive substructures and less overall installation time is required. However, scaling-up reduces the weather windows for installation and requires more specialised and expensive lifting equipment, increasing the installation cost per device. In addition, land transport of extremely long components (blades, tower) is difficult and often impossible, so shore-side manufacturing facilities are required. This has been the main factor limiting the size of wind turbines to about 5–8MW for the last 5–10 years until the recent introduction of 10MW designs. This is also one of the main challenges in developing 10 MW+ turbines, and is one of the driving factors behind the innovation of new concepts, such as multi-rotor systems (e.g.[51], [52]). There may be potential for large scale WECs to build upon the large scale wind supply chain for manufacture and installation.

4.1.2.3 Floating Offshore Wind

Floating Offshore Wind Turbines (FOWT) are in their relative infancy compared to bottom fixed devices. Such systems may therefore have a stronger association with the potential challenges faced by 10MW+ scale wave energy devices. [46] considered the feasibility of fabrication and installation of floating substructures for 10MW WTGs by analysing publically available data on existing FOWT systems. The study emphasised that industrialisation of FOWT technology is a key enabler for the required cost reduction.

Regarding fabrication, [46] states that many of the constraints are dependent on floater design or other site and project specific factors. However, two key general challenges were identified, which may also apply to large scale WECs; the choice of a suitable construction site/port and the selected port’s infrastructure. If a dry-dock is required, only a few worldwide are capable of supporting the dimensions and the floating structure needed for 10 MW+ FOWT. For example, the Japanese

Fukushima Shimpuu 8MW FOWT was constructed in one of the 17 widest dry-docks in the world [46]. If serial production capacity is required, the number of suitable facilities reduces further. Alternatively, if a device is designed to be constructed on a barge or quayside, there are fewer constraints, a consideration worth noting when developing 10 MW+ WECs. However, [46] suggests that most ports could not be used for the construction of devices of this scale without upgrade to the infrastructure. A review of the Scottish West coast identifies many suitable ports, however suggests that most would need upgrading [47].

Regarding installation challenges [46] identifies port choice, vessel choice and weather considerations to all be of significance. This will be the case for FOWT and WEC devices of all scales. However, the increase in device size is expected to potentially limit port and vessel choice. Possible increases in installation time as devices become larger will also increase the difficulty of identifying suitable weather windows, a problem further exacerbated if suitable ports are further from deployment sites.

[48] states that FOWT have greater flexibility of construction and installation procedures compared to fixed wind turbines. They can also be relatively easily removed from offshore wind farms for maintenance and repair. Such advantages should also be considered when developing large scale WECs (e.g. when designing a common platform from which to mount multiple point absorbers).

4.2 Literature Review: Large Scale WEC Devices

4.2.1 Background and Approach

A literature review was conducted to identify existing research into large scale WEC devices. It included devices presently under development, those that have been previously considered and those that have only been considered from a theoretical point of view.

The review identified WEC types that may have the potential to scale to 10MW+ generation capacity and device concepts that are already at that scale. It also identified potential sector wide limitations. The review comprised academic publications and developer websites where other information was not available.

4.2.2 Results

The detailed results are presented by WEC types in Appendix A and summarised below.

Attenuator

No attenuating devices were identified that were presently aiming for 10MW+ capacity, although numerical modelling of the M4 WEC predicted this might be achievable with multiple floats. Increased capacity requires increased device length or adding additional floats to raft based concepts. It is unclear at what point this would become uneconomical compared to having an array of smaller units, as well as the impact of wave attenuating down the device.

Point absorber

No individual point absorbers were identified aiming for 10MW+ capacity and some published CAPEX estimates suggest that low to medium rated devices may be an optimum scale.

A number of concepts incorporating multiple point absorbers on a single platform were identified, including Wave Star, Pontoon Power, Manchester Bobber, FO3 WEC and WaveSub. Theoretical studies identify the hydrodynamic potential of such concepts. However, the experience of Wave Star indicates the cost of the common platform is critical.

Oscillating wave surge converter

The flap size of oscillating wave surge converters is limited. Capture efficiency increases up to the point at which width is similar to wavelength and then decreases as terminator effects and wave phase variations begin to dominate. To mitigate against this, modular flap designs have been proposed, which could aid the scaling up of capacity. Alternatively, multiple flap floating wave surge converters have been identified, including the Langlee WEC and the Polygen Voltra device, where additional flaps could theoretically be added to increase capacity.

Oscillating water column

No individual OWC were identified targeting 10MW+ capacity. The size of an individual unit is believed to limited by chamber dimensions, and the point at which a lack of uniformity of the water surface inside the chamber reduces conversion efficiency. The integration of multiple resonant chambers into a single device, or multiple OWC units onto a single platform avoids this issue and offers the potential for large scale generation. Examples of this approach identified include the Mighty Whale, LeanCon and OWEL concepts.

Overtopping / terminator

Overtopping devices can theoretically be increased to very large scale capacity, by increasing reservoir size and the number of low-head turbines. Proposals for the Wave Dragon to reach 11MW capacity are reported as requiring a 14,000m^3 reservoir with 16-24 turbines. Regarding terminators, the Salter's Duck has the potential to achieve very large scale capacity, with a 2GW scheme consisting of 334 ducks considered in 1998. One study reports that for the Duck, efficiency is related to the width not the length of the device but that the mechanical power was related to both parameters. Other concepts such as the AWS-III multi-cell wave power could be theoretically expanded using additional units.

Submerged pressure differential

No individual submerged pressure differential devices were identified targeting 10MW+ capacity. The original Archimedes Wave Swing concept had a rated power of 2MW. The bottom-mounted Bombora concept could theoretically be increased in capacity with additional cells to increase air flow, although it is unclear what the advantage of this would be compared to having an array of smaller units.

Bulge wave

Reported modelling results for bulge wave converters suggest that wave radiation from the tubes limit the advantage of increasing tube length to increased capacity. A distributed PTO along the converters length potentially addresses this issue, allowing tube length to be increased. Modelling results predicting 1MW are reported. The relationship between resonance frequency, tube diameter and tube thickness prevent tube diameter being simply scaled without consideration of the specific deployment site conditions.

Rotating mass

Some rotating mass concepts are reported as being designed to have capacity approaching 10MW. Limited information was publically available for these designs. The limiting factor of such devices is considered to be the wavelength of the resource relative to the device.

Other devices

The Vigor, PowerGin and Waveline Magnet WEC all quoted 10MW+ capacity, however little detail was publically available for these concepts.

4.2.3 Conclusions

The review identified several WEC types that have potential for large scale deployment or are already designed at that scale. Although some of these comprise an individual large absorber, the majority identified are grouped devices. These consist of several prime mover of typically <1MW rating mounted on the same common structure, with either an individual or shared PTO system. Such systems have the advantage over individual larger devices of a potentially less risky development pathway. The majority of grouped devices identified exist at a concept or theoretical level. The cost and feasibility implications of these structures is yet to be considered in detail. It is therefore unclear from the literature review whether grouped structures present a more attractive option compared to large scale individual devices. This comparison is quantified in Stage II and Stage III of this study.

4.3 Sector Wide Survey

4.3.1 Approach

Stage I comprised a sector-wide review that aimed to characterise the scaling potential of current state-of-the-art WECs. An online survey was circulated among leading technology developers to assess their current plans and ambitions regarding large scale wave energy generation. Those contacted included those developing full WEC devices and key subsystems e.g. power take-off systems (PTO).

The survey was conducted between the 27th March and the 11th April 2018 and sent to 34 technology developers. The survey comprised eight questions depending on the respondents' previous consideration of 10MW+ WEC designs, as illustrated in Figure 2. The questions were designed to capture the respondents' opinions regarding:

- Feasibility of 10MW+ WEC designs.
- Opportunities and limitations presented by 10MW+ WEC designs.

A response rate of 50% (17 respondents) was achieved. The key survey results and their analysis are presented and discussed in Section 4.3.2.

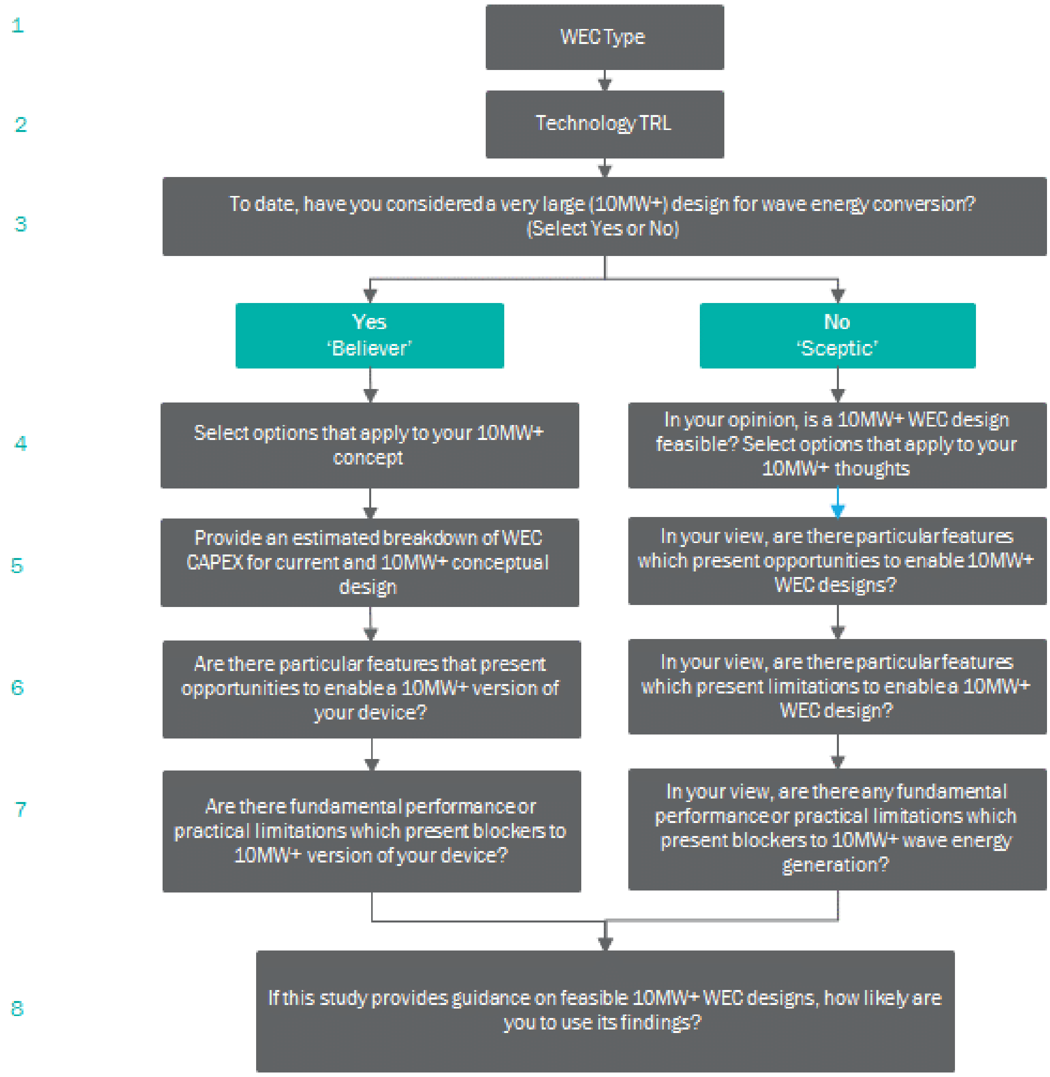


Figure 2 Outline structure of the Stage I online survey

4.3.2 Results

As illustrated in Figure 2, the online survey comprised eight questions. The first two questions aimed to capture the types of WEC currently under development and their current technology readiness level (TRL). It should be noted that the TRL was self-assessed by the respondents. The majority of respondents were developers of point absorber WECs and technologies at an intermediate TRL as shown in Figure 3. The results were similar to recent consultations e.g. [1]. The list of respondents were intended to cover the current state-of-the-art WEC technology.

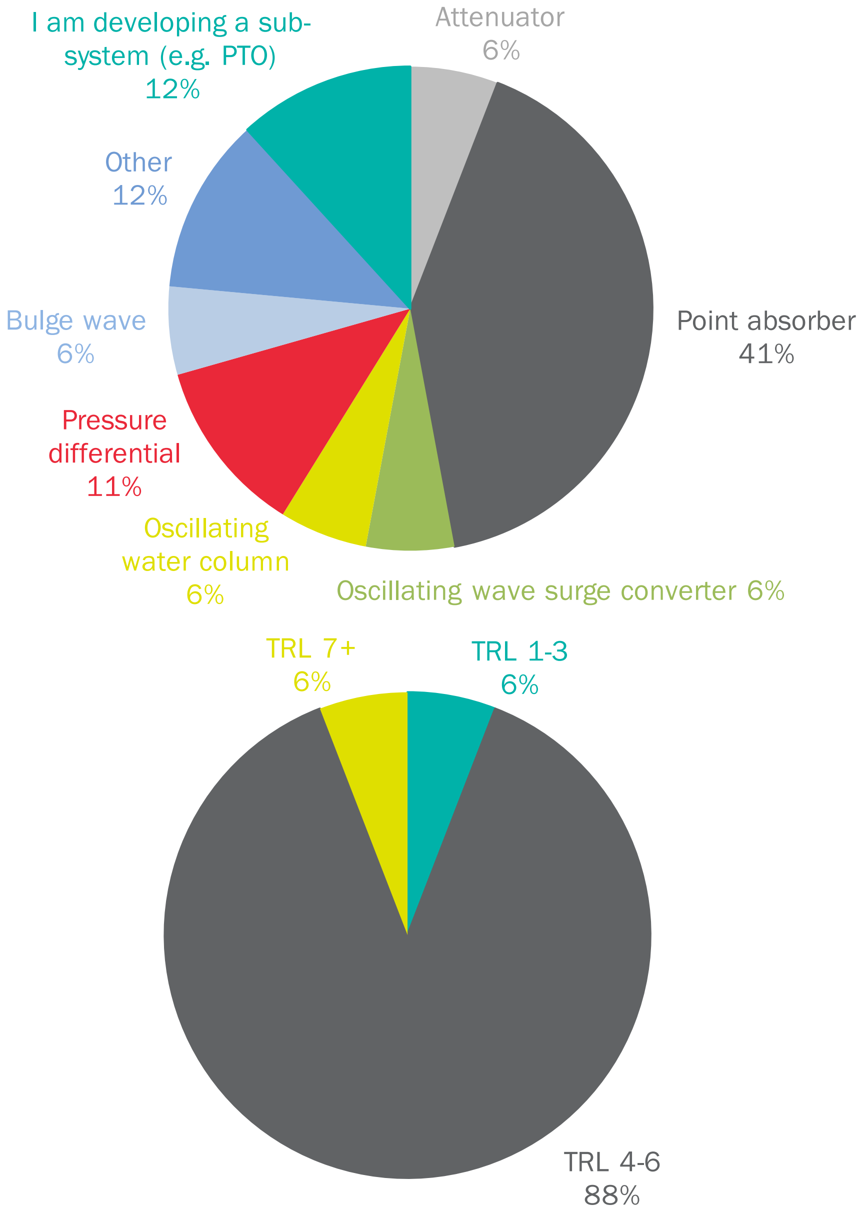


Figure 3. WEC types under development (top) and their current TRL (bottom)

Question 3 assessed if very large scale WEC designs (10MW+) had been considered by the survey respondents. The results showed an even split; 53% 'No', while 47% responded 'Yes'. Two types of respondent were considered based on these responses:

- Those that have already considered very large WEC generation and are convinced of its merits: the *Believers*.
- Those that have not considered very large WEC generation and are doubtful of its merits: the *Sceptics*.

The survey comprises two branches based on these categories. These branches share some commonalities but aimed to also extract specific information based on the type of respondent.

4.3.2.1 'Believer' Responses

Figure 4 summarises the options respondents considered feasible for scaling their current very large scale WEC design(s). The integration of multiple units in a single large platform was the most common response, with an approximately 60% selection rate. Other alternatives were also suggested, e.g. integration with offshore wind technologies. None of the respondents considered 10MW+ scaled-up versions of their current WEC designs feasible.

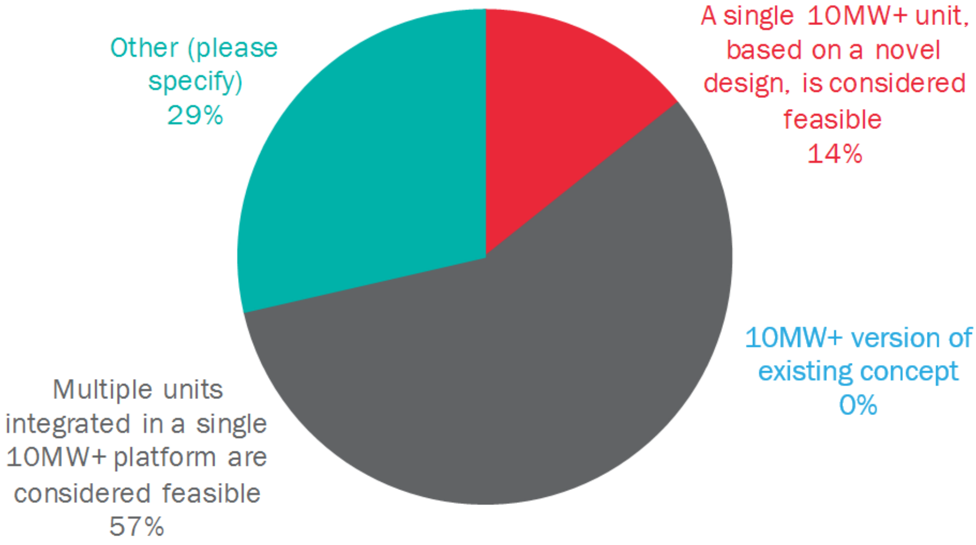


Figure 4. Developers that have considered 10MW+ designs: feasible options

In an effort to assess developer's opinions regarding the impact of very large scale designs on WEC CAPEX, Question 5 requested a breakdown of the expected WEC CAPEX for both current designs and the most feasible 10MW+ option. Table 1 illustrates the results in terms of the ranges of the responses. The key findings can be summarised as follows:

- Most respondents are not expecting big changes in the prime mover contribution to CAPEX.
- There is considerable uncertainty surrounding the expected PTO / control system contribution to CAPEX, with very wide ranges recorded.
- Developers expect increases in the foundations / moorings contribution to CAPEX.
- Developers expect decreases in the connection / installation contribution to CAPEX.

	% WEC CAPEX	
	Current Design	10MW+ Design
Structure and Prime Mover	0-10	0-10
Power-Take-Off (PTO) and Control	20-40	10-80
Foundations and Moorings	0-10	0-20
Connection	20-30	0-20
Installation	10-20	0-10

Table 1. WEC CAPEX breakdown: current designs (left) and very large scale designs (right)

The uncertainty shown by the responses listed in Table 1 is also clear in the response to Question 6 and 7. This captures the *Believers*' perceptions of the key opportunities and limitations that may affect the creation of a very large scale WEC design. The response to this question was in the form of comments.

With regard to opportunities, simpler solutions to adjust to large tidal ranges and the use of a shared structure as a common reference source for multiple prime movers were suggested. However, the latter was also considered a potential limitation, as the CAPEX of non-absorbing (large) structures may severely impact the LCoE. The cost / efficiency trade-off was also identified as a potential limitation, with practical limits on efficiency being referenced. In particular, some developers questioned '(…) *how many kW can actually be generated per kW/m of wave power flux?*', and if realistic wave power flux estimates *'(...) limit the width of the design to a 4-5MW rating?*'. These and other considerations are investigated, at theoretical and practical levels, in Section 5 of this report.

4.3.2.2 'Sceptic' Responses

As illustrated in Figure 5, 75% of the *Sceptics* do not consider a very large WEC design feasible. Respondents were asked to comment / justify their answer as listed in Figure 5. The remarks illustrate considerable pre-conceptions regarding the feasibility of large scale WEC generation, potentially lacking any previous research.

In terms of practical limitations, the *Sceptics* considered manufacturing techniques, PTO scaling and upper theoretical limits of WEC absorption as the main constraints to very large scale wave energy generation. Opportunities to share experience from the oil & gas industry were also suggested by respondents. These were understood by the project team as e.g. the recognition that large isolated single structures, of considerable CAPEX and long design life, may be required to make wave energy feasible, potentially carrying a substantial amount of up-front risk. These and other considerations are investigated in Section 5 of this report.

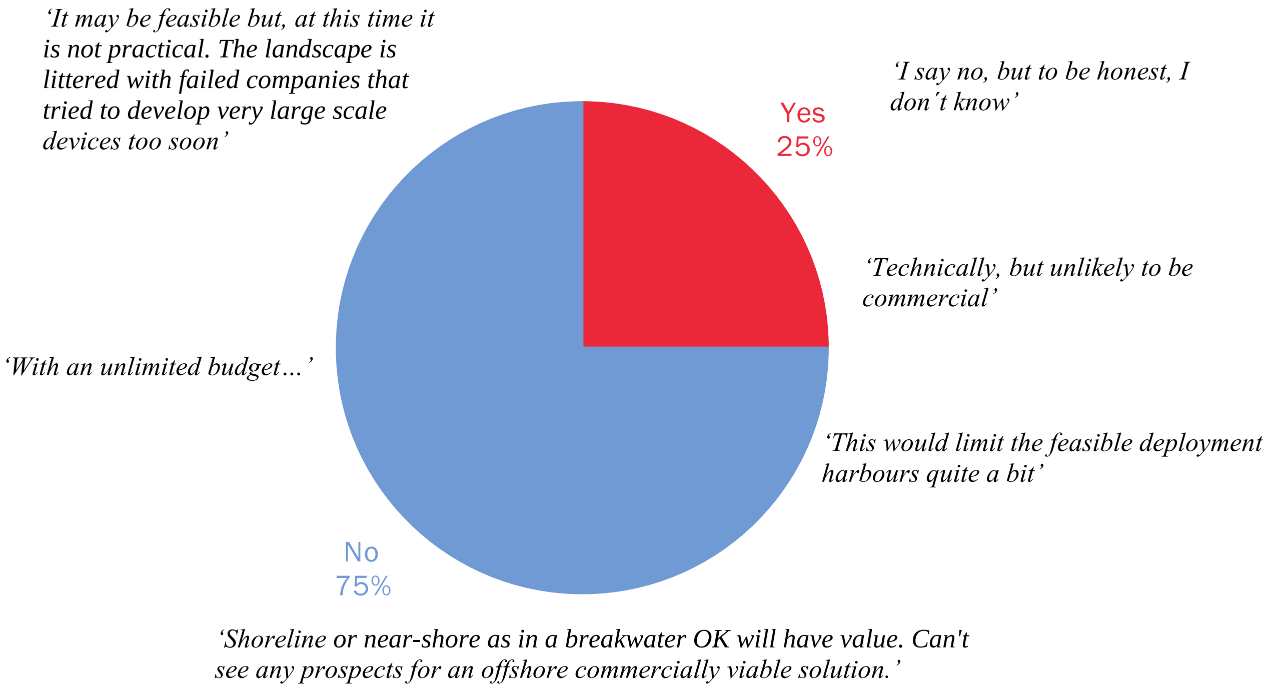


Figure 5. *Sceptics* responses to '*In your opinion, is a 10MW+ WEC design feasible?*'

4.3.2.3 Interest in the Study

The final question targeted both *Believers* and *Sceptics* to assess the interest in the large scale WEC landscaping study. As shown in Figure 6, 70% of respondents were either '*Likely*' or '*Very Likely*' to use the findings of the study when seeking guidance on feasible 10MW+ WEC designs.

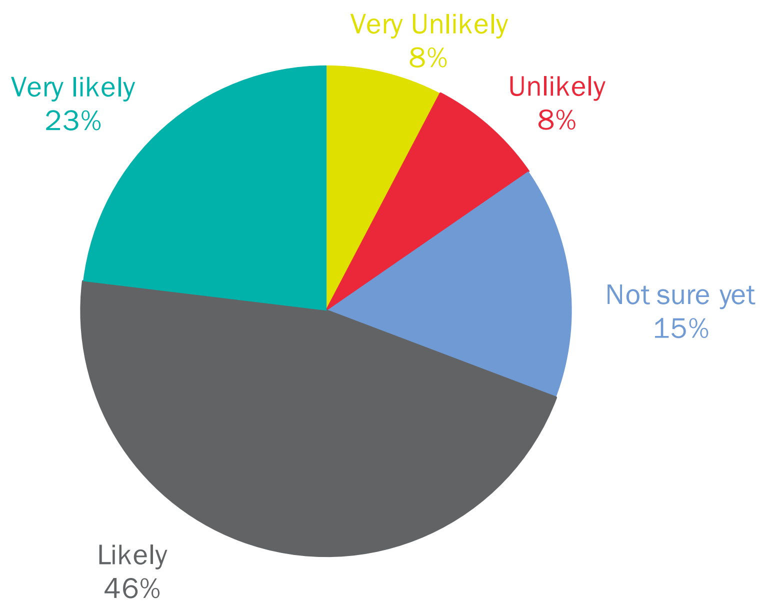


Figure 6. Survey responses to '*If this study provides guidance on feasible 10MW+ WEC designs, how likely are you to use its findings?*'

4.3.3 Conclusions

The Stage I sector-wide survey aimed to provide insights into the current plans and ambitions of leading technology developers regarding large scale wave energy generation. The key findings from the responses can be summarised as follows:

- There is considerable division in the wave energy community regarding the feasibility of very large scale wave energy generation. Two groups of respondents – *Believers* and *Sceptics* – were identified, each occupying around half of the responses received.
- Even *Believers* do not consider that a scaled-up version of their current concept is the ideal way forward. The grouping of multiple units on a single platform is seen as the most feasible option.
- There is considerable uncertainty regarding key aspects such as the WEC CAPEX breakdown of very large scale designs. This is consistent with a general lack of specific studies dedicated to the topic.
- A common theme of commercial viability of 10MW WECs was evident in responses from *Sceptics*. This is not unreasonable considering the potentially very high CAPEX required for large WECs, even at the demonstrating phase.
- There is wide interest in the topic, and further work (qualitative and quantitative) is required to assess the relative merits of different large scale WEC designs and configurations. This forms the focus of Sections 5 and 6 of this report.

5 Stage II: Initial Assessment

5.1 Stage II Methodology

Stage II comprised quantitative assessment into the potential opportunity and limitations based on scaling the main existing state-of-the-art WEC types. Scaling calculations included energy performance, structural sizing, construction and feasibility limits and PTO arrangements. Theoretical calculations were also undertaken to highlight fundamental energy performance limits applicable to large scale novel devices. High level metrics, for example CAPEX/MW, were used to compare the scaling potential of these devices.

Section 5.2 provides a basis for the Stage II assessment and the remainder of Stage II is presented as follows:

- Section 5.3 describes the energy scaling assessment and theoretical performance limits for large scale WEC devices;
- Section 5.4 describes the structural scaling assessment;
- Section 5.5 describes the practical limits associated with construction and installation of large scale WEC devices;
- Section 5.6 describes the practical limits associated with large scale PTO-systems;
- Section 5.7 describes the CAPEX assessment based on the scaled geometries.

Conclusions regarding the opportunity and limitation associated with scaling existing WEC devices are presented in Section 5.8.

5.2 Assessment Basis

The Stage II assessment considered scaling existing device types and their energy performance at a range of sites.

5.2.1 Key Assumptions

- Large scale devices were considered as those with a rated generation capacity of 10MW.
- The large scale devices were based on scaling state-of-the-art existing concepts, described in Section 5.2.2. Existing concepts were taken from the 2011 NumWEC study [2], an independent benchmarking exercise for WEC energy generation potential. Assumptions from the NumWEC study are therefore applicable.
- Froude scaling was applied when considering the upscaling, described in Appendix B. The energy performance potential of the large scale devices may be improved through control optimisation. The theoretical maximum energy yield for the devices investigated has therefore also been estimated.
- Devices were separated into common structural components, which were scaled in a consistent way across multiple devices. This provided a more realistic estimate for structural mass than Froude scaling where mass is scaled as length cubed. A portion of the required mass is likely to be provided by low cost ballast, for example water.
- Devices were scaled based on peak loads during operation, i.e. the devices will operate in a “survivability mode” during the most extreme storms, which will limit the loads.
- Steel was assumed as the primary material for the device structure to enable a consistent comparison.
- The feasibility of construction and installation was considered based on existing shoreline facilities in Scotland, and without consideration of specific deployment sites.
- The energy performance was calculated for three locations described in Section 5.2.3 to assess the influence of wave resource on large scale WEC yield. Site dependent CAPEX assumptions, e.g. electrical connection length, are described in Section 5.7. Stage II conclusions regarding the energy performance and CAPEX scaling for large scale WECs are therefore presented separately.

5.2.2 Device Geometries

Scaling calculations were undertaken for WEC designs based on the NumWEC (Numerical benchmarking study of a selection of Wave Energy Converters) project [2]. This provided a first approximation and covered a range of WEC types in the absence of large scale WEC reference models.

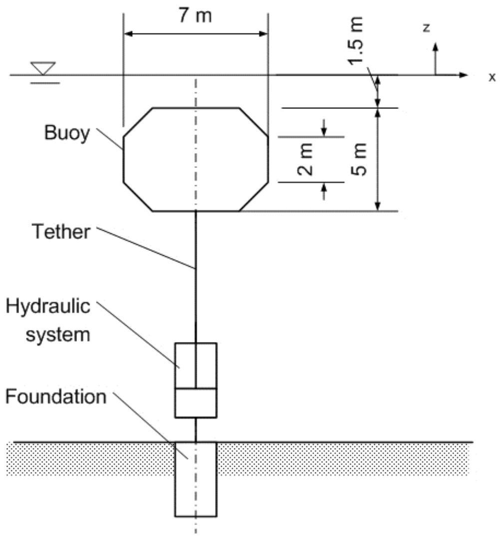
The NumWEC project considered a range of generic concepts, comprising heaving buoys, surging flaps and oscillating water column WECs. The NumWEC project assessed the performance of eight WEC concept designs, including floating, bottom-referenced and bottom-fixed devices, in five European sites.

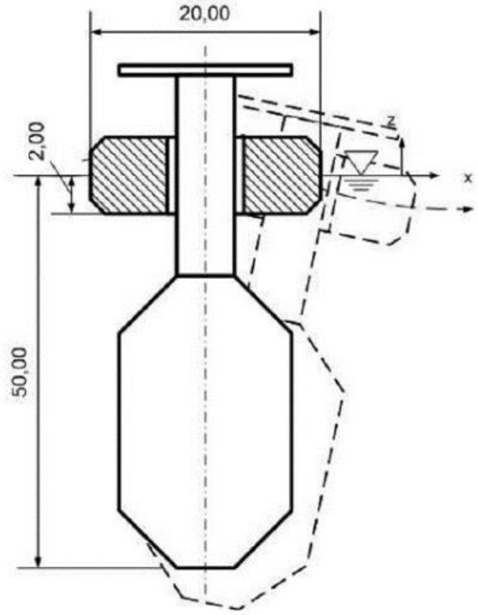
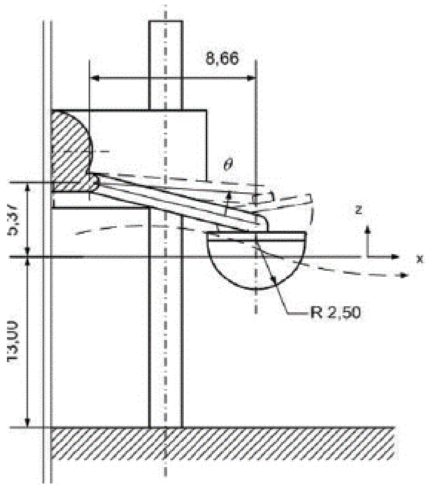
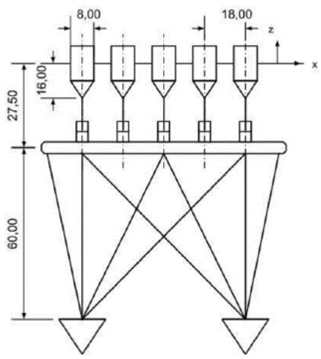
A description of reference WEC types presented in NumWEC is provided in Table 2. Table 3 summarises the geometric and mass properties of the reference NumWEC devices, along with their associated power rating. Note that the BrefHB device considered in NumWEC was not included in the large scale landscaping study, due to its original rating (30kW) being too small to envisage an upscaling to 10MW.

The NumWEC project aimed to benchmark performance estimates for this range of WEC types. For the majority of the concepts, the data available includes the following:

- Mechanical absorbed power matrices;
- Minimum, maximum, mean and RMS power-take off (PTO) force;
- Minimum, maximum, mean and RMS excitation force.

Table 2. Description and schematics of the WEC types modelled in NumWEC [2]

Device	WEC Description	WEC Schematics
Bref-SHB	A bottom-referenced submerged heaving buoy, inspired by the Ceto WEC (most similar to the Ceto 3 device) [2]. The prime mover is connected via a tether to the seabed. The tether houses an hydraulic system that consitutes the WEC’s power take-off (PTO).	

F-2HB	A self-referenced, dual-body point absorber that converts wave power via the relative vertical displacement between the two bodies (primarily heave). A linear PTO was considered in the model [2]. System inspired by the Wavebob WEC design and representative of a large, self-referenced, multiple body point absorber.	
B-HBA	Inspired by the WaveStar WEC, this concept design uses a jack-up structure to provide a fixed reference to an array of floating buoys (20 in the assumptions made in [2]). The buoys are submerged hemispheres, which are connected to the main structure via a mechanical joint with one degree-of-freedom. The motion of the buoys relative to the jack-up is used to absorbed wave energy.	
F-HBA	A multibody floating WEC, composed of 10 heaving buoys connected to a common submerged reference structure. The total buoyancy force from the buoys is balanced by the gravity forces of the support structure and the ballast baskets. The concept is inspired by the Pontoon Power WEC.	

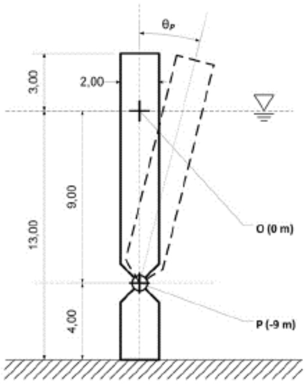
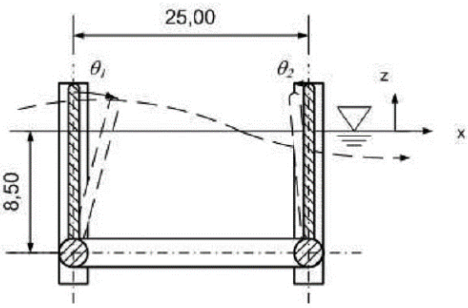
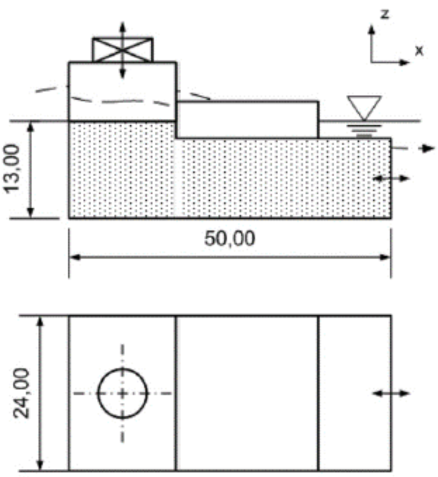
B-OF	A bottom mounted oscillating flap, inspired by the Aquamarine Power Ltd Oyster2 WEC design. Similar to the F-3OF concept, wave power is absorbed via the relative pitch between the flap and the reference, which is in this case is the seabed. In [2], a linear PTO characteristic was assumed.	
F-3OF	A floating system with four flaps hinged to a central structure. Wave power is absorbed via the relative pitch between the flaps and the central structure (linear PTO characteristic in [2]). System inspired by the Langlee WEC design and representative of a floating, self-referenced, multiple body hinged flap.	
F-OWC	A floating oscillating water column (OWC) device, based on the OE Buoy WEC. It consists of a floating platform with a single air chamber. The motion of the water column relative to the OWC platform creates an oscillating pressure in the chamber and an air flow which is forced to pass through the turbine. The device is constructed of thin steel walls enclosing the water column and it converts power using an air turbine (linear PTO characteristic) connected to an electric generator.	

Table 3. Summary of original geometric and mass properties and power rating of the NumWEC devices [2]

Device	Diameter (m)	Characteristic area (m^2)	Characteristic mass (te)	Rating (MW)
Bref-SHB	7.0	220	200	0.1
F-2HB	20.0	2120	5704	1
B-HBA	5.0 (1 float)	4350	1600	1.2
F-HBA	8.0 (1 float)	4750	5233	1.4
B-OF	26.0	2020	3800	2
F-3OF	9.5 (1 flap)	2160	1622	0.5
F-OWC	50.0	6500	1800	0.6

5.2.3 Sites

The energy performance of the large scale devices was assessed for the following locations:

1. The European Marine Energy Centre (EMEC), representative of moderate conditions in Scottish waters.
2. The most energetic area in Scottish waters (Figure 7).
3. The most energetic area in the world (Figure 8).

While noting that for the latter two sites, distance to shore and other realistic constraints were not taken into account, their consideration is expected to allow upper-level performance / response thresholds to be considered when envisaging large scale WEC designs.

Three sites were considered to enable evaluation of the combined influence of the environmental conditions and scale on the estimated WEC performance.

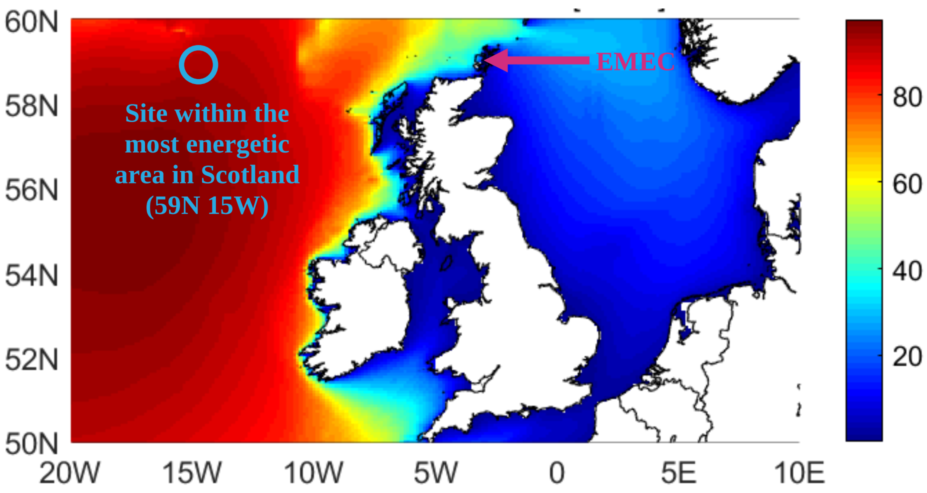


Figure 7. Annual mean wave power (in kW/m) around UK and Ireland. EMEC location (purple arrow) and a random site from the most energetic area in Scotland (blue circle)

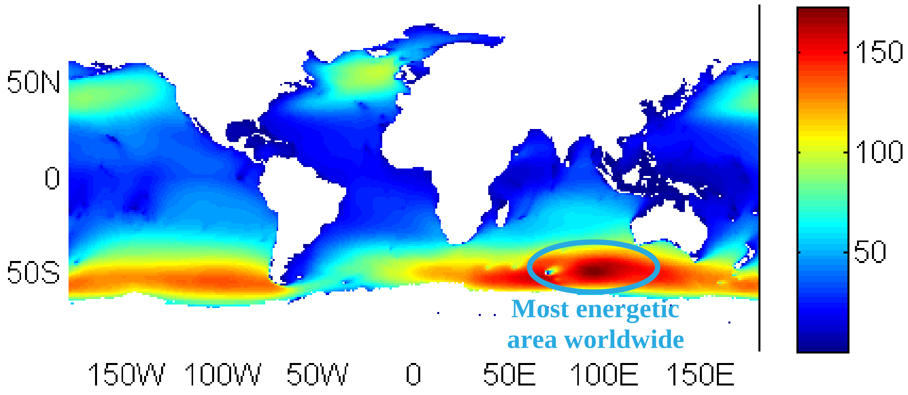


Figure 8. Worldwide annual mean wave power (in kW/m) and most energetic area worldwide (blue circle)

The wave statistics were derived from a global offshore wave resource database compiled by Cruz Atcheson, based on the US National Center for Environmental Prediction (NCEP) hindcast and covering the period between January 1979 and December 2009. The 30-year hindcast was generated using WAVEWATCH III [3] and was driven by winds from the NCEP Climate Forecast System Reanalysis (CFSR), a coupled reanalysis of the atmospheric, oceanic, sea-ice and land data from 1979 to 2010. The following parameters are currently archived for each grid point:

- Significant wave height, H_s.
- Peak wave period, T_p.
- Peak wave direction, D_p.
- Wind speed, W_{spd}.
- Wind direction, W_{dir}.

Note that the seabed elevation was sourced from the 1minute bathymetric grid of the GEBCO (General Bathymetry Chart of the Oceans) Digital Atlas[1].

The scatter diagrams detailing the probability of occurrence of each sea state (based on annual means) related to each of the target sites are illustrated in Figure 9 to Figure 11. Note that the scatter diagrams use the same Hs and Tp axes as the power matrices from the NumWEC study, for later combination into energy yield figures.

[1] https://www.gebco.net/data_and_products/gebco_digital_atlas/

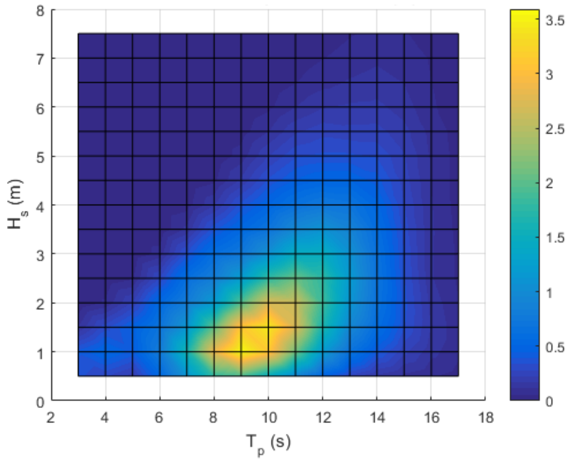


Figure 9. Scatter diagram for the EMEC site (water depth 56m) – probability of occurrence (in percentage)

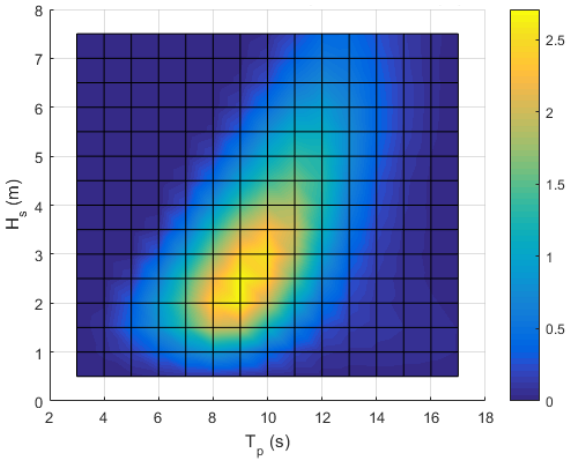


Figure 10. Scatter diagram for the most energetic site in Scottish waters (water depth 515m) – probability of occurrence (in percentage)

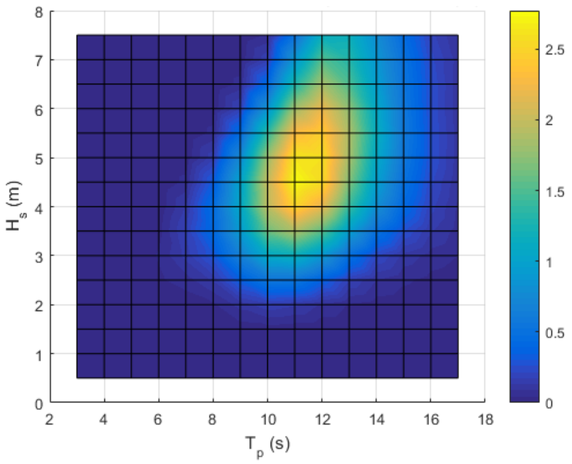


Figure 11. Scatter diagram for the most energetic site in the world (water depth 3517m) – probability of occurrence (in percentage)

Site dependent CAPEX assumptions, e.g. electrical connection length, are described in Section 5.7. Stage II conclusions regarding the energy performance and CAPEX scaling for large scale WECs are therefore presented separately.

5.3 Energy Performance Scaling and Theoretical Limits

5.3.1 Methodology

Calculations were undertaken to quantify the impact of device scale on energy performance for existing WEC types. High-level theoretical calculations were also undertaken to highlight fundamental energy performance limits applicable to large scale novel devices. A detailed description of assumptions and of the energy yield methodology is contained in Appendix B.

5.3.2 Results

5.3.2.1 Froude Scaling

The following metrics were derived for each upscaled device:

- Annual absorbed energy per characteristic mass (MWh/ton);
- Annual absorbed energy per characteristic (wetted) surface area (MWh/m^2);
- Annual absorbed energy per unit of RMS power take-off (PTO) force[2] (MWh/kN);
- Annual absorbed energy per unit of RMS excitation force[1] (MWh/kN).

As an example of the results, Figure 12 illustrates the change in the target metrics between the original NumWEC size and the 10MW upscaled version of the F-3OF device at the most energetic site in Scottish waters. The peak responses are shifted towards higher H_s and T_p values in the upscaled design.

[2] It is noted that not all forces were reported in the NumWEC data for the F-HBA and F-OWC devices. The related metrics, namely the annual absorbed energy per unit of RMS PTO force and per RMS excitation force, were therefore not derived for these cases.

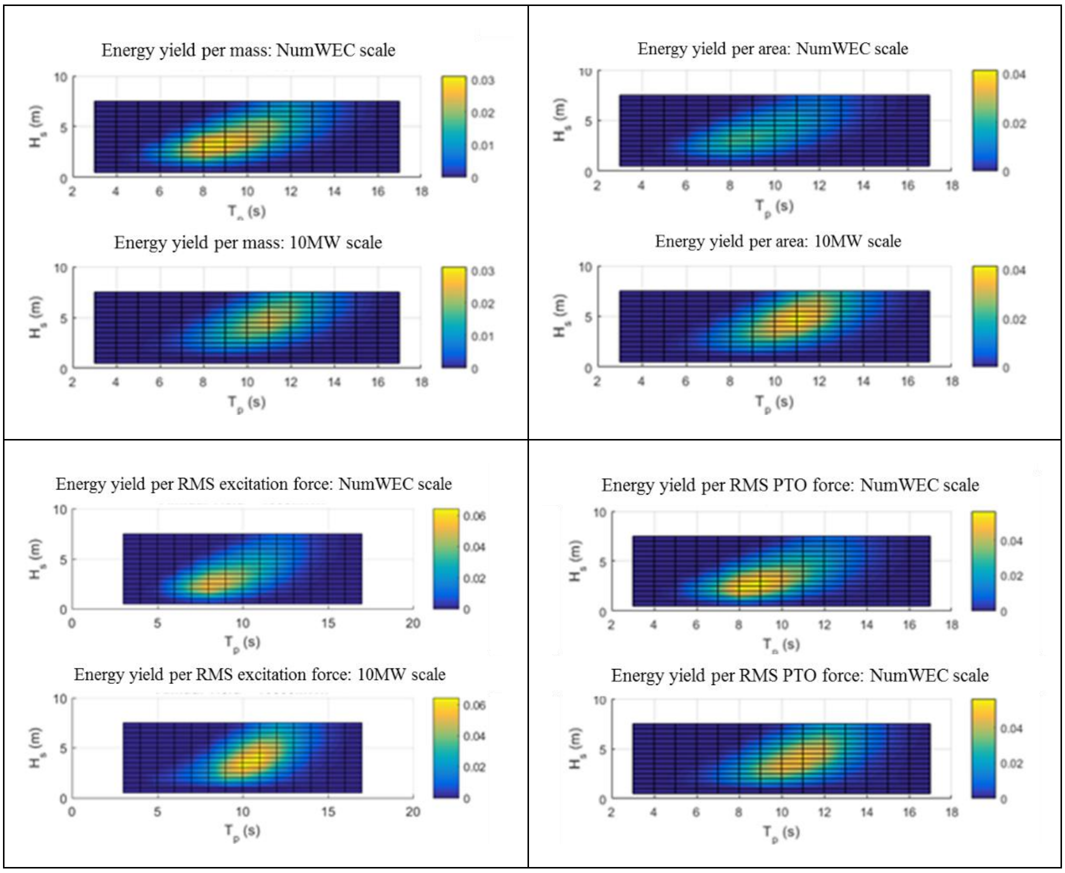


Figure 12. High-level WEC metrics for the F-3OF device at the most energetic site in Scottish waters – comparison between original NumWEC size (top rows) and 10MW size (bottom rows); from top left, in the clockwise direction: energy yield per mass, energy yield per area, energy yield per RMS excitation force and energy yield per RMS PTO force

To provide a summary for all devices, the maximum change in the metrics between the original and scaled size were calculated. Table 4 to Table 6 summarise the changes in metrics from the original NumWEC scale to the upscaled 10MW size. Results are presented for each of the sites considered; EMEC, Scotland+ (the most energetic site in Scotland) and World+ (the most energetic site in the world). A green mark indicates that the maximum in the corresponding metric has increased with the upscaling process, i.e. there is a benefit to device scaling. A red mark indicates a decrease as the scale increases, i.e. there isn’t a clear benefit to device scaling.

From Table 4 to Table 6, and based on the high-level assessment, grouping devices in a single platform emerges as a promising way forward for large scale wave energy generation, as increasing the power rating to 10MW in Scotland benefits mostly the grouped devices, in particular the B-HBA and F-3OF devices.

Table 4. Summary table of the improvement in maximum performance metrics from original NumWEC scale to upscaled 10MW size - EMEC

EMEC	BrefSHB	F-2HB	B-HBA	F-HBA	B-OF	F-3OF	F-OWC
Energy yield per mass	■	■	■	■	■	■	■
Energy yield per area	●	■	■	●	■	●	■
Energy yield per F_{PTO}	■	●	●	-	■	■	-
Energy yield per Fe	■	■	●	-	■	●	-

Table 5. Summary table of the improvement in maximum performance metrics from original NumWEC scale to upscaled 10MW size – Scotland+

Scotland+	BrefSHB	F-2HB	B-HBA	F-HBA	B-OF	F-3OF	F-OWC
Energy yield per mass	■	■	■	■	■	■	■
Energy yield per area	●	■	■	●	■	●	■
Energy yield per F_{PTO}	■	■	●	-	■	■	-
Energy yield per Fe	■	■	●	-	■	●	-

Table 6. Summary table of the improvement in maximum performance metrics from original NumWEC scale to upscaled 10MW size – World+

World+	BrefSHB	F-2HB	B-HBA	F-HBA	B-OF	F-3OF	F-OWC
Energy yield per mass	■	■	■	■	■	●	■
Energy yield per area	●	■	■	●	●	●	■
Energy yield per F_{PTO}	■	■	■	-	■	●	-
Energy yield per Fe	■	■	■	-	■	●	-

5.3.2.2 Optimum Device Size

The Stage II results are based on a device rating of 10MW. As power rating scales with $\lambda^{3.5}$ and length scales with λ, significant gains in rated power can be achieved with reasonable changes in dimension. An assessment into the impact of further increase in device size was therefore undertaken. Given time constraints of the study, this assessment considered grouped arrangements only; F-3OF, B-HBA, F-HBA and Bref-SHB.

The energy yield for devices with ratings up to 1GW were estimated for the three different sites. Figure 13 shows the results for the F-3OF case as an example. It should be noted that an increase in rated power from 10MW to 1GW corresponds to an increase in length scale of only 3.7, i.e. the size of devices are still considered feasible at a 1GW scale.

For the three sites considered, devices first show a rapid increase in energy yield with the device rating, verifying the merits of increasing the size on the energy yield. However, the energy yield plateaus at higher ratings, eventually decreasing in absolute terms when the size vs. site relationship is fundamentally detuned (noting that the control strategy remained unchanged). The reduced energy yield at very large scales also occurs due to the shift in the peak of the device power matrix towards higher H_s and T_p when upscaling the design, reaching waves that have minimal occurrences in the scatter diagram. The effect of plateau evidences the decreasing merits of higher ratings in absolute terms.

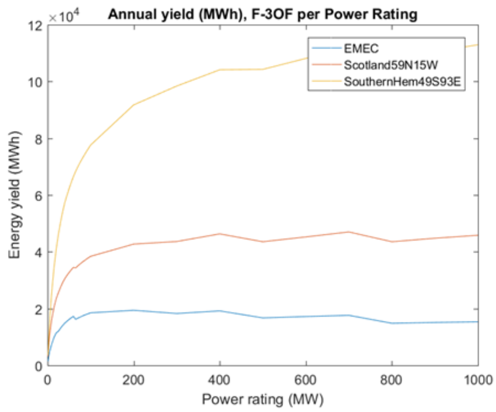


Figure 13. Energy yield (in MWh) vs. power rating (in MW) at the different sites considered: EMEC (blue line), Scotland+ (red line) and World+ (orange line) – F-3OF case.

The energy yield scaling was combined with CAPEX scaling estimates to estimate the influence of scale on cost per energy yield. CAPEX estimates are summarised in Table 7, assuming steel as the primary structural material. The derivation of these costs is described in Section 5.7.

Figure 14 shows the normalised CAPEX per energy yield for the grouped devices at each site for ratings between 1MW and 25MW. The costs per energy yield are normalised by their mean for each device and each site.

Table 7. WEC CAPEX cost summary

CAPEX (k£)	1MW	5MW	10MW
B-HBA	£7,774	£23,353	£38,167
F-HBA	£5,335	£15,892	£27,026
F-3OF	£6,162	£21,544	£38,523
BRef-SHB	£2,287	£7,900	£13,215

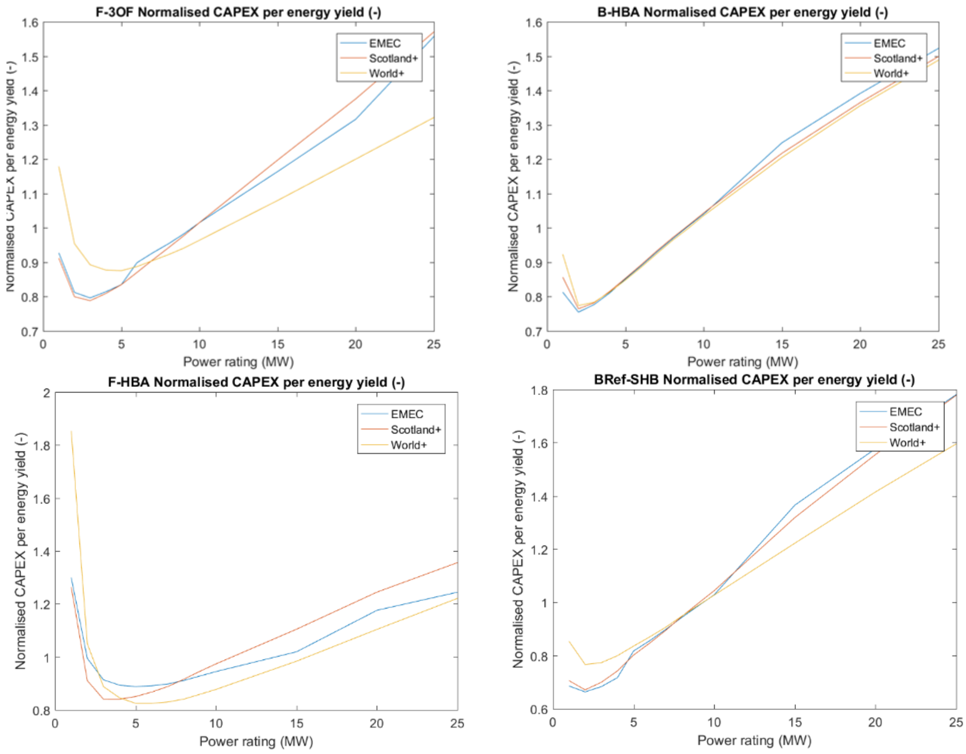


Figure 14. Normalised CAPEX costs per energy yield (-) against power rating (in MW) at the different sites considered: EMEC (blue line), Scotland+ (red line) and World+ (orange line) –F-3OF (top left), B-HBA (top right), F-HBA (bottom left) and BRef-SHB (bottom right).

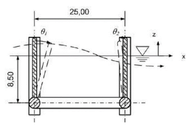
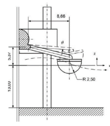
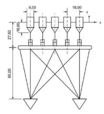
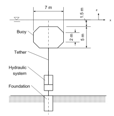
An inflection point is seen in all cases, suggesting an optimum device rating. It is noted that the optimum is relatively site insensitive, with the inflection point roughly coinciding for the three target sites. The optimum size ranges between 2 and 10MW rating for all devices, suggesting decreasing merits of ratings above 10MW.

5.3.2.3 Theoretical Limits and the Importance of Control

Scaled energy yield results were derived assuming a simple, sub-optimal PTO and control strategy. To enable a less conservative assessment of the energy yield of 10MW devices, the theoretical maximum energy that could potentially be converted has also been estimated assuming optimum PTO design and control strategy. Such assessment is relevant both for idealised versions of the 10MW NumWEC designs and for novel WECs with similar characteristics in terms of their absolute volume and modes of operation.

The hydrodynamic and physical limits of absorbed power were calculated for the 10MW versions of the B-HBA, F-HBA and F-3OF grouped devices and the BRef-SHB individual device. Table 8 presents the volume stroke and horizontal extension characteristics used for the calculation of the theoretical limits of each device.

Table 8. Volume stroke and horizontal extension characteristics per device

Device type	**Terminator**	**Attenuator / point absorber**		
Device	F-3OF	B-HBA	F-HBA	BRef-SHB
				
Volume stroke (m^3)	4,766	619	1 898	11 960
Horizontal extension (m)	45.6	N/A		

The volume stroke was calculated as following, per actuator, using parameters as provided in NumWEC [2] (scaled up where required):

$$V_{F-3OF} = l * h^2 * \frac{\pi}{2}$$

$$V_{B-HBA} = \pi * r^2 * \alpha_{stroke} * l_{arm}$$

$$V_{F-HBA} = \pi * r^2 * l_{stroke}$$

$$V_{BRef-SHB} = \pi * r^2 * l_{stroke}$$

Where l and h are the width and height of the F-3OF flap, respectively, α_{stroke} the stroke angle and l_{arm} the arm length of the B-HBA floater, r is the radius of the actuator, l_{stroke} is the stroke length.

Figure 15 shows the radiation (in red) and physical (i.e. Budal, in blue) absorbed power limits for a representative significant wave height of 4.5m, along with the actual absorbed power (passive control) at such wave height (in orange) for the F-3OF, B-HBA, F-3OF and BRef-SHB WECs. The upper limits of maximum absorbed power are presented per sea state for the F-3OF WEC in Figure 16 as an example.

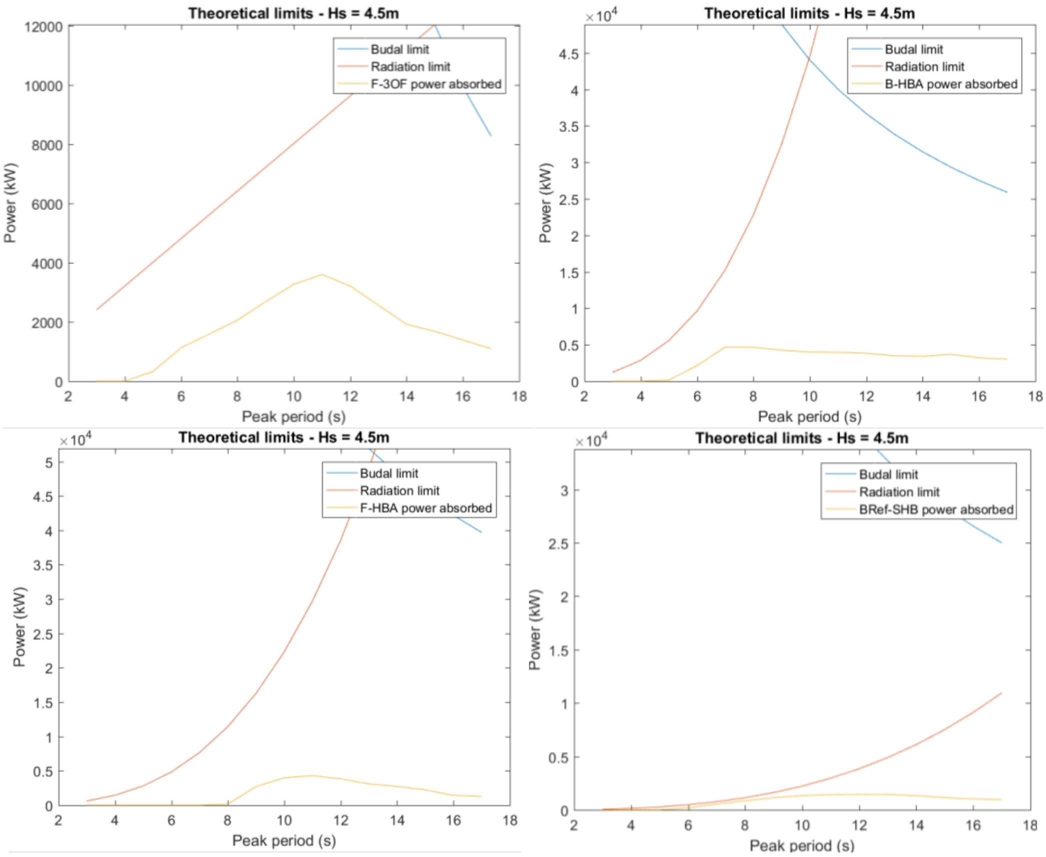


Figure 15. Theoretical maximum absorbed power (kW) at $H_s = 4.5m$: radiation (in red) and Budal (in blue) power limits for terminator-type (top left) and attenuator / point absorber-type (top right and bottom) devices, along with the actual power absorbed (in orange) by the F-3OF (top left), B-HBA (top right), the F-HBA (bottom left) and BRef-SHB (bottom right) WECs

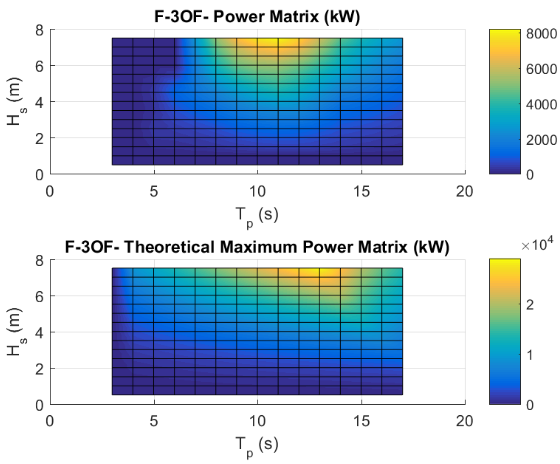


Figure 16. Sub-optimal (top) and maximum theoretical (bottom) absorbed power for the F-3OF WEC (in kW)

Table 9 to Table 12 summarise the maximum theoretical energy yield for each of the target sites, compared to the value assuming passive, sub-optimal control with the NumWEC upscaling. The tables also provide estimates of the maximum theoretical relative capture width (RCW), derived as the ratio between the theoretical maximum energy yield and the incident energy available across the width of the device at each target site. It should be noted that RCW estimates above 1 are feasible, indicating that wave energy is being absorbed beyond the wave-front that has the same nominal width as the WEC(s).

Table 9. Energy yield converted by the 10MW F-3OF (in MWh) and relative capture width (RCW): actual value and theoretical maximum (in MWh); and maximum theoretical relative capture width (RCW)

F-3OF 10MW	**EMEC**	**Scotland +**	**World +**
Energy yield (MWh)	7 704	16 563	26 478
Theoretical maximum (MWh)	25 133	51 600	94 307
Theoretical RCW	0.45	0.48	0.40
Maximum Theoretical RCW	1.46	1.48	1.44

Table 10. Energy yield converted by the 10MW B-HBA (in MWh) and relative capture width (RCW): actual value and theoretical maximum (in MWh); and maximum theoretical relative capture width (RCW)

B-HBA 10MW	**EMEC**	**Scotland +**	**World +**
Energy yield (MWh)	10 878	23 782	38 090
Theoretical maximum (MWh)	106 597	191 120	303 808
Theoretical RCW	0.29	0.31	0.27
Maximum Theoretical RCW	2.83	2.52	2.13

Table 11. Energy yield converted by the 10MW F-HBA (in MWh) and relative capture width (RCW): actual value and theoretical maximum (in MWh); and maximum theoretical relative capture width (RCW)

F-HBA 10MW	**EMEC**	**Scotland +**	**World +**
Energy yield (MWh)	10 763	20 933	32 939
Theoretical maximum (MWh)	92 173	169 516	336 305
Theoretical RCW	0.30	0.29	0.24
Maximum Theoretical RCW	2.56	2.33	2.46

Table 12. Energy yield converted by the 10MW BRef-SHB (in MWh) and relative capture width (RCW): actual value and theoretical maximum (in MWh); and maximum theoretical relative capture width (RCW)

BRef-SHB 10MW	EMEC	Scotland +	World +
Energy yield (MWh)	3 336	7 439	13 173
Theoretical maximum (MWh)	11 262	19 947	43 665
Theoretical RCW	0.44	0.48	0.45
Maximum Theoretical RCW	1.47	1.29	1.50

The results show that the WEC performance related to the passive (sub-optimal) control strategy is significantly lower than the theoretical maximum. The ratio between theoretical maximum energy yield and sub-optimal energy yield reaches a maximum of 10 (for the F-HBA device at the World+ site), with an average ratio of six across all devices and sites.

As illustrated in Figure 52, the significant gap observed between theoretical maximum and sub-optimal WEC performance could be improved through the use of more complex control strategies. However these results also illustrate the sensitivity of a WEC's physical size and its response to the site conditions. For example, it is likely that the scaled BRef-SHB is detuned to the EMEC site.

5.3.3 Conclusions

The Stage II energy performance assessment aimed to quantify the impact of scale on a range of high level WEC energy and load metrics across key WEC device types. It also aimed to identify theoretical energy performance limits applicable to a range of device types and novel WECs with similar characteristics in terms of their absolute volume and modes of operation. The key findings are summarised as follows:

1. *Grouped devices are a promising way forward*
    a. The B-HBA and F-3OF devices show an improvement in high-level WEC metrics when transitioning from original NumWEC scale to the 10MW size. This is explored in more detail in Section 6.3.
    b. It should also be noted that grouped devices were scaled up keeping the same number of individual devices. Some alternative solutions may be considered in optimisation exercises.
2. *Bigger is not always better*
    a. The impact of the scale on WEC performance was assessed by estimating the energy yield at three target sites, showing the decreasing merits of higher ratings, and the existence of an optimum size in terms of CAPEX per energy yield.

   b. Such optimum was found to be relatively site insensitive, with the minimum CAPEX per energy yield coinciding for the three sites investigated, and below 10MW for all devices considered.
   c. The potential differences between scaling single units and grouped devices warrant further investigation. This was undertaken in Stage III, see Section 6.3.

3. *Size is nothing without control*
   a. The maximum energy that could potentially be extracted, if the WEC device was operated in the best possible manner, was assessed for the grouped 10MW devices, (B-HBA, F-HBA and F-3OF WECs) and for one individual 10MW device (BRef-SHB WEC). The results are also applicable to novel WEC designs of similar characteristics (volume and mode of operation).
   b. The results showed that the WEC performance can be significantly enhanced by improving the control strategy to get closer to the theoretical limits, mostly in the operational range related to long peak periods.

5.4 Loads and Structural Scaling

5.4.1 Methodology

5.4.1.1 Loads

PTO force matrices were scaled according to Froude scaling, as described in Section 5.3. The peak PTO force on these matrices is caused by the largest wave heights. The largest significant wave height in these matrices has been limited to 7.5m, as higher waves become increasingly more unlikely. It was assumed that the devices will operate in a "survivability mode" during the most extreme storms, which will limit the loads. This survivability mode may involve some of the following measures to reduce wave loads:

- Floats lifting out of the water (B-HBA);
- Floats dropping to sea bed (Bref-SHB, F-HBA);
- Flaps rotating to close to horizontal (B-OF, F-3OF).

5.4.1.2 Structural

Scaling rules were derived for each of the seven NumWEC device types to estimate the structural mass at a 10MW scale. Common structural components, as described below, were scaled in a consistent way across multiple devices. A reference design and structural scaling rules were derived for each common component as described in Appendix C. Steel was assumed as the primary material for the device structure to enable a consistent comparison. Concrete was included within some foundation solutions.

The following metrics were calculated for the devices investigated:

- Absolute structural mass at 10MW scale;

- Scaling power on the length scale factor, λ. This provided a measure of how the structural mass of the devices investigated scale, in comparison to the power rating which scales as $\lambda^{3.5}$ (Section 5.3.2.2).

The NumWEC devices comprise a number of common structural components as shown in Figure 17. The following common structural components were considered:

- **Floats –** These comprise large volume structures likely to experience substantial loads from both hydrostatic and wave pressures. Structural design of these components was assumed to be similar to shell structures used within existing WEC point absorber devices. These consist of steel plates spanning between ribs and stiffeners supported by stiffened walls. The float structural form and mass for the 1MW baseline were based on design values from a leading submerged pressure differential device developer, described in [12].

- **Flaps –** Similar to floats, these comprise large volume structures likely to experience substantial loads from both hydrostatic and wave pressures. Structural design of these components was assumed to be similar to structures used within existing flap devices. These typically consist of cylinders connected by vertical steel plates.

- **Trusses** – These include any structures required for locating and/or supporting actuator components, such as floats or flaps, in a grouped device arrangement. These trusses may be required to carrying the weight of multiple actuators, such as in the B-HBA device, or to separate the actuators and provide stability, such as in the F-3OF and F-HBA devices.

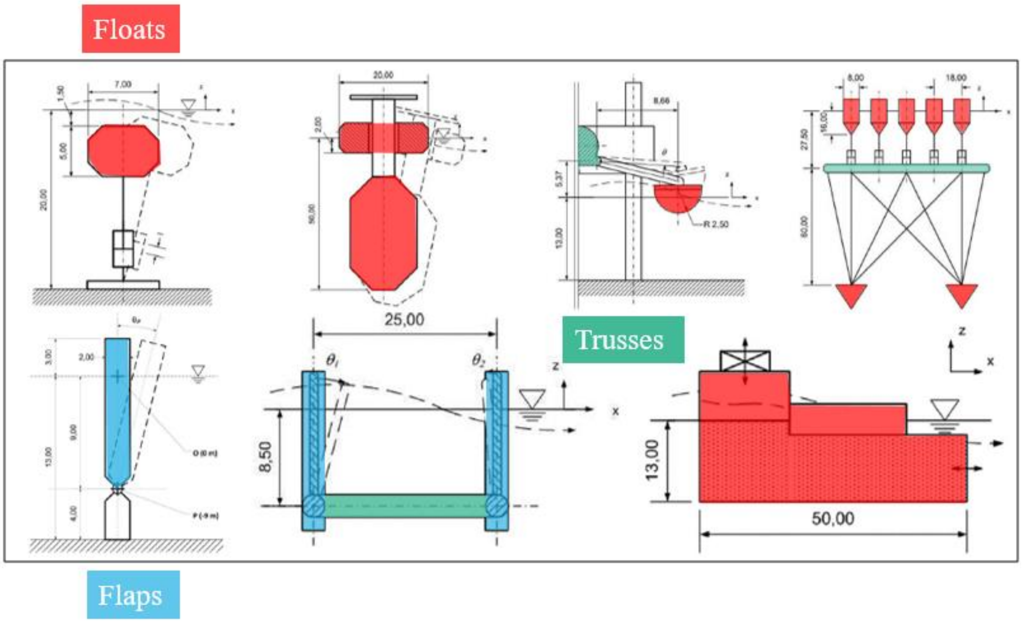


Figure 17. Common structural components

5.4.2 Results

5.4.2.1 Loads

The PTO force matrices for the NumWEC scale and 10MW devices have been compared, and the peak PTO forces have been selected at both scales. Table 13 shows a comparison of these forces for each of the seven devices for which data was available. The final two columns of the table show the geometric scaling factor λ which is used for scaling the device between NumWEC scale and 10MW and the power which this scaling factor λ is raised to obtain the ratio between the peak force at these two scales. RMS PTO force at a 10MW scale was calculated following the method described in Section 5.3. An example of the RMS PTO force outputs at the two scales investigated is shown in Figure 12.

Table 13. PTO force scaling

	RMS PTO Force (kN)		Length scale factor λ	Force Scaling
	NumWEC device	10MW device		
BREF-SHB	320	6500	3.7	$\lambda^{2.3}$
F2HB	2400	11000	1.9	$\lambda^{2.3}$
B-HBA	500	2000	1.8	$\lambda^{2.3}$
F-HBA	-	-	-	-
B-OF	10000	27500	1.6	$\lambda^{2.2}$
F-3OF	3400	24000	2.4	$\lambda^{2.3}$
F-OWC	-	-	-	-

Table 13 shows that the peak forces all scale roughly as $\lambda^{2.3}$, with very little variation from this value across the devices. This force scaling rule has been used to scale the global forces applied to the devices and the local design pressures.

5.4.2.2 Structural

Table 14 summarises the estimated scaling for the different common structural components. These scaling rules have been applied to the components that make up the seven different NumWEC device types. Comparing between the rows of the table, it is clear that some components scale more favourably than others. A lower scaling factor illustrates The structural cost of a device will scale well if it makes use of the components which scale well.

Table 14. Structural scaling rules for different common structural components (see Appendix C for details of the calculation)

Structural Component	Approximate Structural Mass Scaling
Float	$\lambda^{2.5}$ to $\lambda^{3.1}$
Trusses below the waterline (i.e. governed by wave forces)	$\lambda^{3.3}$
Trusses or superstructures above the waterline (i.e. governed by self-weight)	λ^{4}
Flaps	$\lambda^{3.3}$

Figure 18 shows the estimated absolute structural mass at a 10MW scale for the NumWEC devices broken down into components. A large range of structural masses is due to some devices scaling better than others (Table 14) and due to differences in the structural masses of the original designs. The following conclusions can be made from this figure:

- The Bref-SHB and F-2HB have similar sized floats, but the F-2HB has a greater total structural mass due to the mass of the inertia tank.
- The majority of the structural mass of the B-HBA is in the superstructure. The scaled B-HBA has a much bigger total structural mass than the Bref-SHB or F-2HB.

- The truss for the F-HBA has lower total mass compared to the B-HBA. This is partly because the submerged truss scales better than the superstructure above the water line used in the B-HBA.
- The structural mass of the F-3OF is much larger than the B-OF due to the multiple flaps and the truss required between them.
- The F-OWC has a large structural mass due to its very large wetted surface area

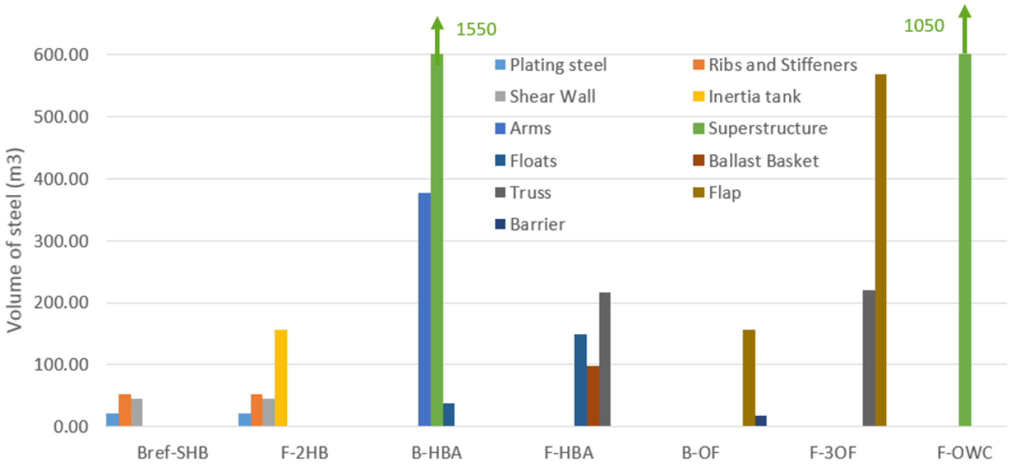


Figure 18. Estimated structural masses for 10MW devices

Figure 19 shows the scaling power on the length scale factor, λ, for the NumWEC devices. The devices considered have similar scaling relationships, highlighting the influence of the structural mass estimate on the original design on the absolute value.

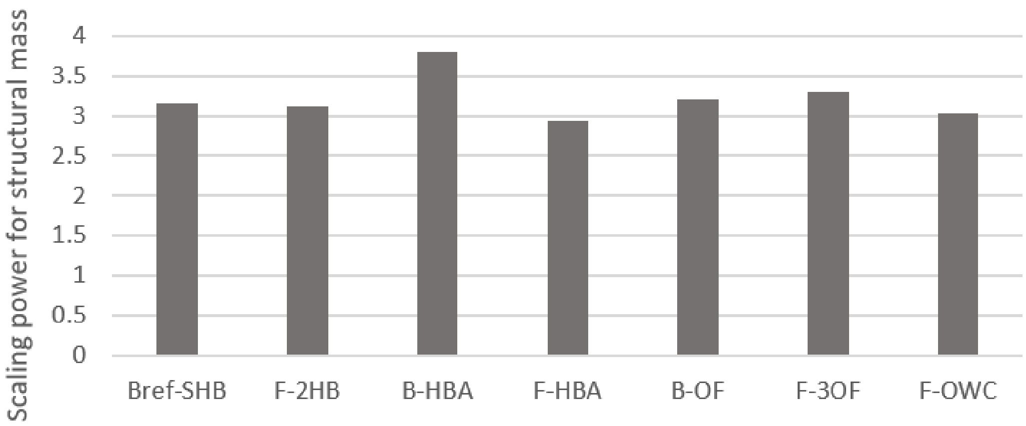
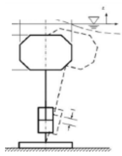
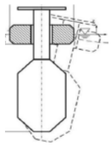
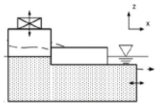
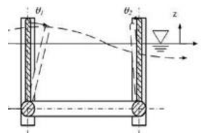
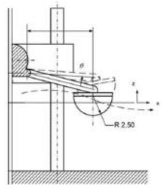
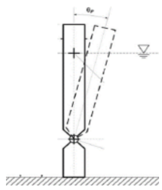
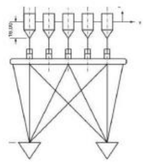


Figure 19. Scaling powers for structural masses

The global characteristics of the scaled large scale WEC devices are summarised in Table 15. Tow draft has been calculated for floating components assuming a relative density of 0.5. Due to the near-shore bottom fixed nature of the the B-HBA and B-OF devices it was assumed that these would be installed using a lift vessel.

Table 15. Global characteristics of 10MW NumWEC device

	Bref-SHB	**F-2HB**	**F-OWC**	**F-3OF**
				
Total Steel Mass (te)	1000	2200	12000	Flap: 800te x 2 Support structure: 1700
Ballast Mass (te)	N/A (water)	N/A (water)	N/A (water)	N/A (water)
Global Dim. (m)	Dia. 40 x H 10	DIA. 30 x H 120	110 x 50 plan	Support structure: 60 x 25 Flap height: 23.5
Tow Draft (m)	5	15	15	10

	B-HBA	**B-OF**	**F-HBA**
			
Total Steel Mass (te)	6700	Flap: 1200 Support: 550	Truss: 1700 Floats: 120te x 10 Ballast basket: 400te x 2
Ballast Mass (te)	N/A (water)	4000 (concrete)	N/A (water)
Global Dim. (m)	130 x 30 x 25	40 x 20 x 3	Truss: 230 x 30
Tow Draft (m)	N/A	N/A	5

5.5 Construction and Installation Assessment

5.5.1 Methodology

Facilities suitable for the construction and installation of large scale WECs were identified and their capacity assessed. The global properties of the large scale WECs estimated in Section 5.4 were used as a basis of the requirements necessary for construction of large scale WEC devices. In particular, facilities used for recent construction of offshore wind structures were considered to identify the capacity of the offshore wind supply chain for large scale WEC devices.

5.5.2 Results

Global characteristics of large scale WECs are summarised in Section 5.4.2. These structures could be constructed in a number of facilities:

- In a ship or graving (dry) dock;
- On a quayside;
- On a slipway.

Limits associated with these construction options are described in the following sections.

5.5.2.1 Dry Dock Construction

A ship or graving dock has the advantage that the float-out of the completed structure is the most straightforward, see Figure 20. Dry docks represent a feasible facility for the construction of the floating structures that make up several of the large scale WEC concepts. They also represent a suitable option for construction of concrete gravity foundations for the devices. These are typically cellular concrete structures, which would be floated to the offshore site and then flooded. This is the choice method of constructing concrete foundations for offshore wind, see Figure 21.

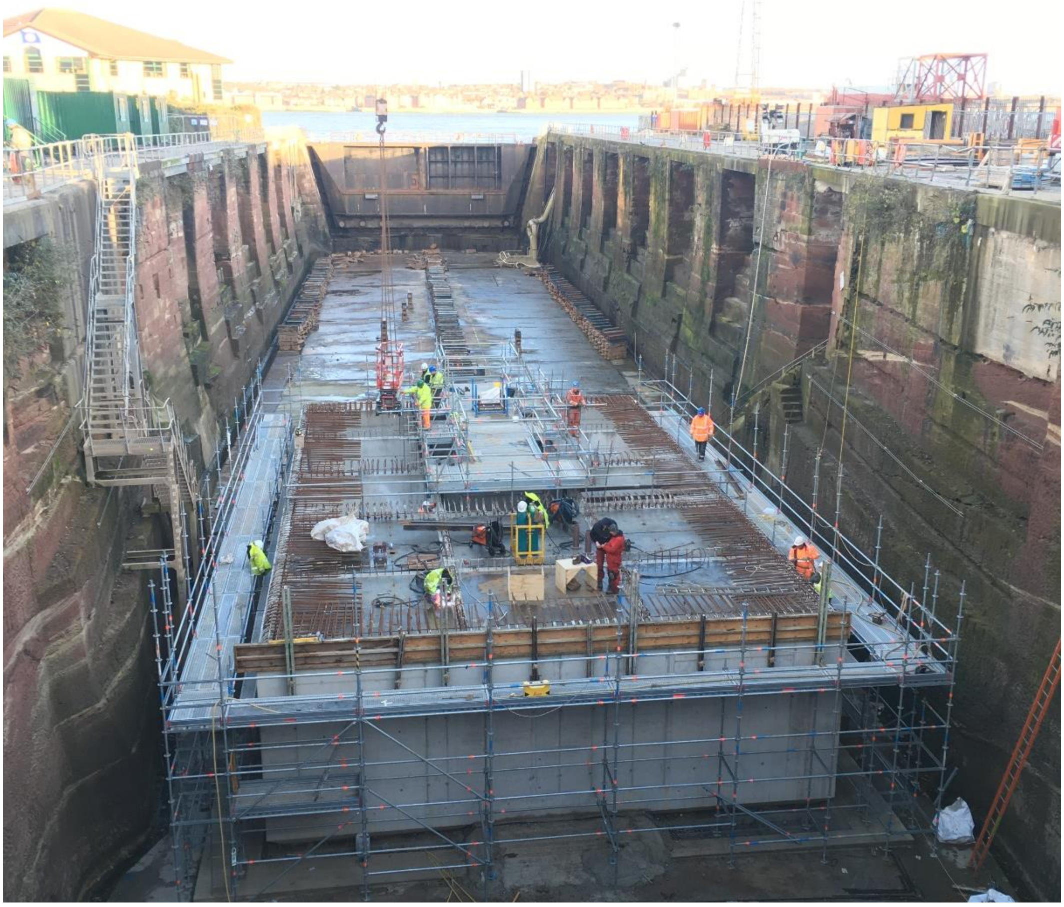


Figure 20. 1250te concrete caisson under construction in Cammell Laird Dock 4

Figure 21. Construction of concrete gravity foundations for offshore wind in a dry dock at Blyth

Table 16 lists the capacities of available dry docks in Scotland. Batches of the floating structures that make up the large scale WEC devices investigated in Stage

II could be constructed within the available facilities. Draft presents a limit for some of the large scale WEC configuration, as shown in Figure 22.

It should be noted that the device draft excludes submerged PTO attachments that would increase the draft substantially. A campaign for offshore assembly at a deep water site would therefore be required for these devices. For some configurations, for example floating actuators grouped on a shared structure, this could represent a complex and lengthy offshore operation.

Table 16. Capacity of dry docks located in or near Scotland

	Kishorn	**Port of Nigg**	**Rosyth Dockyard**	**Port of Blythe**
Gate Width (m)	160	120	30	30
Plan Area	Dia. ~100m	300 x 150m	320 x 40m	30 x 150m
Draft (m)	13	13	7.5	10

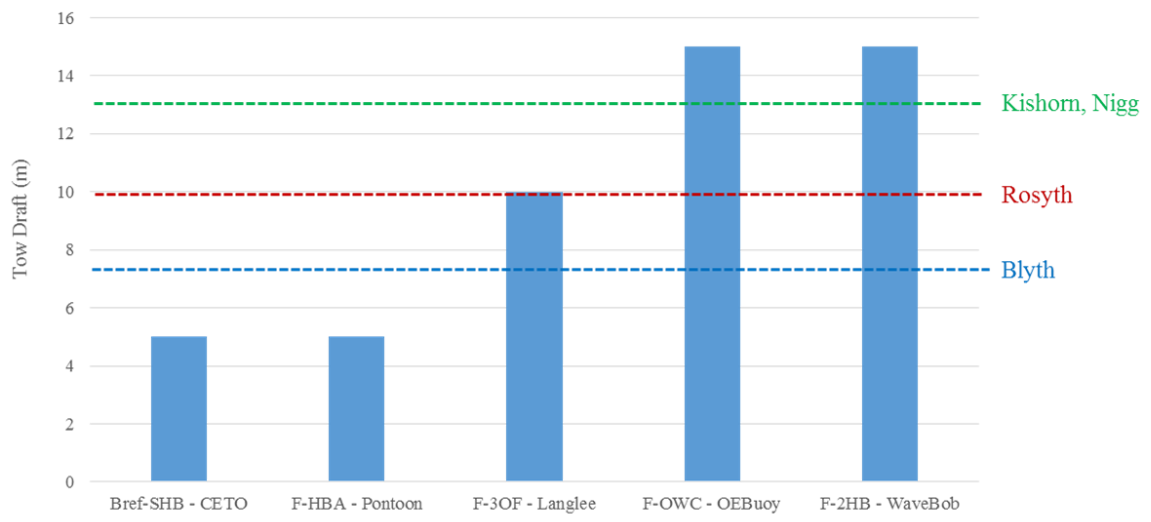


Figure 22. Stage II Large Scale WEC draft requirements and dry dock limits

Although technically feasible, the commercial viability of dry dock construction would need to be assessed. It may be difficult to secure the dry dock for construction of an individual or demonstrator unit as there are usually alternative more commercially attractive uses for the dock leading to a high premium.

A dry dock would be suitable for batch production of ten units, in perhaps two batches of five each batch being floated out together. This might be a more commercially attractive use of the dock for the owner, making the whole construction more viable. For greater than 10 units, the need to build units in batches and the interruption from dock flooding and emptying make dry dock construction less attractive as an option.

5.5.2.2 Quayside Construction

Construction on the quayside is straightforward and several production lines can be established provided there is sufficient space available. This method would become the most cost-effective for mass manufacture of 100 units or more. There is a balance to be struck between the cost of onshore storage of completed units and the day-rate for the vessel needed to receive the completed units for launching offshore. If land is plentiful and inexpensive, onshore storage followed by a short load-out programme would be most cost effective. If the project can justify the use of a dedicated vessel or launch facility, then a much smaller land area can be used. This is the method of construction for steel jacket structures used for offshore wind foundations. These structures are lifted onto a barge then transported to their final site and lifted into place with a specialised jack-up vessel.

Once constructed, quayside structures are lifted or skidded into the water or onto a barge. Mobile cranes have a capacity of a few hundred tonnes and so are unlikely to be suitable for large scale WEC structures at the demonstrator stage. The cost of mobilisation of one or two large onshore mobile cranes would be prohibitively expensive, even though the operation is feasible. Specialised jack-up vessels for offshore lifting developed for the offshore wind market have a lifting capacity of around 1200te. Some facilities have large capacity onshore ship-lifts, however these are unlikely to be suitable considering the overall dimensions of the large WEC.

Provision for elevating the large scale WEC structures to allow them to be loaded out using Self-Propelled Modular Transport (SPMT) units may represent a feasible option (Figure 23). These units would transport the structures onto a submersible barge or slipway, see Section 5.5.2.3.

Figure 23. Two Sarens 6 axle SPMT units with powerpack

5.5.2.3 Slipway Construction

A slipway might be suitable for an intermediate number of units, from say ten upwards. The launch of units is necessarily sequential, so the production rate is limited to that achievable on one line. Investment would be needed in the launch platform and skid rail system to lower the completed units into the water and to retrieve the launch platform, so this option is less suitable for one or two demonstrator units.

Other launch systems might prove feasible with some development. One example is a compressed air bag system used for ship launch. This could be an inexpensive launch method, but the operation is much less controlled.

Figure 24. Ship launch on slipway using compressed air roller bags

5.5.2.4 Potential Construction Facilities

Recent construction activity in a number of construction sites in Scotland has been enabled in part due to growth in the offshore wind market. Suitable construction facilities are summarised Figure 25. These all have dry dock facilities as well as extensive adjacent laydown areas, both of which are likely to be of benefit. As well as ensuring an active material and construction supply chain, this recent activity is likely to increase the commercial interest of contractors and facility owners in the construction of large offshore renewable structures.

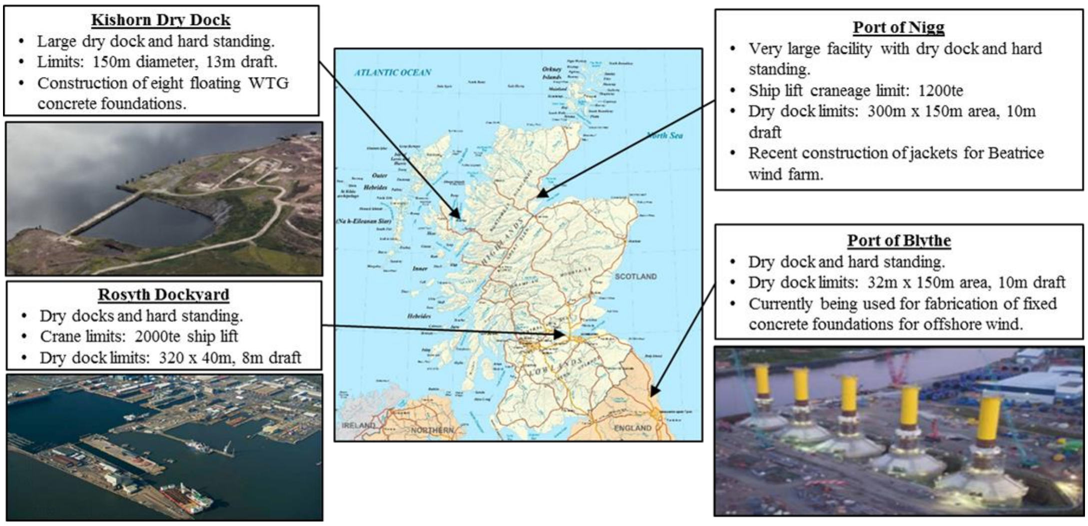


Figure 25. Large scale WEC potential construction facilities (map courtesy of Eric Gaba)

5.5.3 Conclusions

Construction in a dry dock or construction on a quayside followed by skidding onto a slipway or submersible barge represent the most feasible construction methods for large scale WEC devices. The optimum choice is dependent largely on the scale of production.

A number of construction sites in Scotland have been identified with sufficient physical capacity for construction of large scale WECs considering the estimated global dimensions. Recent construction activity for a number of these sites has occurred in line with the growing offshore wind market providing an opportunity for large scale WECs to take advantage of this active supply chain.

Several of the devices comprise floating structures attached to a submerged PTO or devices grouped onto a shared floating sub-structure. The offshore campaign and assembly method for these structures is yet to be developed and may represent a complex and lengthy offshore operation. The implications of this for large scale WECs has been considered in Stage III.

Although the construction and installation of large scale WEC devices is feasible at a commercial scale, a commercially attractive construction method for demonstrator units should be developed. Even at prototype scale, shoreline craneage requirements are likely to be prohibitively expensive for large scale WECs. It may also be difficult to secure the use of a dock for a single demonstrator device. A funding and production roadmap for large scale devices may therefore be required to understand the feasibility of these construction projects at a demonstrator stage.

5.6 PTO Arrangements and Limits

5.6.1 Methodology

A literature review was conducted into the arrangement and limits of Power Take Off (PTO) systems for WECs with 10MW+ capacity. The review considered the following areas:

1. Studies into upper limits on existing PTO systems.
2. PTO systems for devices in the 1MW+ range.
3. Potentially comparable systems from the wind industry.

The review considered hydraulic PTOs, direct drive PTOs, air driven turbines, dielectric PTOs and PTO systems for common shared structures.

5.6.2 Results

The full results of the literature review are contained in Appendix D and summarised below.

No fundamental limitations were found for individual hydraulic and direct drive PTOs at this scale. In both cases the literature also suggested an ability to modularise such systems, with scaling up being achievable through adding additional components in parallel. Such an approach has been evidenced in the wind industry for both hydraulic and direct drive rotary systems. PTOs, especially hydraulic systems, notoriously suffer from reduced conversion efficiency when operating below peak load. Having a modular system consisting of a number of smaller components in parallel offers an immediate control advantage to reduce this issue, with different components being turned on or off.

There are potentially greater issues with scaling up individual self-rectifying air turbines. These PTOs are required for Oscillating Water Column (OWC) concepts and multiple PTO systems in parallel would be required.

PTO systems for grouped concepts were also examined. Often these comprise individual PTO for each of the individual absorbers. The use of shared PTOs and accumulators is also suggested for a number of WEC grouped concepts. This can increase efficiency and durability, as it narrows / stabilises the operating region of the remaining PTO components [99]. If a feasible shared PTO arrangement exists, it may represent the most cost effective solution for grouped devices.

5.7 CAPEX Assessment

5.7.1 Methodology

The objective of the cost assessment was to derive capital costs for each of the NumWEC device concepts at various scales, to allow a relative assessment of CAPEX for the devices investigated.

It is recognised that different WEC concepts will have different general arrangements, some of which will have very different features that impact cost. Nonetheless, many of the most significant cost categories can be considered at a high level to allow a robust relative assessment without a requirement to investigate the specific, detailed configuration of individual WECs.

To estimate the capital costs of scaled NumWEC devices, a high-level bill of materials was created for each concept, using the same cost categories defined in the WES LCoE Calculator [11]:

- Structure and prime mover (£k).
- PTO (£k).
- Foundations and mooring (£k).
- Connection (£k).
- Installation (£k).

Cost estimates were derived for each device concept at 1MW, 5MW and 10MW sizes. The inputs to the estimates are described below.

Structure

Previous work [12] has derived appropriate metrics for evaluating the manufacturing costs of WECs. Cost data is listed in Table 17, considered to be valid in 2018 for structures typical of WECs although it must be noted that costs may fluctuate depending on material costs, fabrication location & method, and the detailed design of the structure.

Table 17. WEC manufacturing cost metrics

Metric	Value
Steel fabrication	£4,000/te
Concrete manufacture (where appropriate for individual elements)	£300/te
Other allowances	13%

Other allowances include the use of a fabrication yard, engineering, certification and other indirect costs such as site management, plant and equipment. These costs are applied as a percentage on top of the direct costs and are based on experience from previous projects. Contractor's overheads and profit are assumed to be captured in the steel cost/tonne rates.

Power Take-Off

Power take-off arrangements vary between concepts. A hydraulic power take-off is suitable for six of the concepts evaluated, and a pneumatic system for one. It is known from the literature review in Section 5.6 that the costs of hydraulic systems vary depending on complexity. This is illustrated in Table 18. A suitable metric for the cost of pneumatic systems is also illustrated.

Table 18. Power take-off costs

Power take-off	Value
Hydraulic (simple)	£800k/MW [13]
Hydraulic (complex)	£1.5m/MW [14]
Pneumatic	£900k/MW [16]

Based on this data, £900k/MW was identified as a suitable PTO cost for this evaluation. This figure was supported when consulting with industry experts during this project. It is assumed that all PTO systems could be scaled using multiples of 1MW modules. Furthermore it is assumed that these arrangements would benefit from some cost reduction opportunities as components are procured in volume. Typical learning curves [12] suggest that a cost reduction of 15% is reasonable to assume for a ten-fold increase in procurement.

Moorings

For this stage of the assessment, a concept mooring arrangement was selected for each device. An arrangement of tendons (similar to a tension leg mooring) was identified as suitable for bottom-referencing devices (Bref-SHB). Catenary moorings with an appropriate number of elements was identified for wave-following devices (F-2HB, F-HBA, F-30F and F-OWC). Stage III presents more detailed mooring arrangements for a subset of these devices

Drawing on Arup's experience and cost estimation, a high-level bill of materials was derived for each, including an estimate of time and cost for a suitable installation vessel. These costs are summarized below. The cost of securing bottom-mounted devices, typically by the use of piles, is accounted for in the Installation cost category described later in this section.

Table 19. Mooring costs

Concept device	Mooring cost		
	1 MW	**5 MW**	**10 MW**
Bref-SHB	£560,000	£800,000	£1,228,000
F-2HB	£1,534,000	£1,846,000	£2,236,000
F-HBA	£1,785,000	£2,201,000	£2,721,000
F-3OF	£1,785,000	£2,201,000	£2,721,000
F-OWC	£1,785,000	£2,201,000	£2,721,000

Electrical Connection

The cost of the electrical connection to shore is directly proportional to the distance from shore. For this assessment, the concepts are assigned to appropriate water depths to illustrate typical minimum connection costs. It should be noted that cable ratings, seabed conditions and specific arrangement of connectors, junction boxes have not been considered. The distance to shore is illustrative only, reflecting that larger scale devices would need to be further offshore whereas fixed-bottom devices would require near-shore sites. Stage III presents a more detailed analysis.

Table 20. Electrical connection costs

Concept	Distance to shore	Applicable cost metrics
All 1MW devices	1km	£100/m cable capital cost £200/m cable lay cost [15]
Floating 5MW, 10MW devices	2km	
Fixed 5MW, 10MW devices	1km	

Installation

For installation of devices, it is assumed that a suitable vessel tows the device from harbour to the offshore site for connection to pre-laid moorings (for floating devices) or for set-down (for fixed devices). When considering fixed devices, a cost for placing foundation piles is also included.

Vessel costs are illustrative of a multi-cat suitable for towing 1MW devices, a small anchor-handling tug for the 10MW devices and a suitable offshore piling rig. Where relevant, these are refined in Stage III.

The duration of the operation allows for installation, commissioning, and standby during early operation.

Table 21. Installation costs

Device	**Cost of vessel, crew and supporting plant**	**Number of days**
1MW device	£10,000/day	5
10MW device	£25,000/day	5
Additional piling for fixed devices	£75,000/day	6

5.7.2 Results

For many concepts, the cost contribution of structures and prime movers will typically comprise a high proportion. To visualise this, it is useful to consider the structural cost first, illustrated in Figure 26.

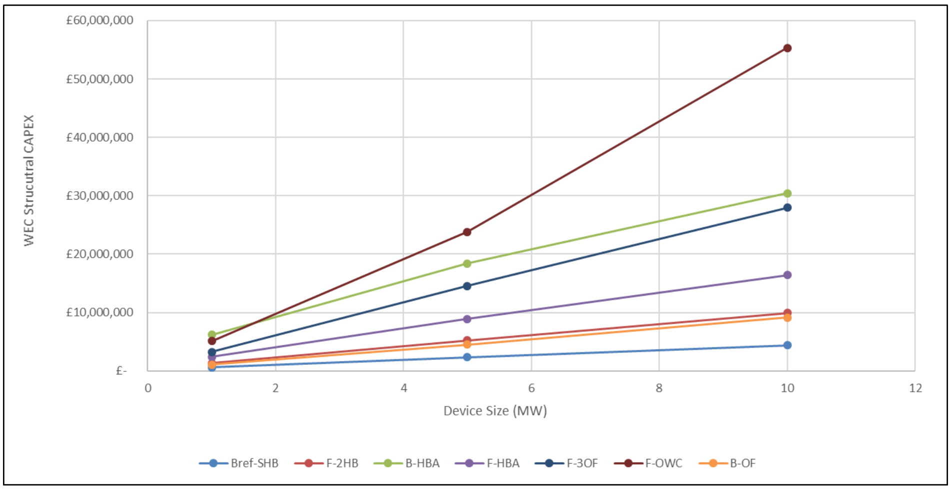


Figure 26. Structural CAPEX

As expected, a clear relationship is visible between scale and cost. However different concepts show different rates of cost increase, as illustrated by the gradient of the curves. For example, the slope of the curve representing the F-HBA Pontoon concept is the shallowest, reflecting its lightweight construction which lends itself well to scaling. The steepest slope is that of the F-OWC which reflects the much heavier construction of this device.

Figure 27 illustrates the total CAPEX which includes all the cost categories described earlier. It is clear that the shapes of the curves are still broadly similar to the structural CAPEX and the structural CAPEX dominates the total.

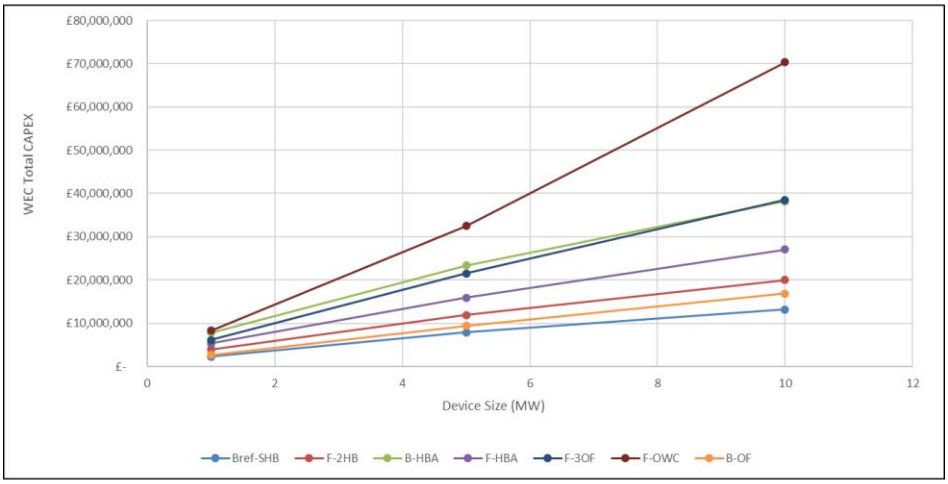


Figure 27. Total CAPEX

Cost per megawatt installed (£m/MW) is a commonly-used metric for comparing different technologies and projects. This is illustrated in Figure 28. This figure also illustrates the typical cost of large capacity offshore wind turbines.

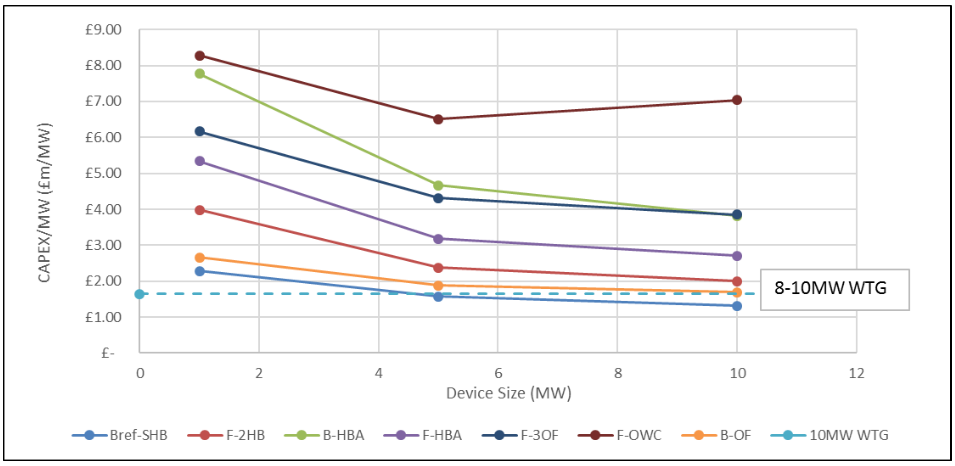


Figure 28. Cost per megawatt installed

5.7.3 Conclusions

Key findings from this cost assessment include:

- For some concepts, the cost of the structure or prime mover of a WEC can dominate the overall capital costs. This is particularly evident in devices which rely on large fabricated substructures which as a consequence do not appear to offer cost-effective scaling.
- When considering the capital costs of the NumWEC devices at a high level, grouped devices and heaving buoy concepts appear to offer the most cost-effective scaling opportunity. This appears to be a consequence of their lighter-weight construction.When comparing with offshore wind, the range of costs (expressed as cost per megawatt installed) for the scaled WEC devices is generally higher.

5.8 Stage II Conclusions

Stage II comprised quantitative assessment into the potential opportunity and limitations based on scaling the main existing state-of-the-art WEC types, based on generic device geometries obtained from the NumWEC study.

Key findings from the Stage II assessment include:

Energy Performance Potential

- The gains in energy yield diminish with device size for large scale WECs and an optimum exists. The optimum size depends on the device in question but was found to be <10MW for the devices investigated in this study.
- Large scale grouped devices have the potential for control optimisation options (which can lead to greater yield) which may not be available to individual large scale devices. The effective volume of grouped devices is distributed across the units, which may make them more readily tuneable to the wave climate.

Structural Scaling and Feasibility

- Shared structures form a significant portion of total device cost and an optimised arrangement is required to make this configuration cost effective. Their advantage is likely realised in deep water sites where mooring costs comprise a greater portion of total costs.
- A number of sites in Scotland have been identified with sufficient physical capacity for construction of large scale WECs considering the global dimensions estimated in this study. Recent construction activity for a number of these sites has occurred in line with the growing offshore wind market, which may provide an opportunity for large scale WECs to take advantage of this active supply chain.
- Several of the devices comprise floating structures attached to a submerged PTO or devices grouped onto a shared floating sub-structure. The offshore campaign and assembly method for these structures is yet to be developed and may represent a complex and lengthy offshore operation.
- Although the construction and installation of large scale WEC devices is feasible at a commercial scale, a commercially attractive construction method for demonstrator units should be developed.

CAPEX Assessment

- When considering the capital costs of the NumWEC devices at a high level, grouped devices and heaving buoy concepts appear to offer the most cost-effective scaling opportunity. Devices which rely on large fixed fabricated structures do not appear to offer cost-effective scaling and are less attractive for large scale WECs. In light of this, Stage III (Section 6) included an investigation into the impact of grouped structures on the cost of large WECs assuming an optimised design for the shared structure.

- When comparing with offshore wind, the range of costs (expressed as cost per megawatt installed) for the scaled WEC devices is generally higher.

6 Stage III: Refined Assessment

6.1 Stage III Methodology

Stage III comprised a quantitative comparison between a baseline array of 100 x 1MW devices, an array of 10 x 10MW individual devices and an array of 100 x 1MW devices on a shared structure. This aimed to quantify the benefit of potential large scale WEC configurations relative to the current state of practice.

The Stage II assessment was expanded to include a more realistic energy performance estimate and an OPEX assessment. The CAPEX assessment was also expanded to include moorings, electrical infrastructure and the installation campaign. This enabled estimation of the LCoE for potential large scale WEC configurations relative to a baseline array of 1MW devices.

Section 6.2 provides a basis for the Stage III assessment and the remainder of Stage III is presented as follows:

- Section 6.3 describes the revised energy performance assessment based on theoretical device limits and a numerical assessment into the scaling effect of control on energy performance and loads;
- Section 6.4 describes additional structural scaling and CAPEX calculations;
- Section 6.5 compares the mooring system feasibility and associated CAPEX for each of the configurations;
- Section 6.6 compares the offshore campaign feasibility and associated CAPEX for each of the configurations;
- Section 6.7 compares the electrical infrastructure CAPEX for each of the configurations;
- Section 6.8 describes a quantitative OPEX assessment for each of the configurations;
- Section 6.9 contains derivation and comparison of the LCoE for each of the configurations.

A summary comparison of the large WEC configurations is presented in Section 6.10.

6.2 Assessment Basis

6.2.1 Key Assumptions

- The assessment was intended to be as device agnostic as possible. Where geometry was required for the comparison, e.g. energy performance and structural scaling calculations, a device of type Bref-SHB [2] was considered. It was assumed that the grouped device comprised a number of these attached to a shared structure to enable fair comparison with the baseline arrangement.
- The energy yield was estimated based on the theoretical maximum values from Stage II (Section 5.3) with the inclusion of realistic constraints.
- The F-HBA (grouped) device was also considered to investigate the trade off between survivability and performance for a specific device (Appendix G). These results are presented independently to the LCoE comparison. Conversion losses between mechanical and electrical output are considered.
- The shared truss structure and mooring systems were sized based on extreme loads estimated by a leading heaving buoy developer.
- Steel was assumed as the primary material for all device structures to enable a fair comparison. Nylon rope technology was assumed for the mooring lines.
- The CAPEX assumptions generally matched those in Stage II, see Section 5.7. Any updated input metrics are described below where these are introduced.
- The moorings CAPEX, electrical infrastructure CAPEX and OPEX assessment assumed a west coast of Scotland site, described in Section 6.2.3. The energy performance was calculated for three locations described in Section 5.2.3 to assess the influence of wave resource on large scale WEC yield. The LCoE and other metrics are presented as a range, depending on the available site resource.

6.2.2 Large Scale Configurations

The properties of the configurations investigated in Stage III are summarised in Table 22. Figure 29 illustrates the assumed arrangement for the grouped structure. The assessment was intended to be as device agnostic as possible, but specific calculations assumed a Bref-SHB [2] type device where necessary, either individually or grouped on a shared truss, see Figure 30.

Table 22. Stage III WEC configurations

	1. Baseline	2. Large Grouped	3. Large Individual
WEC Device Type	1MW Bref-SHB in an array	1MW Bref-SHB on a shared structure	10MW Bref-SHB in an array
Configuration	100 x 1MW	100[2] x 1MW on a shared structure	10 x 10MW
Global Dimensions[3]	Float: Ø20m x 4m	Single Truss: 60m x 6m Grouped Truss: 3 x single trusses Float: Ø20m x 4m	Float: Ø40m x 8m
Device Spacing[4]	200m x 200m grid	Evenly spaced on truss. 200m between parallel trusses.	200m x 200m grid
Electrical Arrangement	10 units with a subsea hub.	10 units with a subsea hub.	10 units with a subsea hub.
Array Area (km^2)	4	0.4	4

[1] Energy performance and structural scaling assumptions are described in Sections 6.3 and 6.4 respectively.

[2] Devices are grouped as three on a shared structure due to practical limitations (Figure 29). However, the array level comparison considered 100 x 1MW devices on shared structures to simplify the assessment.

[3] The 1MW Bref-SHB structural form and mass were based on design values from a leading submerged pressure differential device developer, described in [12].

[4] Device spacing was assumed to be governed by O&M considerations, based on estimate from a leading WEC developer. At a spacing of 10 x diameter, array interaction effects were considered negligible. Interaction effects for grouped devices were quantitatively investigated, as described in Section 6.3.

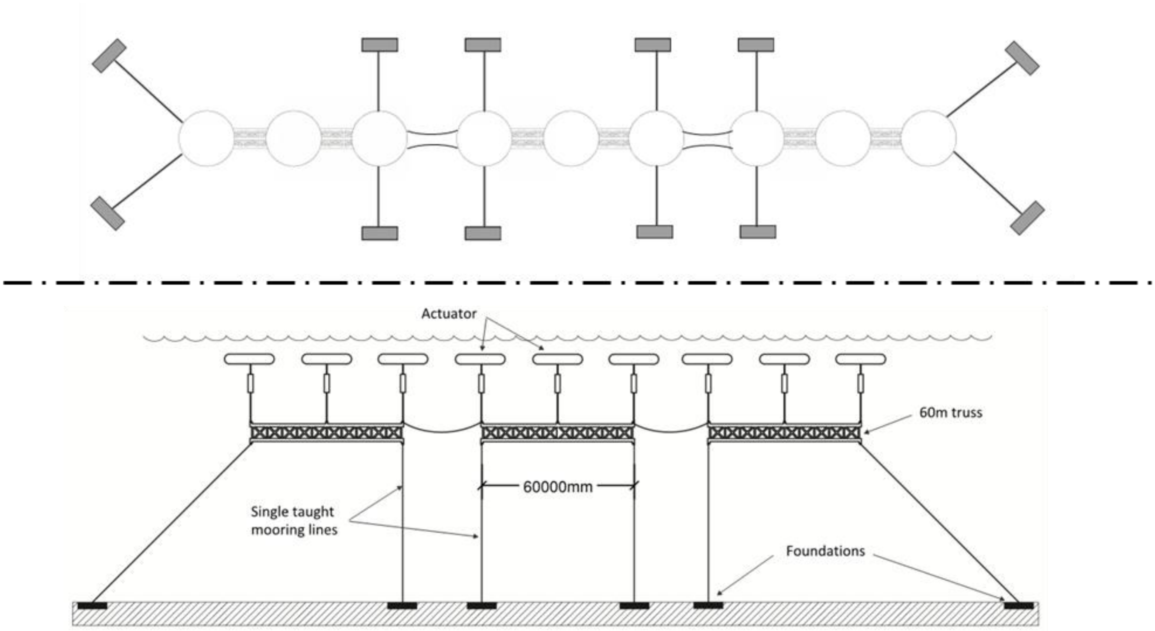


Figure 29. Grouped device arrangement per nine devices – plan and elevation views

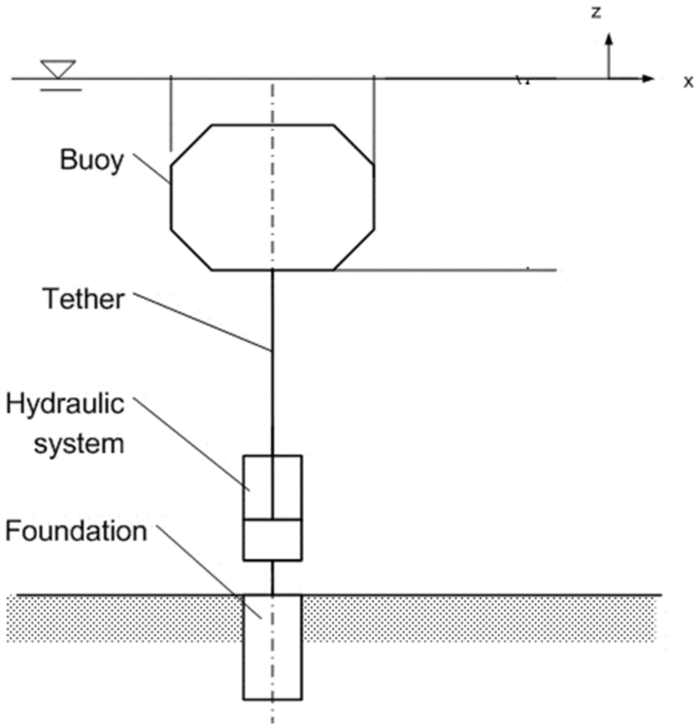


Figure 30. Bref-SHB device schematic. For assumed global properties, refer to Table 22 [2].

6.2.3 Sites

The energy performance assessment was performed for three sites to assess the sensitivity of large scale WECs to available wave resource. The sites covered the range of theoretically available global wave energy resource. Details of the sites matched those considered during Stage II, see Section 5.2.3.

The moorings, electrical infrastructure and OPEX assessment assumed a generic site with properties described in Table 23. An example Scottish site with similar properties is located off the west coast of Uist, see Figure 31. This has been selected to offer a suitable compromise of proximity to the mainland, good levels of incident power and water depths appropriate for very large devices. The LCoE analysis presented in Section 6.9 considers this site for CAPEX and OPEX inputs.

Table 23. Site properties for moorings, electrical infrastructure and OPEX assessment

Property	**Assumed characteristics**
Water depth (m)	110
Distance to shore (km)	50
Distance to O&M base (km)	230

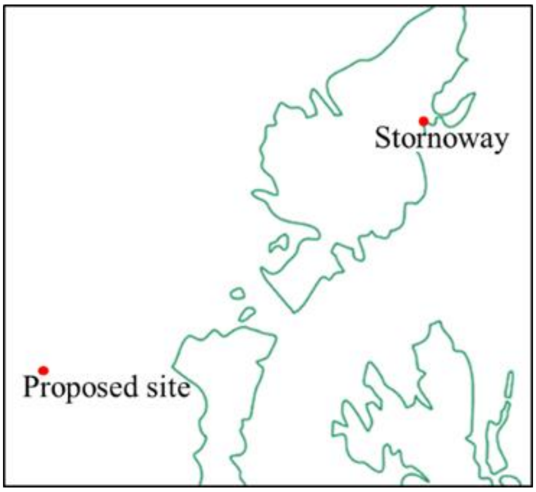


Figure 31. Illustrative site and assumed O&M base location (Stornoway)

6.3 Energy Performance Assessment

6.3.1 Methodology

Stage II indicated that advanced control could significantly improve WEC performance, in addition to the potential benefits of increasing size. To further quantify the influences of control and size, additional investigations were conducted on the relationship between theoretical limits and actual WEC performance, under realistic constraints and considering different control strategies and scales.

In the high-level assessment conducted in Stage II, only mechanically absorbed power estimates were derived. However, most of the relevant guidance documents and technical specifications (e.g. [29]-[32]) emphasise that an assessment of WEC performance should be based on estimations of the net output electrical power, including all elements of the power conversion chain (PCC). As such, realistic constraints should be considered in the power conversion subsystem used in the PTO unit, accounting for losses during the conversion from mechanical to electrical power.

Also in Stage II, the potential gain in WEC performance by improving the control strategy was initially quantified based on relevant literature only. Stage III develops a specific example case to quantify how improved control can impact on WEC performance.

Two key metrics, namely the theoretical maximum relative capture width (RCW) and a ratio of actual to theoretical energy yield estimates, have been investigated at the original NumWEC size and at the 10MW size, leading to a quantitative assessment of the impact of control and scale in relation to the theoretical limits.

Energy yield under realistic constraints

For each device, and following the baseline assumptions in NumWEC, a hydraulic PTO system was considered, where hydraulic cylinders provide primary conversion. In such a PCC, an accumulator is used as primary storage to provide a spring load and stiffness. Accumulators can also be used for pre-conversion storage before passing the fluid through hydraulic motors, coupled to electrical generators. After electrical conversion and as required, further smoothing could be performed by batteries or capacitors before exporting electricity to the grid.

Typical efficiency values for the different components of the PCC can be found in the literature. Regarding hydraulic PCCs, the efficiency of the primary energy conversion mechanisms is expected to vary between $\eta_{hyd} = 0.65$ [33] and $\eta_{hyd} = 0.80$ [34]. Generator efficiencies are reported to vary between $\eta_{gen} = 0.85$ [35] up to $\eta_{gen} = 0.98$ [36], in the context of large generators applied in the wind energy industry. These values are summarised in Table 24. The resulting hydraulic system efficiency coefficient was applied to the energy yield outputs calculated in Stage II (see 5.1) to derive estimates of the electrical output.

Table 24. Summary of the efficiency coefficients used in the hydraulic system considered: components (hydraulic PCC and generator) and overall hydraulic system

Efficiency		**Range**
Hydraulic PCCs	η_{hyd}	0.65-0.8
Generator	η_{gen}	0.85-0.98
Hydraulic system	$\eta_{syst} = \eta_{hyd} * \eta_{gen}$	0.55-0.78

An estimate of the theoretical maximum electrical energy yield $MAEP_{max,elec}$ can therefore be obtained from the theoretical maximum mechanical energy yield $MAEP_{max,mech}$ as following:

$$MAEP_{max,elec} = MAEP_{max,mech} * \eta_{syst}$$

Furthermore, Stage II concluded that the WEC performance can be significantly enhanced by improving the control strategy. In the case of irregular wave fields, various control methods for point absorbing devices were investigated in [37], based on an idealised example of a heaving semi-submerged sphere. It was found that overall improvements in average absorbed power of about 100–330% could be achieved for the investigated controllers, when compared with a passive control strategy (see Table 25).

Table 25. Summary of the improvement coefficients from passive control strategy

Improvement from passive control		**Range**
Coefficient	$t_{control}$	1.0-3.3

An estimate of the electrical energy yield $MAEP_{+,elec}$ for a device using an improved control strategy compared to a passive method can therefore be obtained from the mechanical energy yield using a passive control $MAEP_{0,mech}$ following:

$$MAEP_{+,elec} = MAEP_{0,mech} * (t_{control} + 1) * \eta_{syst}$$

It should be noted that the investigations on control methods conducted in [37] focused on isolated WECs – and that it is assumed in this study that the same improvement coefficients could be applied to grouped devices. Studies e.g. [41] and [42] show that there are likely array destructive interference effects, but these are not accounted for at this stage. A quantitative assessment into the effect of interference is included in Appendix G.

Scaling effect on theoretical limits: key metrics

In order to assess the impact of scaling up on performance from a control and scale perspective, two ratios were considered:

- The relative capture width (RCW), calculated as the ratio between theoretical maximum energy yield and the energy available at the site across the width of the WEC. This evaluates the hydrodynamic efficiency, from the input wave field to mechanical conversion.

- The ratio of energy yield, calculated as the ratio between the actual energy yield from the WEC and the theoretical maximum energy yield. This provides a high-level metric to evaluate the deficit of actual yield to the theoretical maximum.

Survivability and Performance Assessment

In a high-level, preliminary approximation of the upscaling effects on the WEC, the performance and load assessments considered in Stage II were conducted by applying the Froude scaling laws to derive the characteristics of representative 10MW designs (see Section 5.1).

In order to refine the assessment of the opportunities introduced by upscaling, a quantitative assessment was conducted using a more detailed numerical model, focusing on the effect of the control on the performance and loading affecting a large scale WEC. Essentially, the investigation considered three control strategies, and high-level performance and survivability metrics were quantified in one operational and one extreme sea states, respectively.

Appendix G presents this specific assessment.

6.3.2 Results

Energy yield under realistic constraints

The impact of the control strategy when pursuing the theoretical limit is of critical importance. In particular, Table 26 illustrates how a suitable active control strategy may improve the WEC performance in terms of mechanical energy yield. The energy yield values related to the improved control were derived using the improvement coefficients from passive control strategy presented in Table 25, applied to the mechanical energy yield estimates related to passive control obtained in Stage II (see 5.1). Control can therefore be seen as a primary factor to bridge the gap between the baseline WEC energy yield estimates and the maximum theoretical bounds.

Table 26. Impact of control strategy on WEC performance: mechanical energy yields (MWh/year) related to a passive control strategy and an improved control strategy (minimum – improvement of 100%, and maximum – improvement of up to 330%, limited at the theoretical maximum energy yield value)

EMEC	Passive control (MWh/yr)	Improved control (MWh/yr)	
		Minimum	Maximum
F-3OF	7,704	15,408	25,133
B-HBA	10,878	21,756	46,775
F-HBA	10,763	21,526	46,281
Bref-SBH	3,336	6,672	11,262

In keeping with the existing standards and guidelines on WEC performance assessment (e.g. [29]-[32]), a summary of the annual electrical energy production for each WEC (excluding electrical losses external to the WEC) is presented in

Figure 32. The average mechanically absorbed energy yields (theoretical maximum – see Section 5.3, and energy yield related to an improved control strategy – see Table 26) are converted to net electrical energy using the efficiency coefficients given in Table 24. The power conversion from mechanical to electrical was accounted for by considering the typical efficiency for the downstream elements in the PCC. Overall mechanical to electrical efficiencies ranging between 55% and 78% were considered.

It can be seen in Figure 32 that the electrical energy yield for the F-3OF and BRef-SBH WECs can reach the theoretical maximum when considering the improvements potentially gained by using an advanced control strategy. However, the maximum energy yield for the grouped devices is not reached, highlighting that the potential for active control to affect energy yield may be more significant in grouped devices (when compared to large single units).

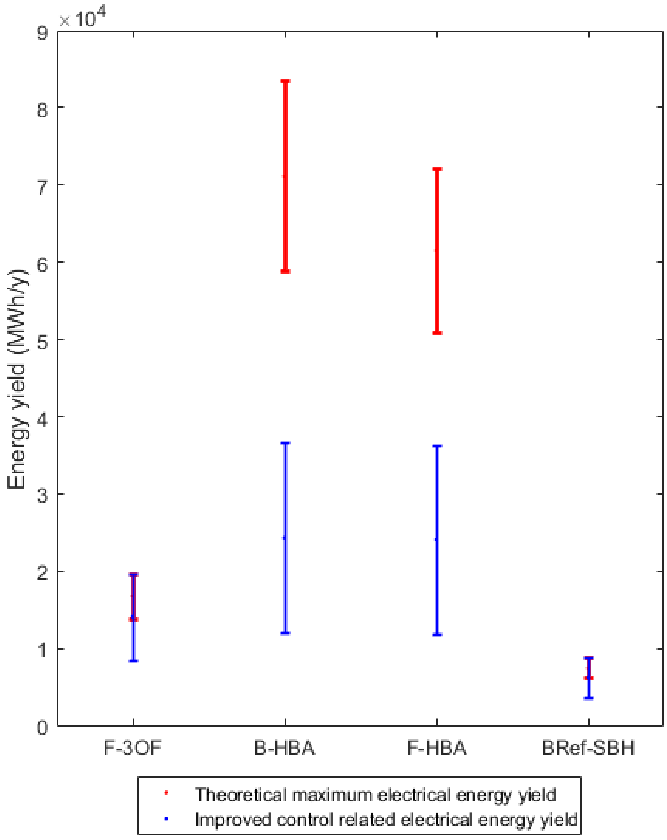


Figure 32. Impact of downstream elements of the PCC on performance: range (minimum and maximum) of theoretical maximum (in red) electrical energy yield and electrical energy yield related to an improved control strategy (in blue) – MWh/year

Scaling effect on theoretical limits

Table 27 summarises the ratio considered to capture the impact of scaling up on performance from a primary efficiency perspective. The theoretical maximum RCW aims to quantify the potential improvement in hydrodynamic efficiency when scaling up. An increase in RCW from the NumWEC original size to the 10MW rating (shown by a green upward arrow in Table 27) evidences an improvement in the WEC's primary efficiency, i.e. from wave to mechanical energy. Overall and at a high-level, it can be seen that scaling up has a positive effect for all the grouped devices, for the same level of idealised control. For the Bref-SHB (an individual device) the RCW decreases between the original and 10MW scale. Based on this, it can be assumed that the Bref-SHB becomes fundamentally detuned at 10MW scale because of its inherent characteristics.

Table 27. Scaling effect on energy yield: capture width ratio at original NumWEC size and at 10MW rating (*for BRef-SHB, a 1MW size was considered)

EMEC	**Capture width ratio (RCW)**		
Size	**NumWEC**	**10MW**	↑/↓
F-3OF	0.50	1.46	↑
B-HBA	1.24	2.83	↑
F-HBA	1.76	2.56	↑
Bref-SBH*	2.22	1.47	↓

Table 28 summarises the ratio considered to capture the impact of scaling up on performance from a control perspective. The ratio of energy yields aims to assess if scaling up can reduce the gap between the actual energy yield (with a basic passive control) and the theoretical maximum (involving idealised control). Essentially, the ratio quantifies the benefit (or penalty) of scaling up (with a baseline controller) relative to the theoretical maximum.

Table 28. Scaling effect on energy yield and theoretical limits: capture width ratio and ratio of energy yields at original NumWEC size and at 10MW rating (*for BRef-SHB, a 1MW size was considered)

EMEC	**Ratio of energy yields**		
Size	**NumWEC**	**10MW**	↑/↓
F-3OF	0.21	0.31	↑
B-HBA	0.13	0.10	↓
F-HBA	0.06	0.12	↑
Bref-SBH*	0.11	0.30	↑

Based on their characteristics, the B-HBA and F-HBA present very high theoretical maximum energy yields (see Table 9 to Table 12), leading to lower energy yield ratios than the other devices. However, in the case of the F-HBA a noticeable increase of the ratio can be observed when comparing the NumWEC and 10MW scales. The same trend applies to the F-3OF device. Such an increase in the ratio indicates better performance of the basic controller at larger scale, i.e. a better physical tuning of the machine even for a basic controller. A significant change in the control strategy is therefore unlikely to be required at a larger scale for these devices. For the B-HBA, there is a marginal decrease in the ratio. This suggests that the device is marginally more detuned at 10MW scale.

For the Bref-SBH, the ratio increases at 10MW scale. However, it can be assumed that the Bref-SHB becomes fundamentally detuned at 10MW scale as indicated by the significant decrease in hydrodynamic efficiency (Table 27). The low theoretical maximum at 10MW scale leads to the increase in ratio observed in Table 28.

6.3.3 Conclusions

Overall, the importance of control when attempting to bridge the gap between the baseline WEC performance and the maximum theoretical bounds is clear, with key literature quoting potential improvements in average absorbed power of about 100–330% from a baseline passive control strategy [37].

However, metrics such as maximum RCW and ratio of energy yield also highlight the benefits of scaling up to reduce the gap between actual energy yield and theoretical maximum, even with a baseline controller. In particular, in the F-HBA WEC case a significant increase in both ratios was found, translating into an improvement in hydrodynamic efficiency for the same level of idealised control and a better tuning of the machine even for a basic controller. A coupled approach of sizing and control therefore appears to be of merit, when considering 10MW scale designs, recognising the additional coupling of the wave-structure interaction characteristics.

The example in Appendix G indicates that a change in control strategy leads to variation of up to 8% in extreme excursion for the front floats in a grouped array. Although this is not a quantification of the WEC survivability, it does illustrate the potential impact of the control methodology for design in survival conditions, which must be considered during a WEC design process.

Finally, it should be noted that the theoretical results, while confirming the potential suitability of large scale grouped devices, also flagged the apparent difficulty of tuning large single isolated WECs (e.g. BRef-SBH). However, the investigations discussed in this section focus solely on benefits in terms of energy yield, and do not include cost assumptions, see subsequent sections for consideration of costs and conclusions.

6.4 Structural Feasibility and CAPEX Assessment

6.4.1 Methodology

A structural feasibility and CAPEX assessment has been carried out for each of the three WEC configurations described in Table 22. The baseline and large individual configurations have already been assessed as part of Stage II. This section describes the consideration of the structural feasibility and costs of the large grouped configuration as this requires an additional truss which must be sized and costed appropriately.

The following assumptions were considered to size the truss, based on typical fabrication characteristics for offshore jacket structures:

- The structure is made up of welded steel tubular sections.
- There are three devices per truss arranged in a straight line with a spacing of 1.5 times the diameter of the devices.
- The devices produce a characteristic tether force of 8MN (unfactored). This is based on the design tether load provided by a leading submerged pressure differential developer for a 1MW device.
- 30% contingency mass has been added to account for connections.

6.4.2 Results

The grouped truss structure is outlined in Figure 33 and a summary of masses used in the CAPEX assessment shown in Table 29.

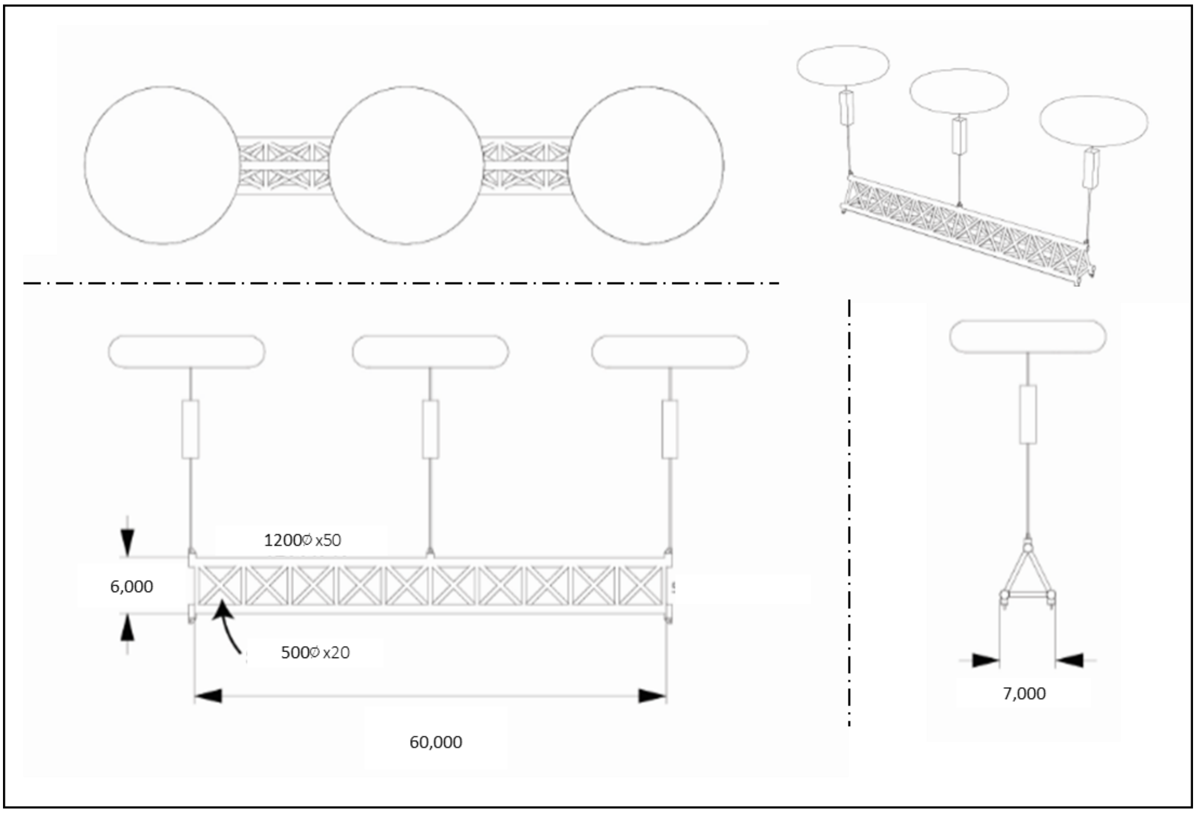


Figure 33. Grouped structure truss sizing (dimensions in mm)

Table 29. Grouped structure mass summary

Number of 1MW Devices	**3**	**4**	**5**
Truss length (m)	60	90	120
Truss steel mass (te)	400	720	1400
Truss mass/device (te)	130	180	280

6.5 Moorings Feasibility and CAPEX Assessment

6.5.1 Methodology

The following method was adopted to determine the feasibility of a chosen mooring arrangement along with a cost estimate:

1. Define a suitable mooring arrangement, using experience from oil & gas and naval industry experience.
2. Assess feasibility of chosen mooring arrangement and mooring type against extreme mooring forces.
3. Determine total length of mooring lines required.
4. Assess feasibility of concrete gravity substructures and determine weight of concrete required. If unfeasible, determine approximate weight of suction bucket foundations required based on a te/kN. This assessment is based on previous project experience.
5. Estimate total cost of moorings and foundations based on the quantities determined above.

Key assumptions:

- The extreme mooring force was taken as a typical value provided by a leading device developer, as described in Section 6.4.1.
- The distance between the device and foundation is determined for each defined mooring arrangement. This is then used to estimate the length required based on:
    - 1 x distance for taught moorings
    - 3 x distance for catenary moorings
- All arrangements adopt nylon moorings.
- The cost of the nylon moorings are an assumption based on previous projects and experience.
- The cost of a suction bucket is based on a weight per force (te/kN) in each bucket. This was estimated from previous projects.

6.5.2 Mooring Arrangements

6.5.2.1 Individual Devices

Two mooring arrangements are proposed for the individual device configurations, as illustrated in Figure 34.

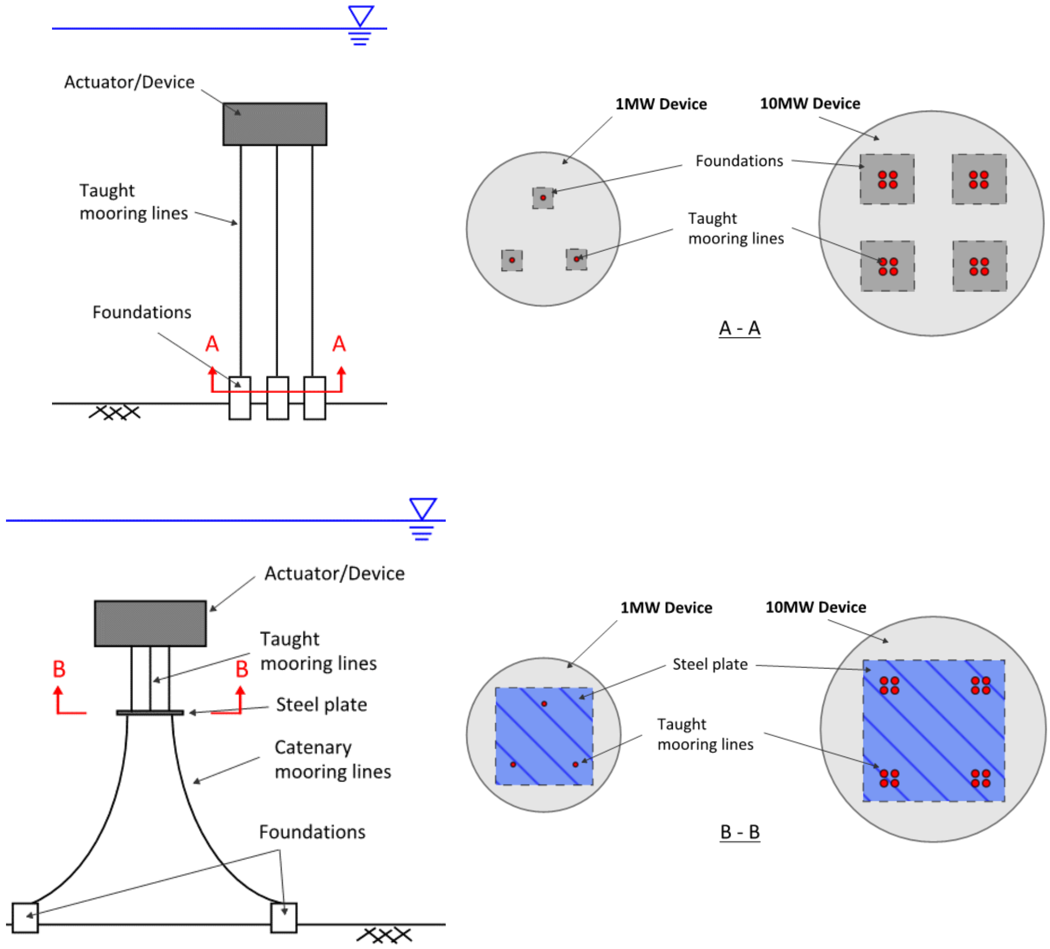


Figure 34. Mooring arrangement options for individual devices. 1MW ‘Tensioned’ arrangement (top) and 10MW ‘Catenary’ arrangement (bottom).

The ‘Tensioned arrangement’ resembles that of a typical tension-legged platform (TLP), which are widely used in the oil and gas industry.

The ‘Catenary arrangement’ is a variation of the TLP concept. The taught mooring lines are connected to a steel plate that is located at an elevation close to the device. The steel plate in turn is held down by catenary mooring lines. Catenary moorings are widely used in the naval and marine industry, and has recently been successfully implemented on the Hywind spar, the world’s first floating offshore wind farm.

Both arrangements are feasible for the 1MW and 10MW individual devices. The preferred concept was chosen based on the lowest overall mooring quantities required. A comparison of quantities is shown in Table 30 resulting in the following preferred concepts:

- Baseline 100 x 1MW – ‘Tensioned’ arrangement
- Individual 10 x 10MW – ‘Catenary’ arrangement

Table 30. Comparison of mooring lengths required for the two proposed arrangements

	'Tensioned' arrangement	**'Catenary' arrangement**
1 MW device	39000m *3 x taught mooring lines per device*	80700m *3 x taught mooring lines; 3 x catenary lines per device*
10MW device	18720m *16 x taught mooring lines per device*	10460m *16 x taught mooring lines; 3 x catenary lines per device*

It should be noted that the tensioned arrangement is associated with a number of technical risks, as summarised Table 31.

Table 31. Comparison between mooring arrangements for individual devices

	'Tensioned' arrangement		**'Catenary' arrangement**	
Array layout		Smaller spacing between devices possible.		Larger spacing between devices may be required due to slack of catenary moorings.
Foundations		Potential use of a single foundation, instead of one for each taught mooring line.		Individual foundations required for each catenary mooring line.
Installation		Potential for a quicker installation procedure as only one set of moorings need to be installed.		Additional installation steps required for installation of catenary moorings with steel plate.
Operation and maintenance campaign		Deep-water O&M campaign adopted requires more complex planning and procedures.		Stable surface at a higher elevation allows for a simpler shallow water O&M campaign to be adopted.
Risk of mooring failure		Higher risk as the taught mooring line will be very long, especially in deep waters.		Lower risk due to the shorter overall length of taught mooring lines, and the flexibility of catenary mooring lines.

6.5.2.2 Grouped Devices

Figure 35 summarises the foundation concept for the grouped device. A single group consists of the following elements:

- 3 x 60m single trusses;
- 3 x 1MW device per single truss;
- 4 x taught mooring lines per single truss;
- 1 x foundation per mooring line;
- 2 x horizontal mooring lines between trusses.

Grouped devices offer a CAPEX saving due to a reduced number of mooring lines per MW.

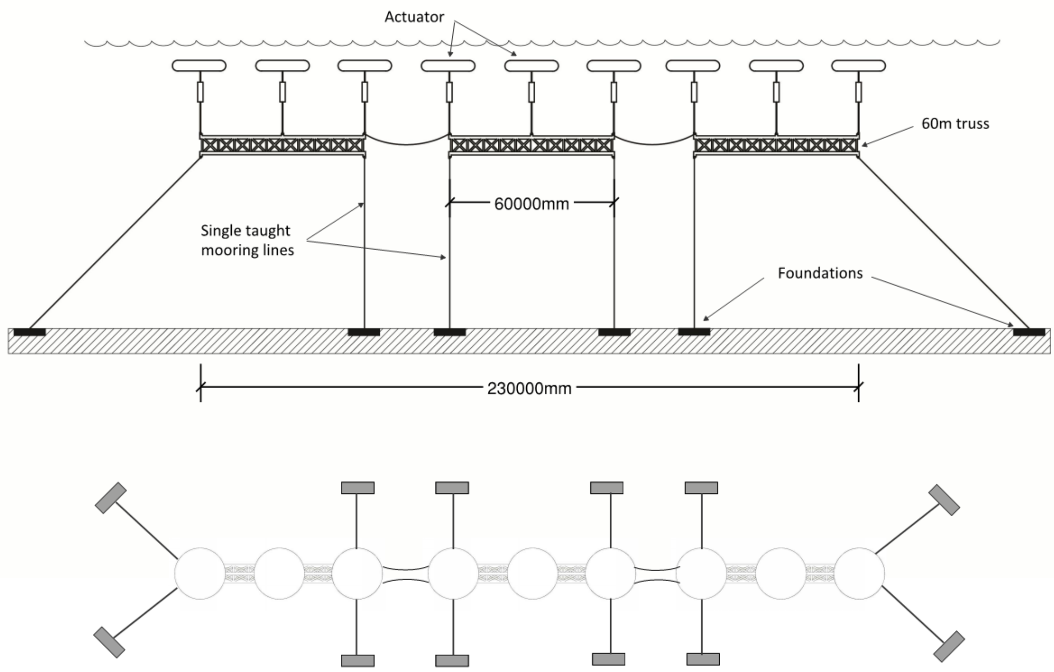


Figure 35. Mooring arrangement for grouped devices

6.5.3 Technical Risks

Technical risks associated with the three mooring concepts are summarised in Table 32.

Table 32. Mooring arrangement technical risks

Risk	Baseline 100 x 1MW	Grouped 100 x 1MW	Individual 10 x 10MW
Entanglement between mooring lines and cables	Medium	High	Medium
Manoeuvring between moorings during maintenance works	Low	High	Low
Nylon rope technology not established in the offshore renewables industry	Medium to High	Medium to High	Medium to High
Relative impact of single mooring line failure	Low *1MW impacted*	Medium *Potentially 3 x 1MW impacted*	High *10MW impacted*

6.5.4 CAPEX Assessment

The CAPEX inputs for the three mooring concepts is summarised in Table 33. Cost assumptions are listed in Table 34.

Table 33. Summary of mooring arrangement for each configuration

	Baseline 100 x 1MW	Grouped 100 x 1MW	Individual 10 x 10MW
Total steel mass (device)	120te	120te x 10	1000te
Total steel mass (truss)	-	1700te	-
Global dimensions (device)	ø20m x 4m	ø20m x 4m	ø40m x 10m
Global dimensions (truss)	-	Single: 60m x 6m Grouped: 3 single	-
Float depth below surface	5m	5m	10m
Mooring arrangement	"Tensioned" (Figure 34)	"Grouped" (Figure 35)	"Catenary" (Figure 34)
Mooring type	Nylon ropes	Nylon ropes	High strength nylon ropes
Total number of mooring lines	300 no.	231 no.	190 no.
Total length of mooring lines	39000m	28310m	10460m
Total extreme mooring force per line	7300kN		
Foundation type	Suction buckets		
Total number of foundation units	300 units	132 units	30 units

Table 34. Mooring cost assumptions.

	Cost	Unit
Nylon mooring ropes	£100	/m
High strength nylon mooring ropes	£200	/m
Foundations - suction buckets	£2600	/te
Catenary length	3.0 x depth	
Taught length	1.3 x depth	

The total foundation and moorings cost for each configuration is shown in the figures below.

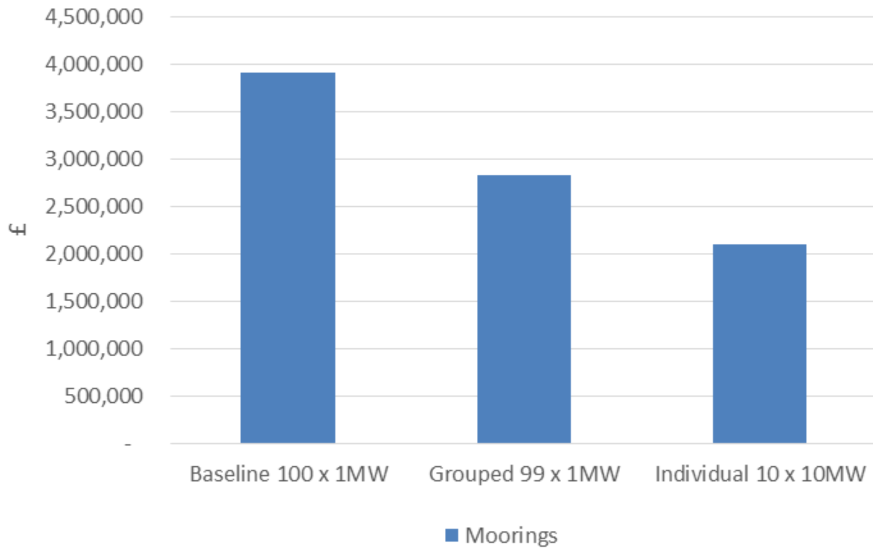


Figure 36. CAPEX estimations for moorings

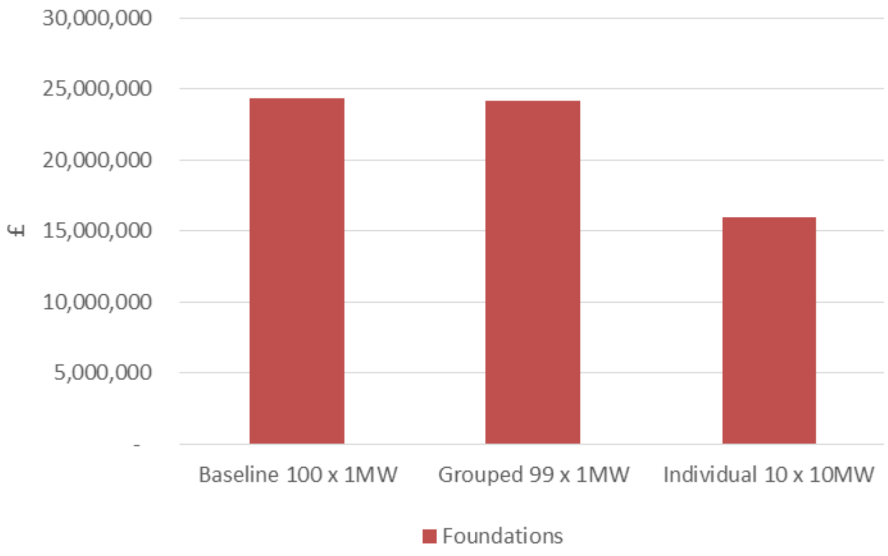


Figure 37. CAPEX estimations for foundations

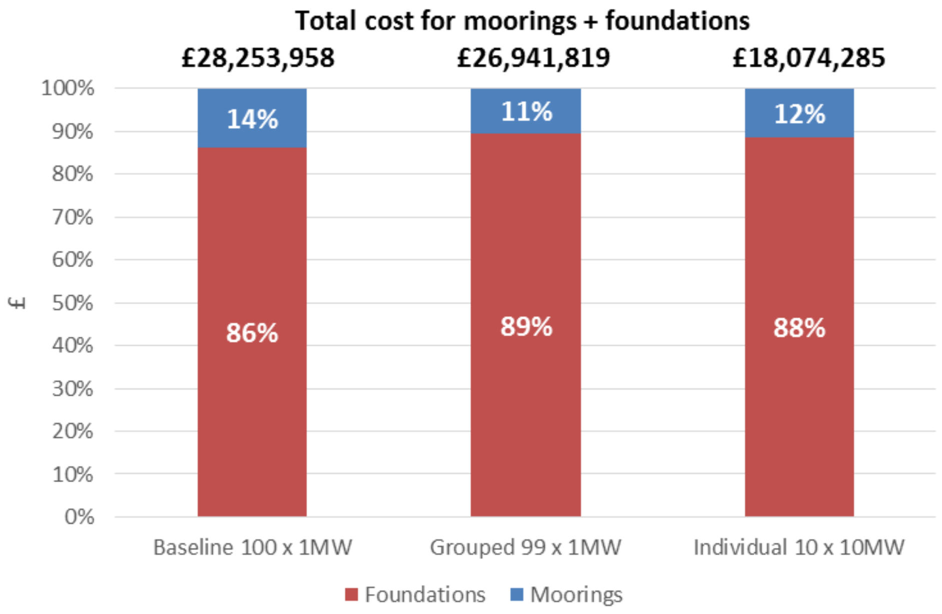


Figure 38. Comparison of cost of foundations and moorings

6.5.5 Conclusions

Key findings from this assessment include:

- The grouped configuration has approximately 5% less CAPEX compared to the baseline 100 x 1MW configuration. The grouped arrangement has less moorings per device relative to the baseline array.
- The 10MW arrangement has 36% less CAPEX compared to the baseline 100 x 1MW arrangement.

6.6 Offshore Campaign Feasibility and CAPEX Assessment

6.6.1 Offshore Campaign Description

The offshore campaign varies considerably between the grouped and individual large scale WEC configurations. A detailed description of the offshore campaign for each arrangement was developed alongside examples of existing large scale operations. These are summarised in Appendix E.

6.6.2 Technical Risks

Table Table 35 summarises the technical risks associated with the large scale WEC configurations.

Table 35. Offshore campaign technical risks

Risk	Baseline 100 x 1MW	Grouped 100 x 1MW	Individual 10 x 10MW
Lowering/ballasting trusses and connection to pre-installed moorings	N/A	Medium	N/A
Operation and maintenance	High *Deep water O&M campaign*	Medium *Deep water O&M campaign*	Low *Shallow water O&M campaign*

6.6.3 CAPEX Assessment

A high-level offshore campaign programme was developed for CAPEX assessments. The programme, along with assumed vessel rates based on past projects and experience involving comparable fleet of vessels (shown in Figure 39 and Table 36 respectively), provided the basis of cost estimates for each configuration. The following assumptions were made:

- 250km tow from nearest port;
- Tugs tow at 5 knots;
- Same tugs assumed for 1MW and 10MW tow, with an upper tow limit of 1500te (therefore 10 x 1MW devices and 1 x 10MW devices);
- All foundations are transported using the conventional barge and tug arrangement, then lifted into place with conventional offshore craneage;
- All trusses and devices are floated-out using tugs.

Table 36. Assumed vessel rates

	Cost	Unit
Tug 1	£20,000	/day
Tug 2	£8,000	/day
Anchor Handling Tug Supply (AHTS)	£35,000	/day
Barge	£20,000	/day
Mobilisation and demobilisation	6	days/vessel
Weather contingency	10	% of total cost

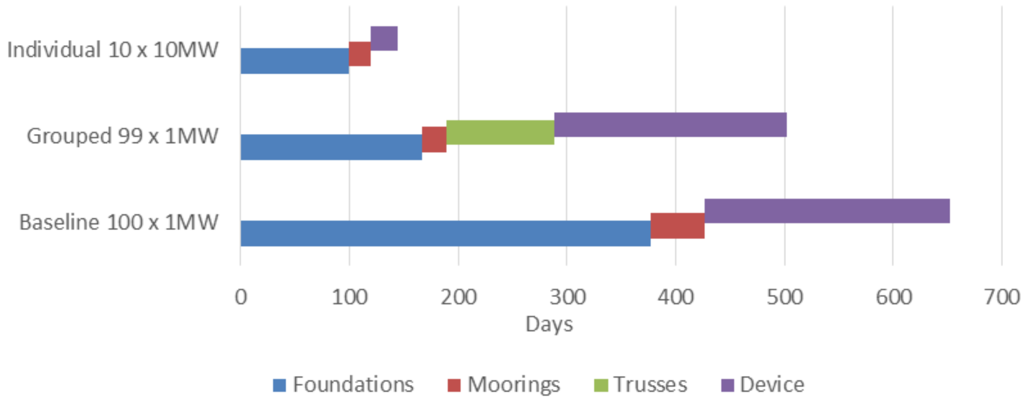


Figure 39. Assumed offshore campaign programme for CAPEX assessments

The total CAPEX for each configuration is shown in Figure 40, and a breakdown of cost concerning each element is shown in Figure 41.

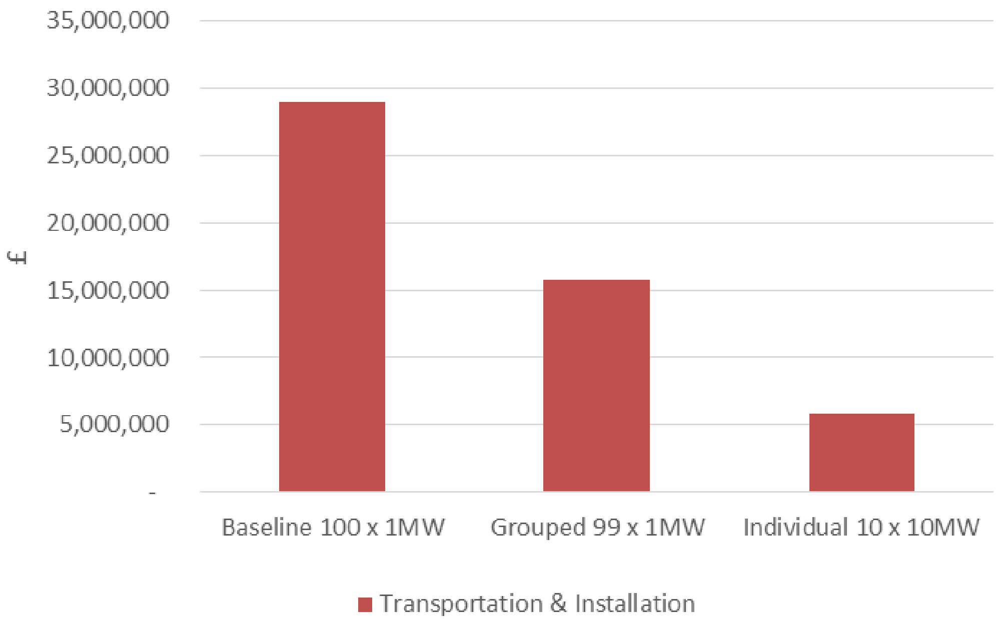


Figure 40. Offshore campaign CAPEX

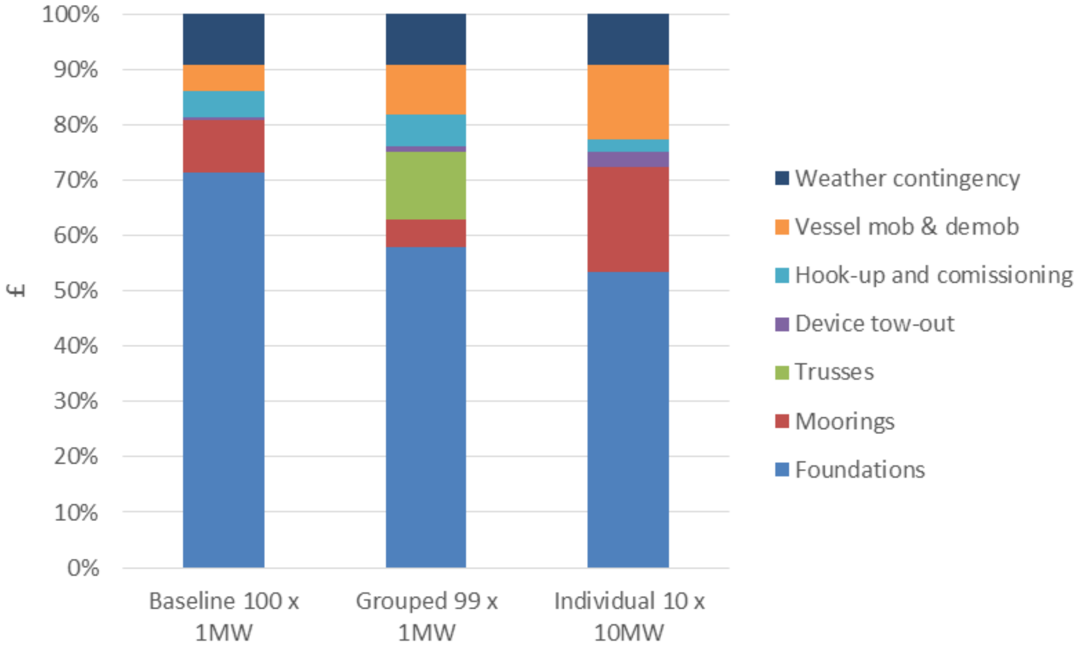


Figure 41. Offshore campaign cost breakdown

6.6.4 Conclusions

Key findings from this assessment include:

- The individual 10 x 10MW configuration has the lowest overall timescales and CAPEX. This is primarily due to significantly lower quantities of foundation units and devices that need to be transported and installed.
- A consequence of the shorter installation time would be to allow power export and project revenue to commence earlier.

- The grouped configuration shows a 45% cost saving when compared to the baseline arrangement. This is primarily due to the need for 50% more foundation units that need to be installed for the baseline array.

6.7 Electrical Infrastructure CAPEX Assessment

Any arrangement of WECs requires an electrical connection to shore, to allow export of power generated to the grid. Conceptually there are no barriers and a number of WEC demonstration projects have already demonstrated this functionality both with individual WECs and in small arrays [17]. However, for large arrays, it is generally recognised that approaches analogous to typical offshore wind arrangements would be attractive to optimise layouts and to manage the capital cost. Notably the use of:

- Appropriately rated array cabling connected to individual WECs;
- Hubs centrally located in the array to which the array cables connect either in;
- Optionally a transformer in the hubs to increase the voltage for export; and,
- Appropriately rated export cable to connect the hub to a grid connection point onshore.

All of these features have been considered to derive electrical arrangements and cost assessments for the three scenarios.

6.7.1 Methodology

The following assumptions were made in preparing electrical arrangements:

- Arrays were sub-divided into groups of ten WECs (nine in the case of the grouped arrangement).
- The water depth, distance to shore and spacing between devices is as per the descriptions in 6.5.
- A single array cable connects each WEC to a central hub (which may itself be subsea or floating) forming a radial arrangement.
- Each hub has a single export cable to shore.
- "Daisy-chaining" array cables between WECs is feasible [17] and analogous with string configurations seen in offshore wind farms, but has not been considered.
- Onshore components (cable from landfall, any onshore substation, grid connections) have not been considered as these would likely be the same for each scenario.

The figure below illustrates this architecture.

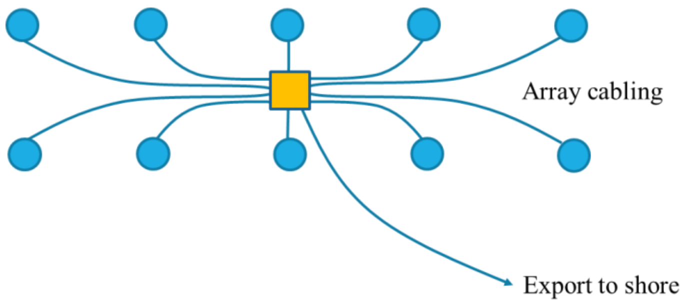


Figure 42. Array electrical arrangement

The assumed costs of individual offshore components are detailed below.

Table 37. Component costs for electrical arrangements (all courtesy [18])

Item	**Cost**
Dynamic array cable (1MW capacity)	£126/m
Dynamic array cable (10MW capacity)	£137/m
Static cable (10MW capacity)	£100/m
Static export cable (50MW capacity)	£262/m
Cable installation cost	£150/m
Hub cost	£10m each

In developing total electrical CAPEX, it was found that costs could be reduced by introducing additional hubs to collect output from five of the central hubs each. This arrangement is illustrated in the figure below. This reduces the length of export cable required while still offering a suitable level of redundancy for the array overall (two 50MW export cables to shore).

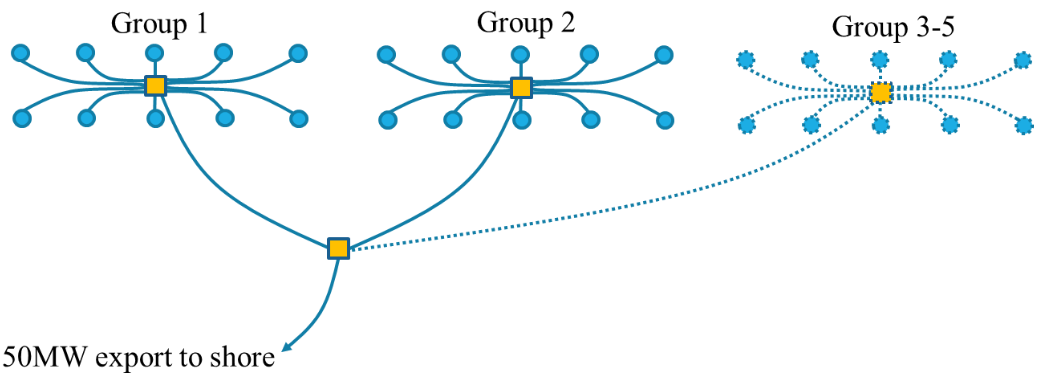


Figure 43. Introduction of additional hubs

It is reasonable to assume that there are other options to optimise the arrangement for further cost reduction but such steps are likely to be more project- or site-specific. For example, daisy-chaining between WECs is likely to be a strong contender to reduce total array cable lengths but this configuration may not be suitable for all WEC concepts. Additionally, water depth, distance shore, export voltages and the required properties of dynamic cables will all have a direct impact on cost. Report [19] provides a broad overview of arrangement options.

6.7.2 Results

The relative total costs of the electrical arrangements are illustrated below.

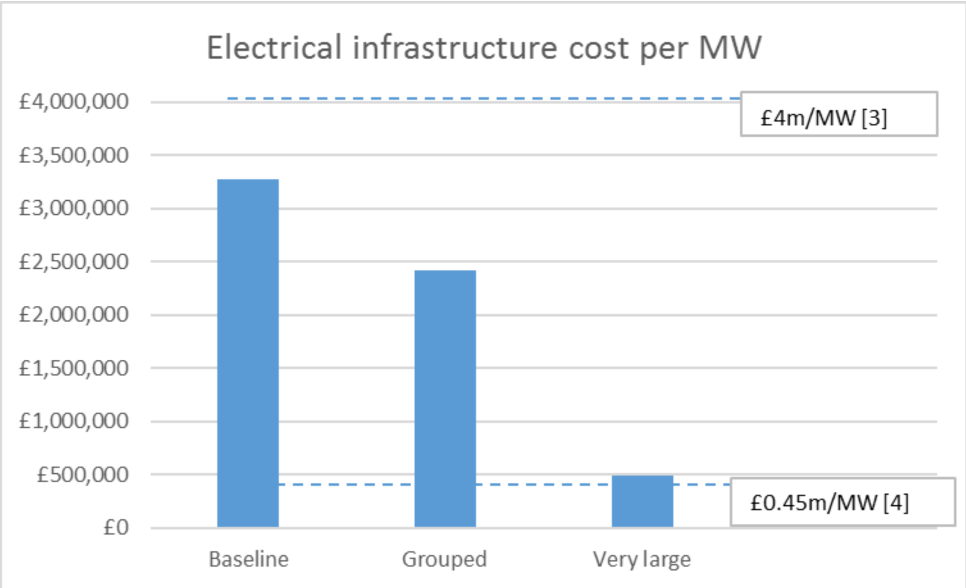


Figure 44. Electrical infrastructure cost per MW

It is clear from the results that the baseline array of 1MW WECs, with the assumed variables described in this report, incurs a high cost. The total of £3.4mMW is on a par with the £4m/MW assumed by [19] for marine energy arrays.

The tighter packing of WECs (as evidenced by the grouped scenario) has a direct impact on cost, indicating a 25% reduction. The array of individual large WECs shows an even more powerful cost reduction driven simply by the reduced number of cable lengths and hubs required. The cost per MW for this scenario is on a par with typical costs per MW of offshore electrical infrastructure observed in offshore wind [20].

The overall spread in cost across the scenarios indicates how sensitive the electrical CAPEX is to project specifics, and that relying on high-level cost/MW metrics may not always be robust.

It should be noted that although assuming the use of hubs/transformers is conceptually similar to offshore wind, and has been a long-standing topic of discussion and intermittent development in the marine energy industry [17][19] , there is a risk associated. Namely these hubs/transformers have not been demonstrated at scale in the wave industry and it is likely that a substantial R&D programme would be required to develop these prior to volume deployment.

6.8 OPEX Assessment

The cost of Operations and Maintenance of an array will depend on the O&M strategy adopted which in turn will be in influenced by the array specific. The scenarios considered in this study vary in WEC numbers, scale and offshore arrangement and it is likely that the cost of O&M will vary between scenarios. The objective of this assessment is to highlight any sensitivities which should be assessed when considering an array of grouped or large individual WECs.

The cost of O&M for offshore renewables is typically presented as a cost per MW installed or percentage of total CAPEX. It is useful to consider assumptions which have been presented elsewhere the wave industry to provide context. It is also useful to consider data from offshore wind, an industry which makes use of several classes of vessel to manage costs. These figures are presented in Table 38.

Table 38. Sample OPEX benchmarks and forecasts

	Cost/MW	**% of CAPEX**
Offshore wind high [21]	£70,000-£90,000	4%-5%
Offshore wind low [21]	£30,000-£50,000	2%-3%
WES LCoE Calculator [11]		4%
100MW wave farm [22]	£50,000	
Commercial-scale wave farm [25]	£60,000-£290,000	

6.8.1 Methodology

The WES O&M Simulation Tool [23] has been used to carry out a sensitivity study. In order to assess the scenarios on a common basis a number of assumptions have been made, leaving some common inputs constant across all scenarios. Detailed inputs are described in Appendix F. The study is generic in nature, but efforts have been made to assume a number of example project and site specifics to validate the assumptions.

The site selected for this study is off the west coast of Uist, illustrated in Figure 45. This has been selected to offer a suitable compromise of proximity to the Isle of Lewis, good levels of incident power and water depths appropriate for very large devices. The distance to site is assumed to be 230km, assuming the O&M base is located in Stornoway. Although this is reasonably long distance for O&M operations, there are currently no suitable sites on the west coast of the Western Isles. The cost of establishing a new base and the required infrastructure would need to be weighed against the cost of operating out of Stornoway.

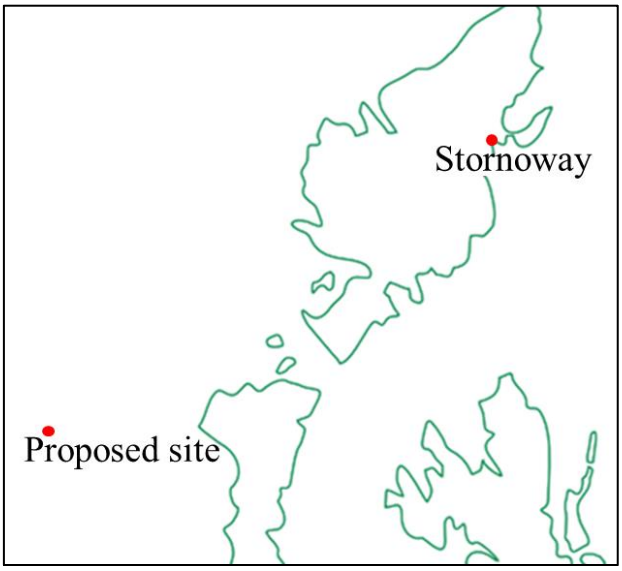


Figure 45. Proposed site and assumed O&M base location

6.8.2 Results

OPEX

The O&M simulation tool has been run with the inputs outlined above. 50 runs of each 20-year period were carried out to gain maximum, minimum and mean values.

Table 39. Costs of vessel hire and labour for all scenarios

	Mean O&M cost per annum per MW	Min O&M cost per annum per MW	Max O&M cost per annum per MW
1MW point absorber	£16.7k	£16.2k	£17.2k
10MW point absorber	£15.5k	£13.7k	£17.2k
10MW grouped device	£16.4k	£15.9k	£16.9k

As noted earlier, these costs do not include parts cost as the exact nature of the devices is unknown and challenging to meaningfully price up replacement part costs. However from analysis of offshore wind O&M costs we note that labour and vessel costs may be around 50% to 60% of the total O&M costs.

When allowing for parts, the total OPEX for these scenarios would be ~£35,000/MW which is consistent with the lower end of offshore wind.

The average annual O&M costs, split into vessel costs (hire costs and fuel) and labour costs (O&M base labour plus additional contract labour) is displayed in Figure 46.

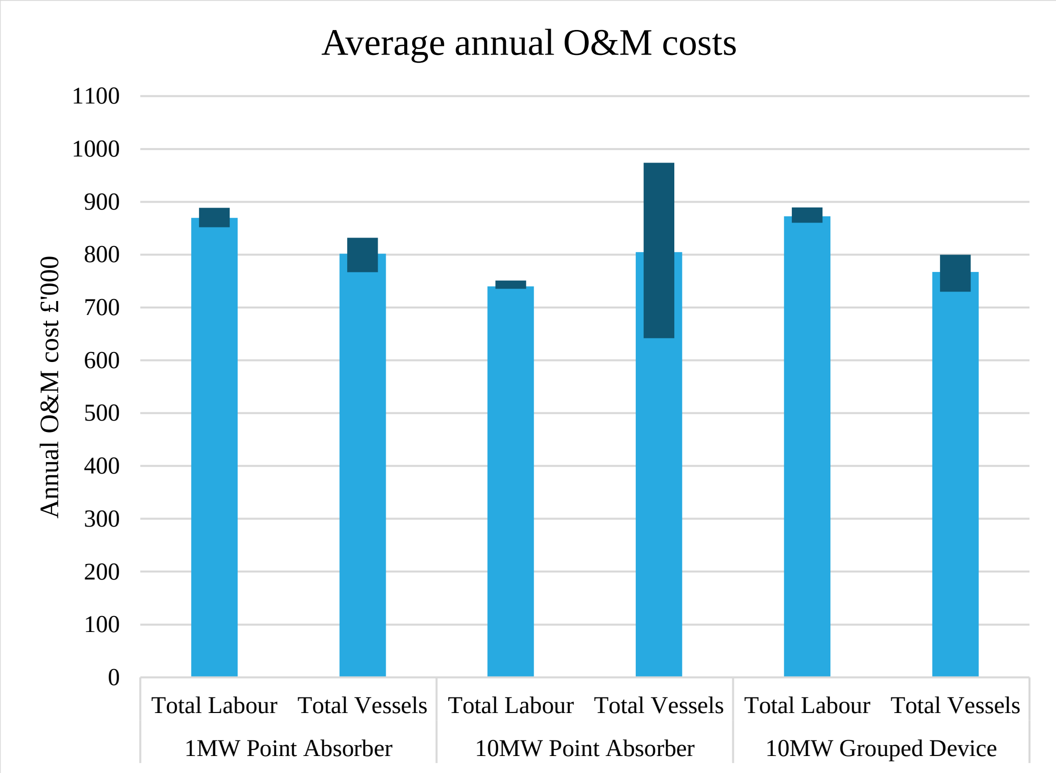


Figure 46. Average annual O&M costs broken down by labour and vessel costs

The error bars illustrate the maximum and minimum costs generated over the 50 runs of the simulation tool. The variation in vessel cost is driven by the number of failures experienced by the WEC array and shows more variability than the labour cost as the base labour is able to deal with the failures in most cases.

The 10MW large individual device requires a more expensive AHTS to deal with major failures, which accounts for the larger variation in the vessel cost for this array. If the cost of the vessel required to tow the 10MW could be reduced this would have a positive impact on cost.

Availability

The tool can also estimate the availability of the WEC array. Mean availability from 50 simulation runs over the 20 year lifetime of each WEC array is shown in Figure 47.

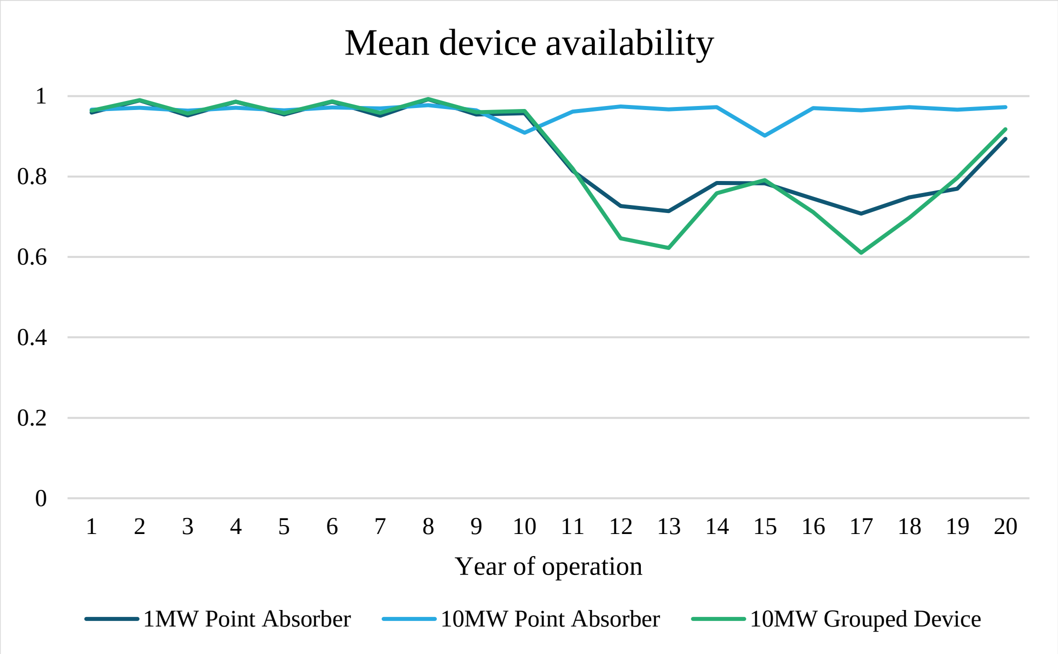


Figure 47. Mean device availability from 50 simulation runs

Figure 47 shows that, for the projects as modelled, the availability for the array of 10MW devices is better than that of the 1MW and grouped devices. The availability of these suffer in the later years of operation due to major overhauls taking a long time to complete. As described in Appendix F the major overhauls have been set at year 10 and year 15 in the simulation tool.

The simulation indicates that the major overhauls for the 1MW and grouped devices take several years to complete, having a detrimental impact on the overall availability of the array. In contrast the 10MW device shows a slight decrease in availability during years 10 and 15 when the major overhaul takes place but otherwise has a high availability.

This decrease in availability may be mitigated by employing several vessels to complete the major overhauls, however it is not possible to include these additional vessels in the current version of the simulation tool.

6.8.3 Conclusions

- The use of contemporary Service Operations Vessels has a direct beneficial impact on OPEX, enabling much better use of vessel time particularly for annual WEC inspection or for executing minor repairs offshore.
- For an absolute OPEX to be calculated for any array, in-depth knowledge of the WEC parts and their specific failure modes is required. The location of a suitable O&M base is also critical, notably its capacity to accommodate large numbers of devices, or large scaled devices. In the absence of this detail, typical industry assumptions are reasonable to accept.
- It is reasonable to assume that to maintain high WEC availability in the baseline or grouped device array, OPEX will be higher than for the large individual devices.

- Consequently, it is reasonable to assume that the default OPEX assumption of 4% [11] is reasonable for the baseline and grouped arrays, and 3% is reasonable for arrays of large individual devices.

6.9 LCoE Assessment

The objective of this assessment is to derive indicative LCoE figures for the three scenarios considered. The LCoE was also calculated for a range of incident wave powers, to observe the impact this has on the relative performance of the scenarios.

6.9.1 Methodology

The WES LCoE calculator [11] was used, with the CAPEX and OPEX inputs described in the preceding sections. It is noted that in the absence of specific device design data, many of these inputs have been derived at a high level, but care has been taken to ensure all costs have been built up on a common basis so that the scenarios can be compared relative to one another.

Performance data was described 6.3.1. A grouped arrangement may differ in energy performance due to constructive/destructive interference (refer to Appendix G). As this effect has not been quantified, the LCoE assessment assumes the same annual energy production for both the baseline and grouped arrangements.

The moorings CAPEX, electrical infrastructure CAPEX and OPEX assessment assumed a west coast of Scotland site, described in Section 6.2.3. The energy performance was calculated for three locations described in Section 5.2.3 to assess the influence of wave resource on large scale WEC yield. The LCoE and other metrics are presented as a range, depending on the available site resource. It should be noted that the CAPEX and OPEX estimates are not applicable to the World+ site.

Table 40. LCoE Calculator Inputs

	Baseline	Grouped scenario	Individual Large
CAPEX category (£k/MW)			
Structure & Prime Mover	£411	£411	£369
Power Take-Off	£640	£640	£759
Moorings, foundations and installation[3]	£572	£427	£239
Electrical connection	£3,268	£2,387	£494
Total CAPEX	£4,892	£3,865	£1,861
OPEX			
Annual O&M costs	4% of CAPEX	4% of CAPEX	3% of CAPEX
Yield (MWh/yr)			
Annual Energy Production (EMEC)	214,000	214,000	63,000
Annual Energy Production (Scotland+)	470,000	470,000	119,000
Annual Energy Production (World+)	677,000	677,000	244,000
Availability	95%	95%	95%

All other inputs to the model are maintained at their default model values. These are detailed in Table 41.

[3] This category includes the cost of the subsea truss for the grouped arrangement.

Table 41. Default LCoE Calculator inputs

LCoE Calculator input	Value
Decommissioning	10% of total CAPEX
Refurbishment CAPEX costs (year 7)	10% of total CAPEX
Refurbishment CAPEX costs (year 14)	10% of total CAPEX
Discount rate	10%

6.9.2 Results

Model output is presented in Figure 48. As described earlier, the scenario of individual 10MW WECs offers the potential for significantly lower CAPEX per MW installed than the baseline or grouped arrays. However, the lower energy yield offsets this benefit. This difference is particularly evident at the site of lower incident wave power. This highlights two key points:

- When considering a large scale WEC, the concept choice is fundamental to its performance at scale.
- When considering a large scale WEC, the device scale is very sensitive to the site conditions.

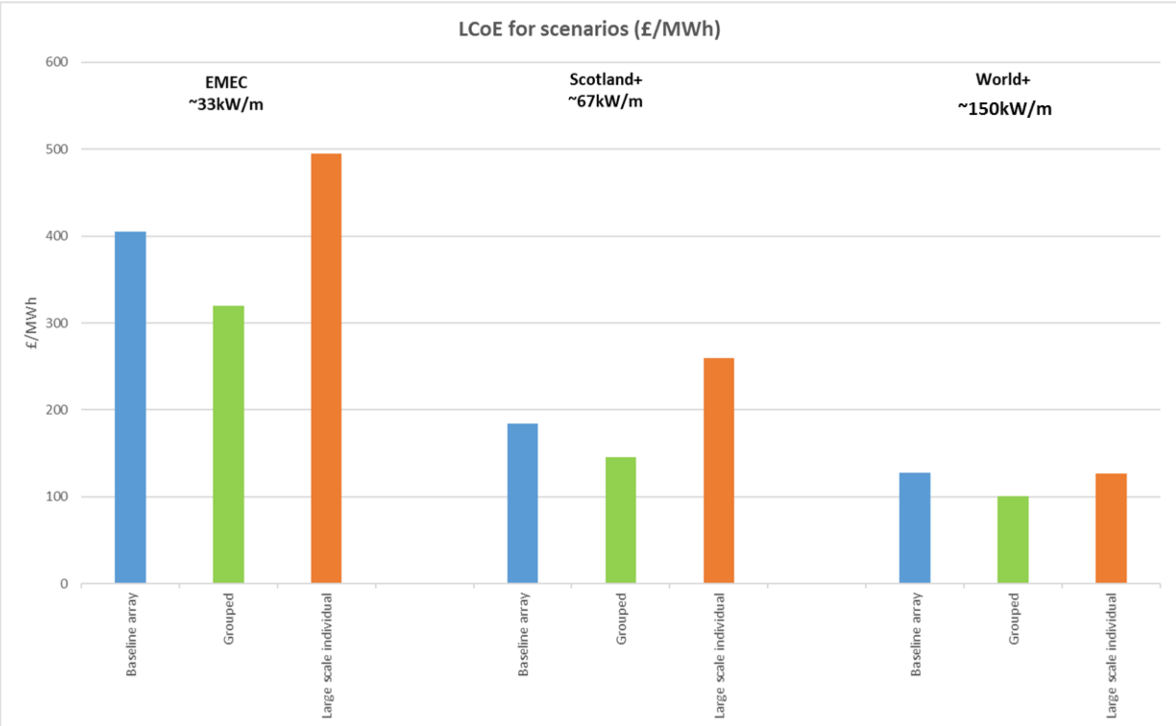


Figure 48. Relative assessment of scenario LCoE

6.10 Stage III Conclusions

Table 42 summarises the Stage III outputs. Similar cost reduction drivers to those demonstrated by large scale offshore wind are predicted for both large grouped and individual WEC devices. These include shared electrical infrastructure and reduced fixed installation costs. A further advantage of reduced OPEX/MW is predicted for large scale individual devices.

The energy yield per MW diminishes significantly at a 10MW scale for the individual large scale WEC investigated, resulting in poor LCoE performance. If an individual WEC concept that maintains power performance at a large scale could be developed, significant cost reduction could be realised.

Smaller devices grouped on a shared structure realise fixed cost reductions whilst maintaining similar energy performance. If the technical risks associated with this configuration could be overcome, it may represent a promising option.

Table 42. Stage III Output Summary

Metric	**Baseline Array (100 x 1MW)**	**Large Grouped Device (100 x 1MW on a shared structure)**	**Large Individual Device (10 x 10MW)**
Energy yield (MWh/yr)	214000 - 677000	214000 - 677000	63000 - 244000
CAPEX (£k/MW)	£4,892	£3,865	£1,861
OPEX	4% of CAPEX	4% of CAPEX	3% of CAPEX
LCoE (£/MWh)	410 - 130	320 - 100	500 - 130
Structural feasibility	No barriers to manufacture, although large-area dry dock/slipway required.	No barriers to manufacture, although large-area dry dock/slipway required. Truss represents a critical failure risk as supporting a number of devices.	No barriers to manufacture, although large-area dry dock/slipway required.
Moorings feasibility		Manoeuvring risk during O&M due to close device spacing. Mooring entanglement.	Large scale anchors required.
Installation and offshore campaign		Deep-water installation campaign required to connect devices to truss.	

Metric	Baseline Array (100 x 1MW)	Large Grouped Device (100 x 1MW on a shared structure)	Large Individual Device (10 x 10MW)
		Device O&M risk due to close spacing.	
Electrical infrastructure	Extensive array cabling required. Hubs required.	Extensive array of dynamic cabling required in close proximity to moorings components. Hubs required.	Less extensive electrical arrangement

7 Conclusions

This study aimed to quantify the opportunity associated with very large scale wave energy generation and provide recommendations for the future approach to its realisation.

For the purposes of the study, large scale wave energy generation was defined as an energy rating of 10MW in line with established offshore wind capacity. Three possible large scale WEC configurations were considered:

1. Scaling existing individual WEC types;
2. Grouping devices on a shared structure; and,
3. Development of a novel large scale WEC.

Throughout the study, these configurations were compared to a baseline array of 1MW devices representing current WEC technology. A three-stage tiered approach was undertaken:

- Stage I comprised a sector wide literature review and developer survey to identify large scale WEC opportunities considering the entire WEC landscape.
- Stage II comprised a CAPEX/MW comparison between 1, 5 and 10MW devices scaled from those presented in the NumWEC study [2]. The construction and installation feasibility of the scaled devices was also investigated.
- Stage III comprised an LCoE comparison between a baseline array of 100 x 1MW individual devices, an array of 10 x 10MW individual devices and an array of 100 x 1MW devices on a shared structure. Three sites were considered to assess the influence of wave resource on large scale WEC yield.

Conclusions associated with the individual stages are summarised in the relevant section of this report. Overall conclusions into the potential of large scale wave energy generation are summarised below.

7.1 Summary of Opportunities and Limitations

The study identified the following key opportunities and limitations associated with large scale WECs:

- The main cost reductions enabled by large scale WECs include installation costs of moorings, foundations and electrical infrastructure. These fixed costs represent a high proportion of the CAPEX. Large scale WECs and those on a shared structure require fewer moorings and less infrastructure than an array of 1MW devices. A significant cost reduction associated with these fixed costs is also seen in large scale offshore wind.
- OPEX is reduced for large scale individual devices compared to an array of small devices or those attached to a shared structure. This pattern is seen in

offshore wind, enabled by maintaining the reliability of critical components for large scale WTGs.

- The majority of the large scale WEC configurations could feasibly be constructed in a number of existing facilities in Scotland. The dry dock draft limit, of around 10m, may limit the towing feasibility for some large scale floating components.
- An optimum size in terms of CAPEX/MW was identified to be within the range 1 - 5MW for the large scale WEC devices investigated in this study.
- The energy yield per MW diminishes significantly at a 10MW scale for the individual large scale WECs investigated in this study.
- Shared structures form a significant portion of total device cost for grouped devices and an optimised arrangement is required to make this configuration cost effective. The configuration considered in this study has the additional structural risk that failure of the shared structure would lead to the loss of a large number of actuators. It also requires a feasible but complex marine campaign during installation and decommissioning. The close spacing of devices relative to the individual arrangements may also pose challenges for O&M, increase the risk of moorings entanglement and affect the power production due to destructive interference.
- LCoE results for the large scale configurations relative to a baseline array of 1MW devices are summarised in Figure 49. The difficulty in ensuring the power performance of large scale individual arrangements is reflected in the high LCoE. This difference is reduced for more energetic sites. The most energetic site considered is located in the Southern Ocean. Although this site is useful from a theoretical perspective, it seems unlikely that 10MW+ individual devices could be tuned for sites suitable for actual installation. Grouped devices show potential LCoE reduction relative to a baseline array at all sites.

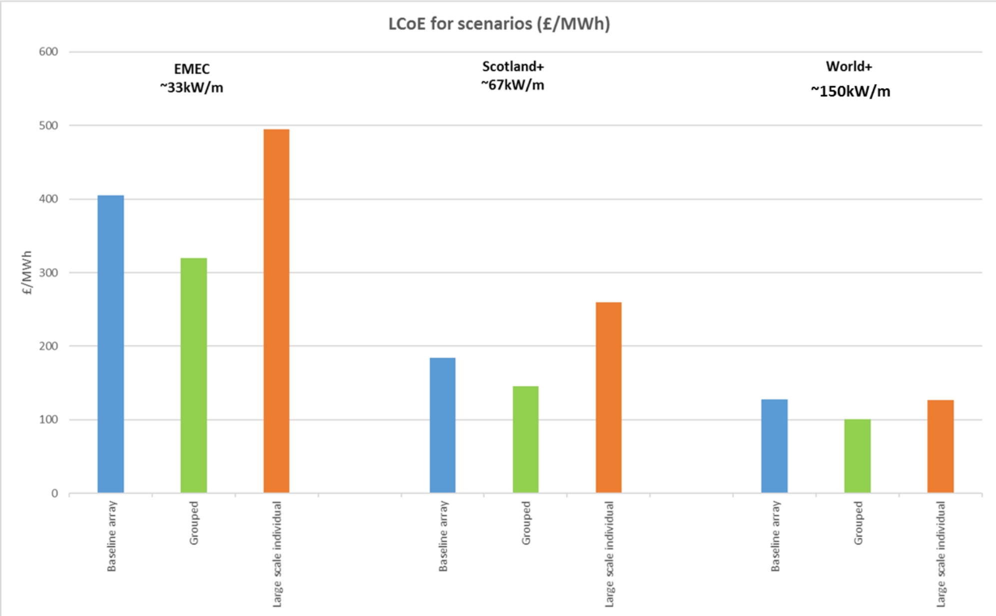


Figure 49. LCoE for large scale WEC scenarios investigated

This study considered 10MW WECs, in line with the established scale of offshore wind. Similar cost reduction drivers to those demonstrated by large scale offshore wind were observed, for example a reduction in fixed costs associated with mooring and infrastructure installation. However, energy yield/MW was found to diminish at 10MW for the large scale WECs investigated. The study suggests an optimum size exists below a 10MW capacity, but greater than 1MW for the devices considered. If an individual WEC concept could be developed that maintains power performance at a large scale, significant cost reduction could be realised.

Smaller devices grouped on a shared structure were found to realise fixed cost reductions whilst maintaining similar energy performance. If the technical risks associated with this configuration could be overcome, it may represent a promising option.

7.2 Generic Criteria and Recommended Future Research

The quantitative Stage II and Stage III assessments focused on scaling existing individual WEC geometries or grouping existing smaller devices on a shared structure. The feasibility of *novel* individual large scale WEC configurations was investigated through the Stage I literature review and survey, however few examples of novel devices were found.

In light of this, generic criteria for an idealised large scale WEC have been developed based on the findings of the study. These criteria aim to detail the limitations and areas of most opportunity for large scale WECs to provide guidance for future development of novel devices. The criteria are listed in Table 43, including recommendations for further research to enable future development of large scale WECs.

Table 43. Generic criteria and recommendations for future research for the development of large scale WECs

Metric	Large Scale WEC Criteria	Additional Information	Potential Further Research	Potential Researcher
Power Performance	Selection of an optimum device rating for an individual device. This is likely to be less than 10MW.	The gains in energy yield diminish with device size for large scale WECs and an optimum exists. This varies depending on device type and deployment location. For the devices investigated in this study, an optimum rated capacity between 1 and 5MW was identified (Section 5.3).	It is recommended that the energy performance and CAPEX for a given novel device is estimated at a range of scales to identify an optimum size. This is likely to be greater than 1MW.	Developers, Wave Energy Scotland, Academia
Power Performance	Selection of a suitable, high energy, site.	Large scale WECs become more cost effective relative to a baseline of 1MW devices at higher energy sites (Section 6.9). Individual large scale devices investigated in this study were found to have a higher LCoE than a baseline array of 1MW devices for sites suitable for device installation.	It is recommended that high-energy deployment sites suitable for large scale WEC installation are identified.	Developers, Wave Energy Scotland
Power Performance	Individual large scale WECs: maintained energy yield potential at a large scale.	Large scale WECs have the potential to offer lower per MW installed costs. This must be balanced against energy yield to ensure an attractive LCoE. The study considered three sites covering a range of wave resource levels. The energy	Research and development into individual devices with more energy potential at large scale. More power could be exploited at a large scale if other absorption modes (e.g. rotation, surge) are exploited, though this also applies to	Developers, Academia

Metric	Large Scale WEC Criteria	Additional Information	Potential Further Research	Potential Researcher
		yield per MW diminishes significantly at a 10MW scale for the individual large scale WECs investigated in this study. This is because these individual devices become detuned to the dominant resource even for the most energetic sites. Novel devices would therefore be required to maintain energy performance at 10MW and demonstrate a reduced LCoE relative to a baseline array of 1MW devices. Scaling limits relevant to specific existing device types were identified during the study. These can provide guidance for device scaling. For example, OWSC capture efficiency increases up to the point at which the width between flaps is similar to wavelength and then decreases as terminator effects and wave phase variations begin to dominate.	devices at current (~1MW) scale. Optimisation of geometry and sub-system, per WEC type and scale would also improve energy performance predictions.	
Power Performance	Grouped large scale WECs: optimum scaling and arrangement for grouped WEC devices.	Grouped devices have the potential to offer lower per MW installed costs, similar energy performance and a reduced LCoE relative to an array of 1MW devices. The study considered a fixed number of devices when scaling grouped devices. The energy performance and overall CAPEX are sensitive	Optimisation exercise into the arrangement and spacing for energy extraction for grouped devices. This should include consideration of control strategies to minimise destructive interference between closely spaced grouped devices.	Developers, Academia

Metric	Large Scale WEC Criteria	Additional Information	Potential Further Research	Potential Researcher
		to device spacing and further LCoE reduction may be possible through optimisation of large scale grouped devices.		
Power Performance	Pursue improved control strategies.	The energy performance of large scale devices could be improved through optimisation of the control strategy. Grouped devices may be more readily controllable and tuneable to the wave climate because the effective volume is distributed across the units compared to large individual units.	Investigation into additional control strategies to assess the benefit for large scale WECs (see e.g. [42]). This may in turn impact the design of the prime mover itself and / or the key supporting structures. For grouped devices, this should include consideration of control strategies to minimise destructive interference between closely spaced actuators. Investigation into the implications of control on PTO force and stroke length for large scale individual devices to confirm the suitability of existing PTO technologies.	Developers, Academia
Survivability	Pursue improved control strategies.	Optimising control for power performance may lead to increased device excursions, which may have survivability consequences. This was demonstrated for grouped devices in this study (Section 6.3). Larger individual units may become more easily detuned than grouped large scale WECs, which could be exploited during survivability conditions.	Control optimisation considering the implications of performance improvement on survivability and minimising loading during survivability conditions.	Developers

Metric	Large Scale WEC Criteria	Additional Information	Potential Further Research	Potential Researcher
Survivability	Use of minimal/optimised shared structure for grouped structures.	Shared structures form a significant portion of total device cost and an optimised arrangement is required to make this configuration cost effective. Shared structures below the waterline (i.e. governed by wave forces) were found to scale better than shared structures above the waterline (i.e. governed by self-weight).	Development of load relief strategies considering grouped, floating large scale devices. Development of an optimised truss for grouped structures. Where feasible, a floating shared structure below the waterline is likely to represent the most cost effective configuration. Development of suitable mooring configurations for floating grouped structures.	Developers, Moorings supply chain
Affordability	Developed commercial and logistical strategy for demonstrator stages of a large scale WEC.	There is evidence of large scale devices being commercially unfeasible at demonstrator stage due to high costs associated with early deployment.	Roadmap for funding, commercial and logistical deployment of large scale WECs at demonstrator stage.	Wave Energy Scotland, other Government Stakeholders
Affordability - Structure	Optimised structural and moorings system to reduce CAPEX.	Large scale manufacturing presents a high CAPEX element. There may be scope to reduce structural CAPEX by optimising for large scale rather than scaling up existing concepts. Conservative structural scaling rules were considered in this study (Section 5.4).	Design of optimised large scale WEC structures.	Wave Energy Scotland, Developers

Metric	Large Scale WEC Criteria	Additional Information	Potential Further Research	Potential Researcher
Affordability – Material Choice	Suitable material choice to reduce structural CAPEX and proof of supply chain capacity.	Structural mass requirements were found to typically scale at a lower rate than the mass required to maintain energy performance. The use of heavier structural materials with a lower unit cost in place of additional ballast may be cost effective for large scale WECs.	Investigation into alternative material choices for large scale WECs.	Wave Energy Scotland, Developers
Affordability – PTO	Selection of an appropriate large scale PTO. Usage of multiple PTOs connected in parallel, where possible.	No fundamental limitations were found for individual hydraulic and direct drive PTOs at a 10MW scale. There are potentially issues with scaling up individual self-rectifying air turbines. These PTOs are required for Oscillating Water Column (OWC) concepts and multiple PTO systems in parallel would be required. In both cases the literature review suggested an ability to modularise such systems, with scaling up being achievable through adding additional components in parallel. PTOs, especially hydraulic systems, suffer from reduced conversion efficiency when operating below peak load. Having a modular system consisting of a number of smaller components in parallel offers an immediate control	Research into modular PTO solutions for large-scale WEC devices.	Wave Energy Scotland, Developers

Metric	Large Scale WEC Criteria	Additional Information	Potential Further Research	Potential Researcher
		advantage to reduce this issue, with different components being activated individually.		
Affordability – PTO	Design and optimisation of large scale PTO.	Primary PTOs typically require significant concept design and engineering effort to manage operating and extreme load cases at large scale. As loads scale, up there will be breakpoints in PTO applicability & availability.	Investigation into the implications of control on PTO force and stroke length for large scale individual devices to confirm the suitability of existing PTO technologies.	Wave Energy Scotland, Developers
Affordability – Electrical Infrastructure	Large scale, shared electrical infrastructure to minimise CAPEX.	Larger scale WECs offer significant cost savings in terms of subsea electrical architecture.	Development effort on subsea infrastructure (hubs, transformers, junction boxes) to enable large scale deployment.	Wave Energy Scotland, Electrical & Marine supply chain
Affordability – Mooring Systems	Large scale, shared mooring systems to minimise CAPEX.	All large scale configurations investigated in this study realise reduced mooring CAPEX relative to a baseline array of 1MW devices. A number of technical risks associated with moorings for large scale grouped structures were identified.	Design of mooring systems for large scale grouped structures, including mitigation of key risks (Section 6.5) Optimisation of large scale mooring systems for grouped structures to reduce CAPEX.	Wave Energy Scotland, Developers

Metric	Large Scale WEC Criteria	Additional Information	Potential Further Research	Potential Researcher
Availability	Usage of multiple PTOs connected in parallel.	Modular systems are expected to offer a more reliable system overall compared to single large scale PTO solutions. These are prevalent in the drivetrain of large offshore wind. Large scale individual devices reliant on a single PTO are likely to have reduced cost effectiveness due to a critical point of failure.	Research into modular PTO solutions for large-scale WEC devices.	Wave Energy Scotland, Developers
Availability	Installation within the bounds of the offshore wind supply chain, e.g. towing draft limit ~10m, offshore lifting limits ~1200te.	Remaining within the operational limits established by the offshore wind marine operations supply chain is likely to be necessary to ensure cost effectiveness of large-scale WEC devices. The study concluded that, in general, existing construction facilities do not represent a blocker to large scale WEC development. Dry docks and slipways represent feasible installation sites for large scale WECs. If land is plentiful and inexpensive, onshore storage followed by a short load-out programme would be most cost effective. If the project can justify the use of a dedicated vessel or launch facility, then a much smaller land area could be used.	Investigation into the supply chain requirements and capacity for mass production of large scale WEC devices. This will highlight supply chain opportunities and limitations to enable development of large scale WEC devices in Scotland.	Wave Energy Scotland, Developers

Metric	Large Scale WEC Criteria	Additional Information	Potential Further Research	Potential Researcher
Availability	Development of offshore campaign and operations for large scale assembly.	Large scale WECs require complex offshore assembly and connection, particularly for grouped structures. Towing floating components is typically cost effective compared to offshore lifting operations.	Development of cost effective offshore campaigns associated with large scale WECs, maximising tow of floating components.	Developers, Marine Contracting supply chain
Availability	Optimised O&M strategy for a given site and scale.	Large scale devices can enable significant OPEX reduction due to a reduced number of vessel interventions throughout the lifecycle of the project.	Detailed assessment into the optimal O&M strategy for large scale WECs. The WES O&M model could be updated to allow the use of multiple vessels simultaneously. Development of a sector wide tool may enable optimisation of the O&M strategy for individual developers at a range of scales.	Wave Energy Scotland

Appendix A: Stage I Literature Review

Attenuator

A wave energy attenuator is a device that operates parallel to the wave crest (along the direction of travel of the wave) and uses the relative motion of two or more bodies to generate power. The Pelamis device is one of the best known attenuator examples, with power extracted from the relative motion between cylinders by interconnecting hydraulic rams. The second generation P2 had 5 cylinders with 4 m diameter and 36 m length and was rated at 750 kW [53]. Theoretically this power rating could be increased by increasing both cylinder diameter and the number of cylinders. However it is unclear whether this would be economically advantageous in regards to the resulting increase in mooring loads compared to deploying multiple smaller devices. The influence of wave attenuation down the length of the attenuator would also become increasingly significant as length increased. The final choice of cylinder diameter and device length will clearly be influenced by the deployment wave climate.

The Pelamis can be considered to be raft-type WEC. Other raft-types include the Cockerell raft, the McCabe Wave Pump and more recently the Sea Power Platform developed by 4c Engineering and the Mocean WEC, both of which have received WES funding under the Novel Wave Energy Converter programme. The M4 WEC is another more recent adaption of the raft-type concept, for which modelling results of 10MW+ configurations have been published. As developed to date the M4 can be considered to be an attenuating wave energy device consisting of three circular floats spaced to respond approximately in anti-phase. The bow float and mid float are rigidly connected. A hinge with the PTO above the middle float is connected by a beam to the stern float and power is generated from the relative angular rotation. Increases in diameter and volume from bow to the stern allow a range of natural periods in heave and pitch, providing a broad band response [53]. Time-domain linear diffraction models [54] have suggested that expanding this to an 8-float system (1 bow float, 3 middle and 4 stern as shown in Figure 50) results in power outputs ranging from 3.7 MW to 17.3 MW, with a reduction in cost of electricity compared to the 3 float arrangement based on a consideration of steel cost.

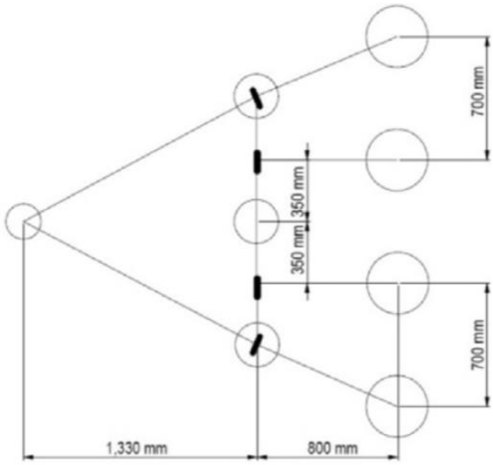


Figure 50. 8-float M4 WEC system [54] . The solid bar represents a hinge, normal to plane of rotation, with power absorbed from dampers at the hinge points.

Point Absorber

Point absorbers are devices whose dimensions are generally small relative to the wavelength and thus are not dependent on wave direction [55]. For the purpose of this review point absorbers are also consider to absorb energy through movement at or near the surface typically a buoyant float reacting against a structure, an anchor or a mooring system. Devices operating under different operating principals are considered elsewhere. The majority of individual point absorbers considered in the literature review are currently designed to operate in the kW range, with MW range farms being achieved through the use of arrays. For example, the developers of the CorPower WEC are working on a 250 kW prototype. de Andres et al. [56] have used the CAPEX estimates for this prototype and a techno-economic model to consider several sizes of WEC for use in a 20 MW array. It is reported that there is a tendency for low to medium rated devices (100 kW to 250 kW) to be optimal, although it is acknowledged that these results are heavily dependent on the assumptions made.

Of the point absorbers currently under development, the CETO point absorber from Carnegie is one of the most advanced which is targeting MW level generation from a single device. The CETO 6 is currently under development with a target capacity of 1 MW with a 20 m diameter float [57], a significant increase on its early 1 kW unit [58]. It is a submerged floating buoy with an electrical generation unit at its sea-bed base.

A greater amount of attention has been dedicated to achieving multiple MW capacity from point absorbers by having multiple devices react against a global structure. The Wave Star is perhaps the best known multiple-point absorber device and was conceived in the early 2000s. It has been tested at 1:40, 1:10 and 1:2 scales and Table 44 gives the target power production for different scales of Wave Star device. There is a linear relationship between the size of the float and the target sea state significant height (Hs) and so further scaling up of the individual units would be limited by the resource – typical for WECs of this type. Babarit et al [2] modelled the annual absorbed power of a Wave Star with 20 floats, each 5 m in diameter and height, in 13 m of water. The annual mean absorbed power varied from 127 kW to 612 kW depending on the wave climate simulated. This suggests that the values given in Table 44 are high but not unlikely. It should be noted that in 2016 the Wave Star technical director is quoted as stating: “Our technology works but we know it is too expensive, so maybe it is not the right technology and it’s not for us. We cannot find investors so we must take the consequences” after failing to find investors to match fund Horizon 2020 funding [59].

Table 44. Projected power production at different scales of the Wave Star Device

Scale	Float number and diameter [m]	Length [m]	Water depth [m]	Hs [m]	Power [kW]	Notes
1:10	40 x 1	24	2	0.5	1.8	Physical test
1:2	40 x 5	120	10	2.5	500	Numerical model, physical model
1:1	40 x 10	240	20	5.0	6000	Projected
1.5:1	40 x 15	360	30	7.5	24000	Projected

Various other global structures have been proposed but developed to lesser degrees than the WaveStar. These include Pontoon Power, a multibody floating WEC for which 1:10 scale modelling has been conducted [60]. The concept provides relatively large scale power production (15 – 20 MW) using one turbine/generator driven by many heaving buoys connected to a common submerged reference structure via hydraulic PTO systems. This structure is composed of a single support structure connected through tension wires to a series of ballasts baskets [2]. The Manchester Bobber, consisting of 25 – 50 individual heaving floats each rated at 500 kW attached to a bottom fixed common reference frame, has undergone both physical and numerical studies (e.g. [61]). Another device is the FO3 WEC, which comprises a four-column floating platform with heave plates and up to twenty one surface-piercing point absorbers [62]. Each point absorber would move along vertical guides, extracting energy through the use of hydraulic PTO systems. A 1:3 scale model of the FO3 WEC has been tested, with a 2.5 MW estimate made for a full-scale 36 x 36 m platform [63].

The WaveSub device, developed by Marine Power System, is a series of submerged point absorbers connected to a common structure, in this case a submerged reaction plate. Tests are currently under way on a 1:4 scale device at FabTest in Falmouth, with the company stating that they expect a full scale 100 m long device to be rated at 5 MW. There are no fundamental reasons why additional floats could not be potentially added to increase capacity, although whether this would be economically advantageous compared to using multiple smaller devices is presently unknown.

Garnaud and Mei [64] present a theoretical comparison of the power extracted by a compact array of small buoys with that from a single large buoy. The buoys are vertical cylinders with PTO modelled as linear damping applied to heave motion. The volume of the large buoy is equal to the sum of the small buoy volumes. Compact arrays of smaller buoys are found to be hydrodynamically promising, with greater energy extraction over a larger bandwidth compared to the equivalent single buoy. The study is carried out 'within the framework of linearisation', using regular waves and with the assumption that the buoys and their separation are small compared to the wavelength [65]. Regardless the results support the worth of further investigation into using multiple smaller absorbers. The authors identify a series of technical challenges in the use of multiple small buoys, including the control on the individual absorbers and understanding the influence of the platform of energy extraction. Suggested modelling improvements were the inclusion of frictional losses due to flow separation and modelling the influence of nonlinear effects of finite amplitude waves.

Lee et al. [66] model the coupled dynamic responses of a floating platform with multiple wave energy converters, considering the hydrodynamic interaction between the platform and WECs. Performance was compared to that of an isolated device for an example platform. A q-factor greater than 1 was reported across the frequency range examined for head waves, although this was found to drop as wave direction changed. The study concludes that more 'accurate and sophisticated' analysis is needed for robust system design. However their results demonstrate the need to fully understand device-device and device-structure interactions when considering multi-point absorber systems.

Oscillating Wave Surge Converter

Oscillating wave surge converters (OWSC) exploit the increase in the surge component of waves caused by shoaling as the waves transition into shallower water. They are a flap-type device, either floating or fixed to the sea bed, mounted along the wave front and that convert the surging motion of the waves into electricity (or pressurised water). Examples include the Oyster, Waveroller and the water-pumping surge WEC from Resolute Marine Energy.

The ultimate limiter on scalability of OWSC is the resource but not in the same way as for point absorbers. While they are generally reliant on the period of the waves, they are broadbanded devices [67] with tuning having a minimal influence on performance [68]. The power capture of OWSCs is maximised by occupying as much as the vertical water column as possible to reduce overtopping and spilling. In addition, the wave force should be maximised, which increases approximately with the square of the panel width. Capture efficiency increases up to the point at which width is similar to wavelength and then decreases as terminator effects and wave phase variations begin to dominate [69]. As device width increases load variability induced by non-homogeneity of the wave resource becomes an increasing problem in terms of foundation loads and fatigue [70].

To try and mitigate loads on the structure, modular flap designs have been investigated and it has been proposed that overall scaling up would be easier with a modular device [67]. By adjusting the damping on each segment of a modular flap, it has been found that a segmented flap could outperform a rigid flap [67].

Floating oscillating wave surge converter include the Langlee WEC [72], consisting of a pair of working flaps that are 'placed symmetrically opposing each other mounted on a floating reference frame'. Performance is found to peak when wavelength is twice the length of the distance between the flaps. The flaps then move out of phase, providing a 'significant counterforce to the induce force' on the flaps, 'considerable enhancing performance'. The 'Farley Triplate', investigated during the 1975-82 British Wave Energy Programme is another example of a floating oscillating wave surge converter [71].

Alternatively the Polygen Volta device, consists of flaps located along a floating spine aligned to the direction of wave propagation. In both cases capacity could be theoretically increased by expanding the structures to mount additional flaps. As with other device types that could be deployed on common structures, further analysis is needed to comparing this expansion with the use of multiple smaller devices. The large loads generated by OWSC may make this comparison less favourable than, for example, with point absorbers.

Oscillating Water Column (OWC)

Oscillating water columns (OWC) use the vertical motion of the water entrained in an open cylinder to drive air through a turbine and can be shore-mounted, fixed or floating. Typically, they are narrow-banded: fixed OWCs produce the most power at a frequency at which the chamber resonates whereas floating OWCs can be made so that the device resonant frequency is separate from the chamber resonant frequency, increasing the band width of the response.

An upper limit for OWC WECs has been estimated at 2 MW, based on 'the wave energy available to a structure over a reasonable capture length and the energy losses associated with wave interactions inside the collector structure' [[112], pp110]. If the chamber is very wide; comparable to the prevailing wave length, the wave surface inside the chamber will not move uniformly and sloshing will occur, limiting the power absorption.

Large capacity OWC WECs have been investigated by either integrating multiple resonant chambers into a single device, such as the Mutriku Breakwater wave power plant [74] or multiple individual OWC units on a single platform. The Mighty Whale concept adopted the latter approach, with a full scale prototype deployed in 1998 consisting of three air chambers with individual Wells turbines making up a 4400 t floating structure with a total power rating of 110 kW [75]. The addition of more chambers, plus the integration of technical developments from the last 20 years would be expected to increase this capacity. Similarly, the OE Buoy concept, a floating OWC concept tested at 1:4 scale in Galway Bay [2] as a single air chamber free to move in six degrees of freedom, was envisaged as being scaled up to MW scale capacity by deploying multiple chambers on individual structures. Alternatively, the LeanCon is a floating WEC consisting of multiple OWCs chambers, which drive a common PTO. A 240m-wide version of the concept has been predicted to produce 4.6 MW [76].

An alternative variant of the OWC is the OWEL device: a floating OWC that uses the wave surge to compress the air in the chamber (duct) rather than the wave heave motion. According to [77], there is a reliance on the ratio of the wavelength to physical length of the device, with peak performance measured at wavelength to duct length ratios of 1-1.5 and 3-3.5. This may indicate a limit to the optimum size of an individual duct. In 2014, specifications for a marine demonstrator state that a single floating duct would be rated at around 500 kW, with a full-scale commercial product consisting of serval ducts in parallel. A generation capacity of 12 MW is specified in [78].

Overtopping/Terminator

Various proposals have been made for overtopping devices, involving shore-mounted and both fixed and floating off-shore structures. Shore-mounted overtopping devices are not considered here as the power potential is going to be largely dependent on the local geography.

As the operating principal of overtopping devices is not dependent on achieving resonance, no fundamental limitations are foreseen in this classification of devices being able to achieve power ratings of 10 MW+. Overtopping device performance is limited by the volume of water that can be trapped in a device's reservoir for discharge through low-head turbines. The structural and transportation costs of overtopping reservoirs large enough to reach the target capacity are of concern with this device classification. Greater power take-off efficiency is achieved within overtopping devices through the use of multiple small turbines that are able to either run at full capacity or be bypassed, as opposed to fewer larger turbines running at part capacity. A large device with more turbines therefore enables greater levels of control.

Wave Dragon was involved in the EU-FP6 Energy call from 2006 to 2009 with the aim of developing their overtopping device from prototype scale to a 7 MW rated device. Their projected device sizes are given in Table 45. Owing to funding difficulties, the original aims of the project were not completed. According to the project summary report [79], the projected power in 24 kW/m waves was quantified at 10 GWh/y (compared to the 12 GWh/y cited in Table 45).

Table 45. Proposed power production for different sizes of Wave Dragon [79]

Scale	Total width and length [m]	Number of turbines	Power per unit [MW]	Reservoir size [m^3]	Annual production per unit [GWh/y]
0.4 kW/m	58 x 33	7	0.02	55	--
24 kW/m	260 x 150	16	4	5000	12
36 kW/m	300 x 170	16 – 20	7	8000	20
48 kW/m	390 x 220	16 – 24	11	14000	35

Terminator devices also have the potential to achieve power ratings over 10 MW+ as their operating principals are such that an increase in the primary dimension results in the device covering more of the wave front, as opposed to impacting the device size relative to wavelength. As a terminating device's width is increased across the wave front, wave directionality becomes a more important issue, resulting in uneven loading on the device and reduced conversion efficiency. As such it is expected that terminator devices will be expanded with modules moving independently of each other.

The Edinburgh Duck is such a terminator-type device which has multiple ducks rotating about connected spines. A review of the 1998 version of the Duck [81] considers a 2 GW scheme consisting of 334 ducks of South Uist, suggesting a 6 MW capacity per duck. Each Duck body was 45 m long, with a maximum diameter of 14.4 m and a wall thickness of 0.424 m. It was proposed that hydraulic rams would be used to connect spine sections. In a summary of the technical review of the 1998 Duck, the sheer size of the individual Ducks was identified as being one of the most significant technical challenges – both in regards to the fabrication of the water tight individual units and the marine engineering challenge in connecting each spine section to its Duck or other section. The original design was suggested to be 0.5 – 1.0 km long, with Salter noting that the bending moments arising from the worst waves would be the limiting factor to scale [82]. This concept has been developed in recent years by a group from Aalborg University, Denmark, into the WEPTOS WEC. They note that efficiency is related to the width of the ducks not the length of the device but that the mechanical power was related to both parameters [84].

As with the Salter Duck, the Bristol Cylinder was also investigated during the 1975-82 British Wave Energy Programme . The original cylinder comprised a circular cylinder constrained to move in a circular motion under wave action. The original concept required 'a complicated arrangement of springs and dampers attached to splayed mooring legs to extract energy through this motion' [83] which was considered to be too complicated to produce a viable device. Crowley et al. [83] revisit the concept to constrain the cylinder to move in surge only, simplifying the PTO mechanism. It is predicted that a 28m cylinder, with no losses, could output approximately 740kW from an average 30kW/m sea state. The scaling up of such a concept may struggle to cope with the increasing impact of wave directionality.

Alternatively the AWS-III multi-cell wave power device could also be considered to be a terminator device. This is a floating multi-cell array of flexible membrane absorbers. AWS state that a typical device would comprise 9 cells, each 16 m wide and 18 m deep, arranged around a catamaran structure and rated at around 2.4 MW [85]. It is feasible that the additional cells could be added to such a structure to further increase capacity.

Submerged Pressure Differential

Submerged pressure differential devices are generally mounted to the sea floor in shallow to intermediate water conditions, using the pressure differential induced by overhead waves to drive the WEC's prime mover. These can be mechanical elements (such as the Wave Carpet from CalWave Power Technologies) or pneumatic elements (such as the device from Bombora Wave Power).

The Bombora technology is a series of floor-mounted air-filled chambers that use pressure differences in the cells to drive an air turbine. It has been described as a non-resonant device, meaning that the area over which it can draw power is limited to the area of the device [[86]]. A cost of energy study (undertaken by Bombora Wave Power) [[87]] investigated the feasibility of a 40-unit farm of 1.5 MW devices. Capacity could potentially be increased by increasing cell size, although this is likely to result in increased challenges in membrane and turbine design. Alternatively, additional cells could be added. This could have the advantage of smoothing power generation by spreading energy capture over several wavelengths.

A pilot plant for the original Archimedes Wave Swing concept was tested in Portugal in 2004 with a linear electrical generator. It was rated for a maximum peak power of 2MW and was a fully submerged pressure differential device [88]. The Archimedes Waveswing submerged wave power buoy is also a submerged pressure differential device, with the developer, AWS, giving a rating a rating between 25kW and 250kW depending on scale [89].

Bulge Wave

Bulge wave devices consist of a water filled distensible tube moored such that it is heading into the waves and in which wave action induces the formation of a bulge wave. Resonance occurs when the speed of this bulge wave equals that of the phase speed of the wave, resulting in the bulge increasing in size as it propagates to the stern of the tube. The most well developed bulge wave device is the Anaconda. Farley et al. [90] present simulation results as tube length and diameter are varied. These suggest that bulge wave devices with a stern based PTO have a limit to the increase in capture width with tube length. Although the relationship is initially approximately linear, the increase 'flattens off' due to wave radiation from the tube. It is predicted that for a 2.5 m diameter tube a length greater than 200 m is not beneficial, and for wider diameters (8 m) this drops to 100 m. The concept of a distributed PTO was proposed where power is extracted along the length of the tube before the radiated wave has a significant effect. This results in significantly increasing the benefit of increasing tube length, with capture width increases predicted for both 2.5 m and 8 m diameter tubes up to lengths of 750 m (the largest modelled). The most cost effective Anaconda with a distributed PTO is reported as having a 3 m diameter, 400-600 m length and a CW up to 20 m in a Pierson-Moskowitz spectrum with peak frequency of 0.125 Hz and power level of 50kW/m therefore suggesting 1 MW of capacity.

Distributed PTO systems for Bulge Wave converts have been suggested by [91]. SBM Offshore have also been developing the S3 Wave Energy Converter (S3 WEC). It consists of a long flexible tube made of an electro-active polymer (EAP). Therefore the structural material acts as the power take-off (PTO) [92], providing a distributed PTO bulge wave device. The company has stated that individual units have the potential to harness 2.5 MW of energy per unit [93].

The results of the simulations presented by Farley et al. [90] indicate that capture width also increases with tube diameter. However the distensibility of the rubber tube, which determines its resonant frequency, is proportional to tube radius and inversely proportional to tube thickness. Therefore tube diameter cannot be simply increased without reference to the deployment site wave conditions, and also manufacturability. Considering the modelling results of [90], it appears that individual bulge wave devices would likely require unrealistically long tube lengths to achieve 10 MW+ capacity per units.

Rotating Mass

Rotating mass devices make use of the relative motion of a floating structure and a large mass operating like a pendulum. The limiting factor of such devices is considered to be the wavelength of the resource relative to the device.

Among these devices, the best known is the Penguin from Finnish developer Wello. In March 2018, the Penguin had been continuously deployed for a year in Orkney and the company has plans to export the technology to China and Bali in the coming years. The Penguin's nominal power rating is 600 kW and has a larger power to weight ratio (P/W) than the Pelamis P2 device. Using Froude scaling, a 10 MW device would be 67 m long and have a mass of over 2400 tonnes. This puts its length equivalent to that of a super yacht, albeit three times heavier.

Compare this to the GWave device, which would be 72 m long but would weigh 13,000 tonnes to generate 9 MW [94]. This device was due to be deployed at Wave Hub, Cornwall in 2018 but the company has postponed its deployment. This is an example of a device that was conceived to work at large scales rather than testing at small scales first.

A further example of a rotating mass concept is the WITT device. This extracts power from all six degrees of freedom to create one continuous output, which can then be connected to a PTO (generator). In 2016, the company tested a 200 W device at Southampton University. The technology is not being development exclusively targeting wave energy for large scale power generation, however the company claim that the concept is 'completely scalable'.

Other devices

Several devices were identified in [78] as having 10 MW+ level capacity in a single device. Little detail has been found regarding the specific of these devices. They include the Swedish Vigor WEC, having a quoted generating capacity of 12 MW. It consists of a flexible hose which spans several wave periods. The bow of the hose has a water and air intake and a hydraulic PTO at the stern. Waves compress the trapped air and water as they progress from the bow to stern.

A 'typical' PowerGin is quoted as consisting of two 25 to 30 m long, 3 m diameter rotors arranged on either side of a wave ramp. The rotors consist of a series of 'buckets' mounted in a dense spiral pattern around the perimeter. As waves runs up the ramp these buckets are filled, rotating the rotors. The developers, Kinetic WavePower, state that one PowerGin could be sized to achieve up to 20 MW output [95].

Finally the Waveline Magnet Wave Energy Converter (WM7) has a quoted full size capacity of 15 MW [78]. This is an attenuator device which is believed to uses a series of inter-linked platforms with articulation joints with corresponding PTO [96]. It claims to be 'effectively buoyancy-neutral and adheres to the surface of the water, so its movements follow precisely the contour of the wave as it passes ‘through’ the device’ [96]. The developers have indicated that this result in the ability for the device to be easily scaled.

Appendix B: Stage II Energy Assessment

Froude Scaling: Key assumptions

Froude scaling

- The following properties of the 10MW reference designs were obtained by applying Froude scaling:
  - Characteristic mass
  - Characteristic area
  - Mean mechanical absorbed power matrix
  - RMS PTO force matrix
  - RMS excitation force matrix
  - PTO settings (implicitly, through scaling of power matrix and PTO force matrix) – note also that the control strategy remains identical (i.e. passive strategy, PTO settings constant per sea state)
- When scaling grouped devices, the same number of (larger sized) actuators / prime movers is assumed.

Theoretical limits

- The hydrodynamic limitation (radiation limit) applied to point-absorbers assumes that the body is axisymmetric
- The Budal limit was derived under regular wave field conditions. It was assumed that the limit could be extended to irregular waves using the incident wave amplitude H_s and the wave energy period T_e.
- The theoretical work originally conducted in [5] focused on isolated devices. As a high-level approximation, it was assumed that the theoretical limits could be extended to grouped devices by summing the theoretical limits for each individual actuator.

Froude Scaling: Methodology

The energy performance of Froude scaled 10MW versions of existing WEC concepts was estimated. Seven different devices were considered based on the NumWEC study, as described in Section 5.2.2.

The following metrics were calculated for the scaled devices:

- Annual absorbed energy per characteristic mass (MWh/ton);
- Annual absorbed energy per characteristic surface area (MWh/m^2);
- Annual absorbed energy per unit of RMS power take-off (PTO) force (MWh/kN);
- Annual absorbed energy per unit of RMS excitation force (MWh/kN).

These metrics aimed to provide proxies for WEC performance, loading and cost when scaled to 10MW.

Froude scaling typically aims to ensure geometric, kinematic and dynamic similarity at different scales. The method was applied to derive the characteristics of representative 10MW designs. Table 46 details the applicable scaling indexes when considering Froude scaling. The drag coefficient was not scaled in this methodology, which is considered appropriate for this level of investigation.

Table 46. Froude scaling indexes

Characteristic	Dimension	Froude
Length	[L]	λ
Time	[T]	$\sqrt{\lambda}$
Velocity	[LT^{-1}]	$\sqrt{\lambda}$
Acceleration	[LT^{-2}]	1
Mass	[M]	λ^3
Force	[MLT^{-2}]	λ^3
Pressure	[$ML^{-1}T^{-2}$]	λ
Momentum	[MLT^{-1}]	$\lambda^{7/2}$
Energy	[ML^2T^{-2}]	λ^4
Power	[ML^2T^{-3}]	$\lambda^{7/2}$

Using the original NumWEC power rating P_{rating_i} associated with each device (see Table 3), a length scaling factor λ_i was derived to infer the properties and behaviour of a 10MW equivalent of each machine:

$$\lambda_i = \left(\frac{P_{target}}{P_{rating_i}}\right)^{2/7}$$

The scaling factor λ_i and the resulting upscaled mass and surface area of each 10MW reference design are presented in Table 47.

Table 47. Scaling factor, characteristic mass and characteristic surface area for the 10MW devices

	B-SHB	F-2HB	B-HBA	F-HBA	B-OF	F-3OF	F-OWC
Scale λ_i	3.7	1.9	1.8	1.7	1.6	2.4	2.2
Mass (ton)	10.4	41.0	0.985	28.2	15.1	20.9	20.1
Area (m^2)	3060	7900	1460	1460	5070	1220	3240

It should be noted that the scaling of grouped devices (e.g. B-HBA or F-HBA WECs) does not mean having more actuators but rather the same number of larger actuators.

The mean mechanical absorbed power, RMS PTO force and RMS wave excitation force matrices were also derived for each device using the applicable scaling factors. An example is shown in Figure 51 for the F-3OF WEC.

It is noted that when upscaling the matrices (mean power or RMS force), the vertical (H_s) and horizontal (T_p) axis were also scaled, with a factor of λ_i and $\sqrt{\lambda_i}$, respectively. The resulting upscaled matrices were subsequently interpolated to match the original scales of the vertical (H_s) and horizontal (T_p) axis, to ease the comparisons between the different scales, and for consistency with the scatter diagrams used in energy yield calculations, as presented in Section 5.2.3. This ensured that the upscaled versions of the NumWEC designs were dynamically similar to the original versions in a site insensitive sense, i.e. the same (absolute) dynamic response would be expected if and only if scaled versions of the original NumWEC sites were also considered. The WEC properties that are scaled, namely the geometric properties, power matrices and excitation force, are therefore site insensitive. It was also assumed that all PTO settings were scaled accordingly.

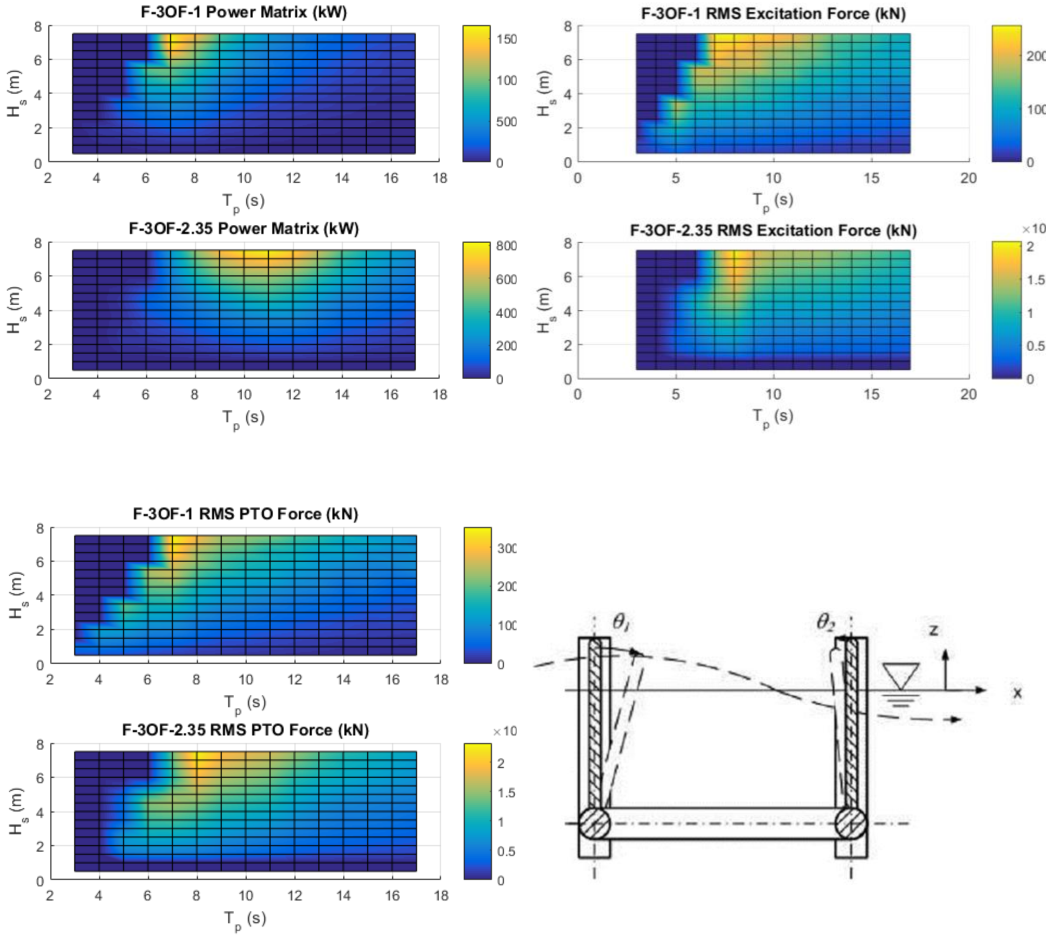


Figure 51. Mean mechanical absorbed power, RMS PTO force and RMS wave excitation force matrices for the F-3OF device: original NumWEC size (top matrices) and 10MW version (bottom matrices)

A range of sites were considered as described in Section 5.2.3. This enabled evaluation of the combined influence of the environmental conditions and scale on the estimated WEC performance.

The original NumWEC site data, including water depth, have not been scaled. The water depth of the sites considered (see Figure 9 to Figure 11) is significantly greater than the geometries of all of the devices scaled to 10MW aside from F-2HB at EMEC. Any change in the ratio of device geometry/water depth was assumed to have minimal impact on WEC performance.

In accordance with [4], the mean annual energy produced ($MAEP_{i,j}$) by each WEC at a site can be obtained by combining its power matrix with the scatter diagram of the respective site (in percentage), and multiplying by the number of hours in a year:

$$MAEP_{i,j} = \frac{T}{100} P_{i,j} . f_{i,j}$$

where T is the average length of a year in hours, $P_{i,j}$ is the absorbed power at bin i, j and $f_{i,j}$ is the probability of occurrence at bin i, j (in percent). In this definition, the $MAEP_{i,j}$ is therefore a matrix, being a function of the input sea state (the sum of which would lead to the absolute $MAEP$).

Finally, the corresponding metric can be derived by dividing each cell $P_{i,j}$ of the power matrix by the appropriate parameter (characteristic mass, surface area, RMS PTO force at bin i, j and RMS excitation force at bin i, j, respectively).

Theoretical Limits

To enable consideration of novel devices, high-level calculations based on the theoretical work originally conducted by Falnes and Budal [5] were undertaken to determine the maximum power that can be absorbed by a large scale hypothetical device.

The calculations consider the following question: *If the WEC device is operated in the best possible manner, assuming optimum design and control strategy, how much energy can it convert?*

Following [5], it can be shown theoretically that the absorbed power is limited by two distinct bounds: a hydrodynamic limitation (a power bound due to the device's radiation pattern) and one or more physical restriction(s) due to e.g. volume stroke limitations.

Hydrodynamic limitation

Using the example of a point absorber, the radiation related bound can be estimated directly. It has been shown (e.g. [6] - [7]) that an axisymmetric body in a three-dimensional configuration obeys the following relation:

$$P \leq \alpha \frac{J\lambda}{2\pi}$$

where P is the absorbed power (in W), J is the wave power flux (in W/m), λ is the wavelength (in m) and α is a constant that depends on the oscillation mode. For the pitch and surge modes, which have a dipole radiation pattern, $\alpha = 2$, while for the heave mode, $\alpha = 1$, due to its source-like radiation pattern.

In the case of a terminator, with horizontal extension parallel to the wave crest and larger than the wavelength, all of the power in the wave incident upon the width of the device can in theory be absorbed. The radiation related bound in such case can be estimated by:

$$P \leq Jl$$

where l is the horizontal extension, or characteristic length, of the device (in m).

Physical restrictions

With increasing incident wave amplitude, the power limit due to the radiation pattern can theoretically be reached until the body motion amplitude starts to affect the absorbed power.

In the case of a heaving point absorber in a regular wave field, Budal estimated an upper limit to the heave excitation from the dynamic pressure of the undisturbed wave field alone, assuming an optimum control where the phase angle is null. Following [8], this relationship is given by:

$$P \leq \frac{\pi}{4T} \rho g H V_s$$

where ρ is the water density, H the incident wave height, T the wave period and V_s the stroke volume (i.e. the maximum variation of the submerged volume when the WEC is operating).

In the case of a pitching raft, in [9] the upper bound for the absorbed power is defined as:

$$P \leq \frac{1}{16} \rho H V_s \omega^3 l$$

where ω the wave frequency and l the width of the raft.

It is noted that Budal's upper limits are derived under regular wave field conditions. In this study, a high-level approximation of Budal's upper limit in irregular waves is proposed using the incident wave amplitude H_s and the wave energy period T_e.

Figure 52 illustrates the absorbed power bounds due to both the radiation pattern and the volume stroke limitation for a heaving submerged sphere in regular waves of amplitude 1.0m. Essentially, the power absorption spectrum is divided into two areas: for short wave periods, the absorbed power is limited by the radiation pattern; a large fraction of the incident wave power is absorbed, but the potential associated with the volume of the device is not fully exploited. For long wave periods, the absorbed power is capped by the device's physical limitations; only a fraction of the wave power is absorbed, but the potential associated with the volume of the device is better exploited.

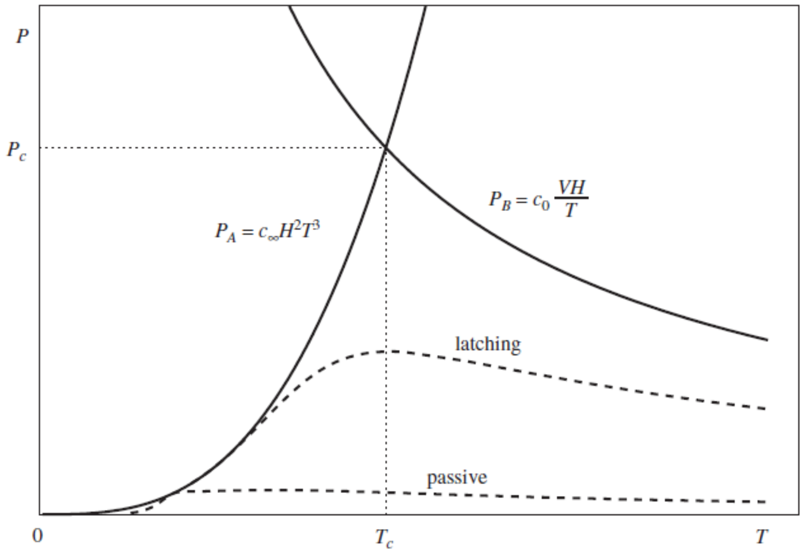


Figure 52. Comparison of theoretical results to the upper power bounds for a submerged sphere in waves of amplitude 1.0 m. The monotonically increasing curve is the upper limit due to radiation pattern, while the monotonically decreasing curve is the upper bound due to volume stroke limitation. The two dashed drawn lines represent the absorbed power for different control strategies [8]

Noting that the theoretical limit is a function of the volume, and therefore of the device rating, an estimate of the upper limit to the maximum absorbed power by each upscaled WECs can be derived by combining the limits from the radiation pattern and the volume stroke limitation. At each wave height, the upper limit to the maximum absorbed power is taken as the radiation limit at small periods (up until T_c in Figure 52) and as the volume stroke limit at larger periods (above T_c in Figure 52). Such assessment is relevant both for idealised versions of the 10MW NumWEC designs and for novel WECs with similar characteristics in terms of their absolute volume and modes of operation. The theoretical maximum energy yield is then obtained by combining the resulting theoretical maximum power matrix with the scatter diagram of the respective site (in percentage), multiplied by the number of hours in a year

Appendix C: Stage II Structural Scaling

Float Structures

A point absorber design derived from [12] was used as a reference for the float structures. This is a stiffened shell structure and is assumed to consist of the following:

- Six radial shear walls. The PTO is connected to the seabed via a central tether, and these shear walls distribute this shear force across the device.
- Ribs and stiffeners spanning between the shear walls.
- Steel plates spanning between the ribs and stiffeners.

The following assumptions were used to derive scaling rules for each of the structural components:

- It was assumed that the number of radial shear walls and the spacing between ribs and stiffeners is kept constant as the device scales.
- The wave forces increase as $\lambda^{2.3}$ and pressures increase as $\lambda^{0.3}$
- The plating thickness has been assumed to vary with the square root of pressure, i.e. $\lambda^{0.15}$
- The sections of the ribs, stiffeners and radial shear walls of the scaled up devices are found by scaling up the sections. The aspect ratios of these sections are kept the same when scaled up.

Using these assumptions, the following scaling rules were derived:

- Volume of steel in plating scales as $\lambda^{2.15}$
- Volume of steel in ribs and stiffeners scales as $\lambda^{3.54}$
- Volume of steel in shear walls scales as $\lambda^{3.3}$

Similar scaling rules were applied to the other floats geometries shown in Figure 17.

Table 48 shows an approximate breakdown of the structural mass for the device. The results show that the total structural mass scales approximately as a factor of $\lambda^{3.1}$. At a larger scale, the ribs and stiffeners make up a larger proportion of the total structural mass.

For different devices, the structural mass scaling depends on the mass breakdown between plating, ribs and stiffeners and shear walls at the original scale. For example, steel plating makes up a larger fraction of the structural mass of smaller floats. Float structures were found to scale within the range $\lambda^{2.5}$ to $\lambda^{3.1}$.

Table 48 Structural scaling for the device. Baseline 1MW data based on recent design values from a leading submerged pressure differential WEC developer.

Device Rating (MW)	1	5	10
Length scale factor, λ	**1.0**	**1.6**	**1.9**
Volume of Steel in plating (m^3)	5.1	14	21
Volume of Steel in ribs and stiffeners (m^3)	5.1	26	52
Volume steel in radial wall (m^3)	5.3	40	73
Total volume of steel (m^3)	**15**	**64**	**119**
Total mass steel (te)	**121**	**508**	**962**

Truss Structures

Truss structures are required for the F-HBA, B-HBA and F-3OF devices. Truss design is typically governed by axial loads in the members, resulting from global bending, shear and axial loads. The baseline reference truss structures for scaling was derived from information in the NumWEC study along with assumptions about the required wall thicknesses to prevent local buckling.

For submerged, buoyant trusses the following assumptions have used to derive scaling rules:

- Truss members comprise Circular Hollow Sections (CHS) with a constant diameter to thickness (D/t) ratio;
- Forces from each device scale by $\lambda^{2.3}$;
- Spacing between members increases by λ;
- The scaled up truss has the same span to height (L/d) ratio.

Based on these assumptions, the volume of steel in a buoyant truss was calculated to scale as approximately $\lambda^{3.3}$.

For suspended trusses above the waterline, for example the B-HBA device, it was assumed that the truss supports the weight of the floats extending off it. The volume of steel in the floats scales as approximately λ^3. The volume of steel in the truss to support this load will therefore scale as approximately λ^4.

Flap Structures

Flaps are used in the F-3OF and B-OF devices as wave absorbing bodies. The baseline reference structural sizes for scaling up to 10MW have been estimated based on information available in NumWEC for the flap devices. The following assumptions have been used to derive scaling rules:

- Forces on each flap scale by $\lambda^{2.3}$ (Froude scaling);
- Flap structures are governed by their base bending moment.

Based on these assumptions, the volume of steel in a flap structures was calculated to scale as approximately $\lambda^{3.3}$.

Appendix D: Stage II PTO Arrangements

Hydraulic PTO

The use of hydraulic PTO systems for wave energy device is well established. The high power density, controllability and robustness provide a means of converting low-speed linear wave motion to high speed rotary motion needed to drive generators ([97], p212). Hydraulic components often already exists in the marine and offshore industry that can cope with the large forces and slow motions that generally exist in WECs, while the use of accumulators can contribute to smoothing of power delivered to the grid [98]. They have high power to weight ratio, are relatively cheap and, with the exception of most OWC and wave-overtopping devices, are applicable to most WEC concepts.

The configuration of hydraulic PTO systems can vary significantly between different devices, often depending on the required force that needs to be provided and the control strategy implemented. Plummer et al. [97] describes two possible approaches: a simple system with limited energy storage driving a variable speed generator or a more complex system able to store the variable wave power and release smoothly to a constant speed generator.

Standard Hydraulic PTO systems are characterised by poor efficiencies when operating at part load [99]. This is commonly the case for wave energy devices, with PTO systems needing to be designed for the maximum operating conditions, whilst during the majority of time wave conditions are lower than this. This could potentially become an increasingly significant issue as devices are scaled to towards 10MW+ scales, and there is a corresponding increase in peak loads.

A number of studies and PTO designs have been proposed to counter the loss of efficiency when hydraulic PTO are operating below peak load. One such system uses several different size hydraulic cylinders in parallel. By activating different combinations of cylinders step changes in the provided PTO system is provided. On the other side of the high pressure accumulator parallel sets of hydraulic motors and generators can be activated / deactivated depending on the extracted power. Such a system was proposed for Wavebob [100]. The Pelamis PTO system operated under a similar principle, where a number of actuator chambers within the hydraulic rams could be selected to be at either high or low pressure, allowing 'quantised approximation to any desired continuously varying load' [101]. These discrete / quantised control systems are significant to this study as they not only demonstrate the feasibility of multiple hydraulic cylinders/chambers, hydraulic motors and generators being used in parallel to increase PTO capacity for larger rated devices, but also show that such configurations have the potential to improve the available control options.

An alternative solution to the low efficiency of the peak to power systems is the discrete displacement or Digital Displacement® pump/motor (DDPM) provides a potential solution to the loss of efficiency in hydraulic PTO systems at part load. Initially devised as part of the Salter Duck team [102], the concept led to the establishment of Artemis Intelligent Power before being acquired by Mitsubishi Power Systems Europe and being developed for multi-megawatt wind-turbine transmissions [99]. DDPM machines are designed to overcome the poor part load performance of conventional variable displacement motors. Instead of mechanically varying the stroke length of pistons within a conventional pump to achieve variable displacement, electronically activated values control the number of active stokes over time of all pistons. This provides discrete control of the average flow and therefore displacement [99]. The use of Digital Displacement PTO has been developed for use in both onshore and offshore wind. It has been demonstrated on the SeaAngel, a 7MW turbine featuring a digital displacement pump, connected to two digital displacement motors which drive two synchronous generators. This again shows the ability of multiple hydraulic PTO components to act in parallel, thereby increasing capacity, but also demonstrates the DDPM system can be potentially applied to WECs with 10MW+ ratings.

The DDPM concept is currently being developed for use in WECs as part of WES's Stage 3 Power Take-Off programme. The system is being integrated into the ex-Pelamis PTO 'discrete / quantised cylinder control' system by Artemis Intelligent Power and Quoceant Ltd to produce the 'Quantor' hydraulic PTO. The system is reported to offer 'high bandwidth and continuously variable control of loads with unrivalled efficiency and power handling capability' for 'power into the MW range' [101]. The 'Quantor' hydraulic PTO team state in [101] that an advantage of MW scale WEC devices is that a hydraulic PTO system could be used to drive a conventional wound-rotor synchronous generator, which 'provides the best support to the local electricity grid'.

Direct Drive PTO

Direct drive PTO systems use generators driven directly by the devices wave induced motion. This removes the need for a gearbox or hydraulic system to convert the slow moving prime mover motion to the velocities needed for a conventional high-speed rotary generator. The relative simplicity of direct drive systems compared to other transmission approaches has the potential to decrease down time and maintenance costs [103]. Direct Drive systems can be used for both linear and rotary systems.

Linear PTO systems are applicable when the prime mover of the WEC generates a linear motion. To date one of the highest rated uses of a direct drive PTO is the Archimedes Wave Swing. This was constructed with a 1MW Linear Permanent Magnet Machine, with a peak capacity of 2MW [104]. Linear Permanent Magnet Machines offer good overall efficiency, continuous force control and a design with few moving parts [99]. However such machines are generally large, with low power to weight ratios and heavy support structures. 'Traditional' direct-drive linear generators are double sided iron cored with a surface-mounted permanent magnet [103]. A stiff structure is required to cope with unbalanced magnetic attraction forces cross the double-sided machine. These arise due to eccentricities in construction or transient deflection. The additional structural stiffness increases mass and cost, and is an issue expected to increase with device scale.

A number of studies of alternative designs of linear direct drive PTO have been suggested and in some cases tested to reduce the power to weight ratio, often by tackling the 'unbalanced' magnetic attraction issue. For example the C-GEN direct drive system claims to eliminate the magnetic forces using a linear air-cored machine [98]. The C-GEN direct drive system has benefited from WES

PTO funding, and is currently at Stage 3. In the stage 2 public report [105], both a linear and rotary version of this direct drive PTO is described. The linear machine for WEC application had only been demonstrated up to 50kW and considered to be at TRL3. However a 1MW multi-stage rotary version, considered to be a slice of a 6MW direct-drive generator has also been demonstrated. This application is considered for the wind industry, where ‘multiple generators consisting of simple, lightweight modules can be “stacked” back-to-back along the shaft of a wind turbine to create a multi-MW rating without increasing the machine diameter’ [105]. The number of operational generators can be adjusted to optimise power output for the wind conditions while also providing redundancy, with energy capture able to continue if one generator has a fault or is undergoing maintenance. Although the linear version hasn’t been demonstrated at multi-MW ratings, the scaling up of the rotary system, plus relative ease of using multiple generators in parallel to increase overall ratings, suggests that such a system could be suitable for 10MW+ WEC systems. The C-GEN team have identified their linear and/or rotary direct drive PTO systems as being potentially applicable to point absorbers, oscillating wave surge converters, oscillating water columns, overtopping devices, submerged pressure differential devices and rotating mass concepts [105].

The application of direct-drive rotary machines within the wind industry is being pursued worldwide due the potential cost savings over more traditional gearbox and high speed generator. The issues of scheduled maintenance and higher failure rates are eliminated, meaning they are the preferred for offshore wind generation [106]. Research effort is ongoing to develop large scale superconducting direct-drive generators in an effort to provide lighter and more compact electrical machines compared to using high energy permanent magnets or copper windings with direct current. For example, [107] proposes a design for a 12MW superconducting direct-drive generator, which is found to be 46% lighter than an equivalent permanent magnet version. Such systems are still at relatively low TRL’s [108] but could foreseeably be a low mass option for large scale WEC devices in the future.

Air-Driven Turbine

Oscillating water column wave energy converters, along with other devices that generate an oscillating air flow (e.g. SQ1 [109]) generally rely upon air-driven turbines as the PTO. A system of non-return valves can potentially be used to rectify the airflow and allow use of a conventional turbine, such as used in the Masuda navigation buoys. Such a system is considered to be complicated, difficult to maintain and is not suitable for large scale individual WECs as the valves would become unfeasibly large [110]. As such self-rectifying turbines are likely to be the only feasible option for individual larger scale devices.

A number of self-rectifying air turbines have been proposed and developed, with the most common being variation on Wells turbine and self-rectifying impulse turbines. It is identified in [111] that the rated power of single air turbines and generators is currently between hundreds of kilowatts to around 1 MW, potentially increasing to 2 MW in future. For example the OceanLynx greenWave device was designed and built with an Dennis-Auld turbine with a rated power of 1MW [111].

An upper limit for future shoreline OWC WECs has been estimated at 2 MW, based on 'the wave energy available to a structure over a reasonable capture length and the energy losses associated with wave interactions inside the collector structure' ([112], pp110). As turbine size increases a greater mass of airflow is needed which in turn requires a greater horizontal chamber area. The larger the chamber area is, the less like a flat piston the water column becomes. As the chamber area increases, eventually wave crests and troughs risk occurring in the chamber at the same time, cancelling the chamber pressure. For example, the Mutriku Breakwater wave power plant [113] has 16 Wells Turbines in segmented sections as otherwise the length of the plant would result in a degree of cancellation within an individual chamber.

Increasing the capacity of a Wells Turbine to 10MW + would necessitate increasing turbine diameter to such an extent that the speed difference between the centre and the outer edge will result in a significant reduction in efficiency. If the ratio of turbine velocity at a point on the blade versus the air flow speed is too low (low turbine velocity with high air flow speed) air flow separation will occur at that point (stall) resulting in very low or zero power transfer. If the velocity at a point on the blade versus the air flow speed is too high the power transfer efficiency is also low because of the unfavourable angle of attack with the flow onto the blades resulting in reduced lift. With a large turbine the turbine velocity versus air flow is only optimal over a narrow section of the blade. A possible solution to this issues maybe to have a large diameter turbine with a large diameter hub. This would mean that the turbine blades were still short in length, while providing a larger turbine area. However such a solution would not deal with the issues of using large chamber areas.

It is considered that it will be more advantageous in the majority of applications to go for multiple smaller turbines arranged in parallel compared to single very large turbine. Although clearly an economic balance has to be struck between the number and size of turbines, using multiple smaller turbines has the potential to decrease construction, transportation and deployment costs while providing a level of redundancy to the device. The use of multiple turbines may also provide the means for innovative control options to be considered.

Dielectric Elastomer PTO

Dielectric elastomer PTO are a relatively new concept of wave energy converter PTO. They are highly deformable electrically insulated polymers, usually deployed as pre-stretched membranes to form deformable electric capacitors. The work done on the WEC is used to deform the membrane, thereby converting mechanical energy into electrostatic energy.

It is claimed that the advantages of a dielectric elastomer PTO include low cost, low weight, reduction in the number of moving parts, low noise, good resistance to impact loads and corrosion and good conversion efficiency at the typical WEC operating frequencies [114]. The dielectric elastomer concept has been considered for various categories of WEC. The WES stage 1, Direct Contact Dielectric Elastomer PTO project [115], identifying potential application to OWC, submerged pressure differential, point absorber, bulge wave, attenuator and oscillating wave surge converter type devices.

A numerical study of the use of this PTO type on an oscillating wave surge device [114] concluded that a 1.56 MW device would be practical and require approximately 15 m^3 elastomeric material. No obvious reasons were found to suggest that such a system could not be scaled up to 10MW+ scale applications. However Dielectric elastomer PTOs are still at relatively low technology readiness levels, and therefore more development would be required before this is confirmed.

Common PTO on common shared structure systems

During Phase 1 it was identified that a number of smaller devices operating from a common support structure was a potential method by which 10MW+ wave energy converters could be developed. A number of these concepts that have been studied and developed. Often these will have individual PTO for each of the individual absorbers. However some have suggested using shared, or partially shared PTO to achieve various possible benefits.

The LeanCon is a floating WEC consisting of a series of OWC chambers arranged in a V shape configuration with respect to the incoming wave direction. The arrangement of multiple chambers in this ways results in the available energy being averaged in space [116]. This, and the use of a system of non-return valves, provides a way of rectifying the generated oscillating air flow. Air is pumped into a high pressure accumulator at wave peaks and flows out of a low pressure accumulator during wave troughs. The rectified air flow means that a typically more efficient uni-directional turbine can be used, compared to using self-rectifying turbines on individual OWC. Configurations such as the Lancaster Flexible Bag also exploit a similar approach with multiple absorbers. Along either side of a beam flexible bags partially filled with air pump air under wave action, via non-return valves, to high and low pressure accumulators. Air passes between the two accumulators delivers a relatively steady flow to a uni-directional air turbine ([117], [118], [119]).

The WaveStar PTO system went through various iterations during its development. A system where the multiple absorbers being connected to the same PTO system was proposed in ([99], pp. 201). Here 20 floats each drive discrete displacement cylinder systems. These cylinders drive hydraulic fluid from high pressure to low pressure lines through four hydraulic motors which drive four generators. A wave-to-wire model of the system predicted overall PTO efficiency beyond 70% in all sea conditions. It is predicted that such a system would be easily scalable beyond the 6 MW system modelled in ([99], pp. 210).

The use of accumulators connected to multiple devices is considered to ‘increase efficiency and durability, as it narrows / stabilises the operating region of the remaining PTO components’ ([99], pp.210). The size of such accumulators is considered to be a balance between these advantages and the cost of the accumulators. The original design institution of the Lancaster Flexible Bag (University of Lancaster) estimates that structural costs associated with having a central beam from which the bags were mounted and the accumulators housed could be in the region of 63% of the total project cost ([120]), one of several reasons why this device evolved into the circular shape SEA clam ([121]), with 12 air cells using 12 Wells turbines. This demonstrates that although using a common

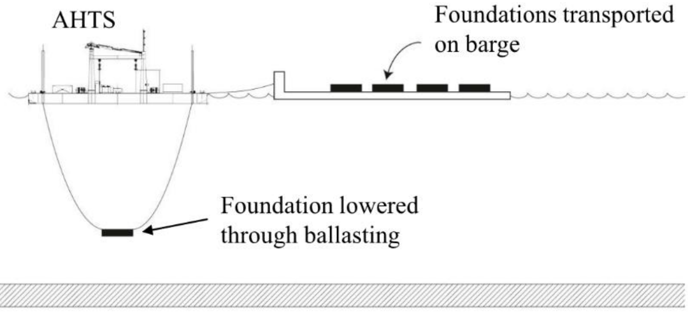
PTO system between individual devices on a common shared structure has several potential advantages, it will not necessarily be the most economical solution.

Appendix E: Stage III Offshore Campaign Description

Individual Devices

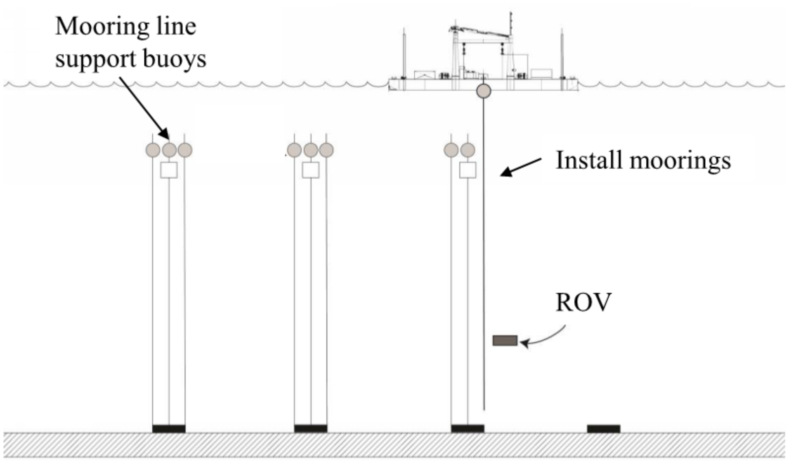
This section describes the offshore campaign for configurations with individual devices. These correspond to the baseline 100 x 1MW and individual 10 x 10MW configurations. The procedure below only illustrates the 'tensioned arrangement', but is equally applicable to the 'catenary arrangement'.

1 Transport and install foundations



Multiple foundation units are transported to site using a conventional barge and tug. Each unit is lowered into place using an Anchor Handling Tug Supply (AHTS) vessel.

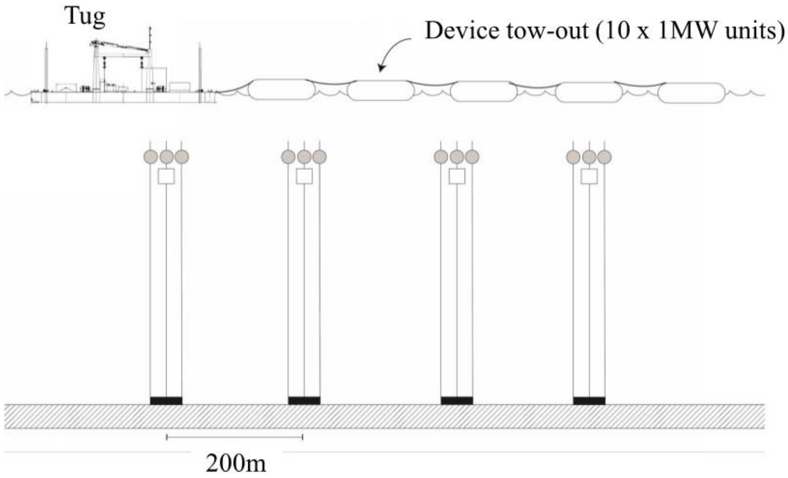
2 Transport and install moorings



Mooring lines are transported to site using an AHTS, which then lowers the mooring lines into place. A Remote Operating Vehicle (ROV) is used throughout the operation.

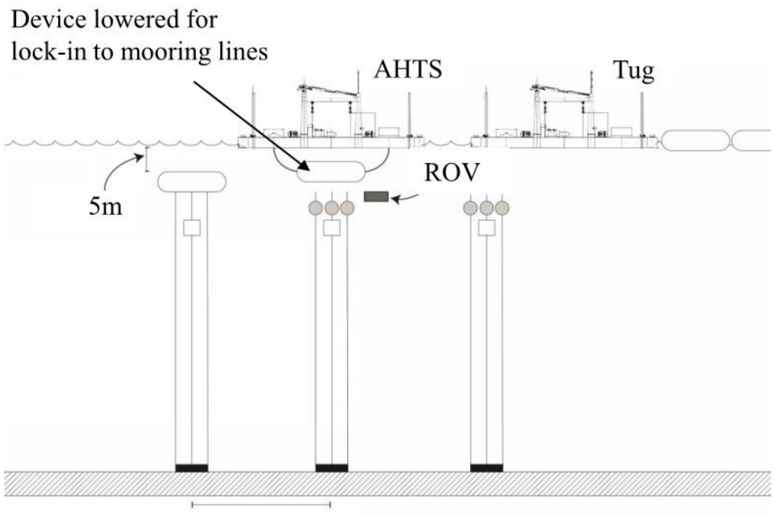
Temporary support buoys are attached to the upper end of each mooring line to provide buoyancy and ensure that the moorings are taught prior to connecting the device.

3 Device tow-out



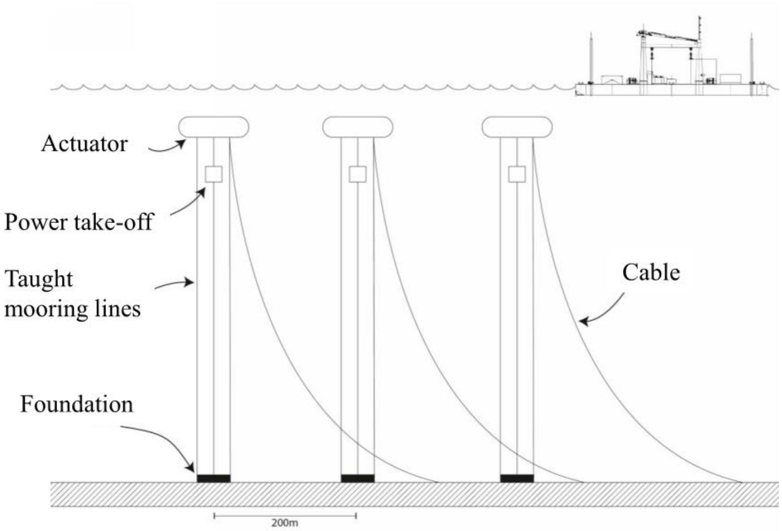
The devices are towed to site for installation via tugs. It is evident that tow-out of multiple devices will lead to potential cost savings, but the feasibility of this operation with specific devices will need to be assessed.

4 Connect device to mooring lines



An AHTS is used to lower and connect each device to the pre-installed mooring lines. Once lock-in between the device and mooring line is achieved, the support buoys are released from the mooring line, back to the surface.

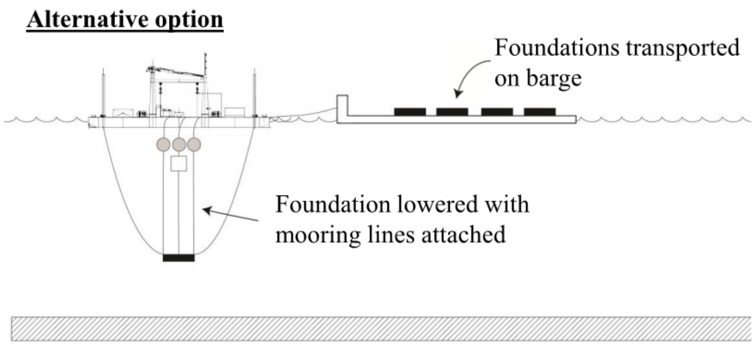
5 Lay cables and connect to device



Cables are laid and connected to each device, ready for commissioning.

An alternative option is to combine stages 1 and 2 above, as described below.

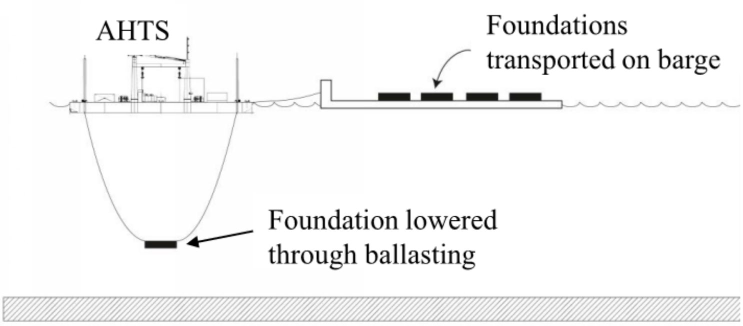
1+2 Transport and install foundations with moorings pre-attached



Installing the foundations with the moorings attached could lead to potential cost savings and reduced offshore operations. The use of an ROV at stage 2 is also omitted.

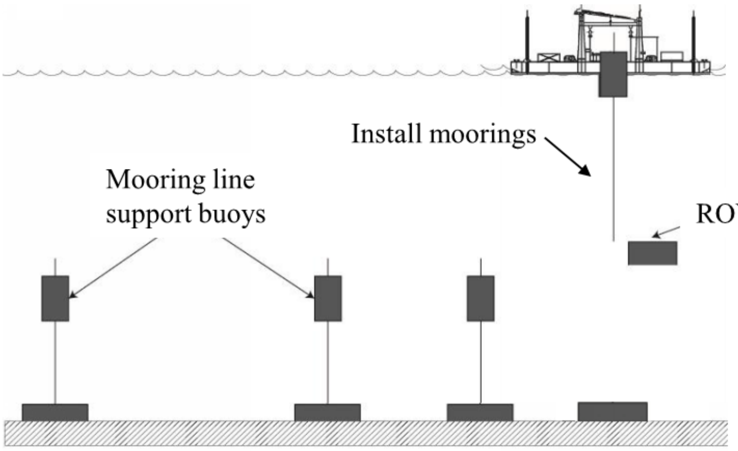
Grouped Devices

1 Transport and install foundations



Multiple foundation units are transported to site using a conventional barge and tug. Each unit is lowered into place using an AHTS.

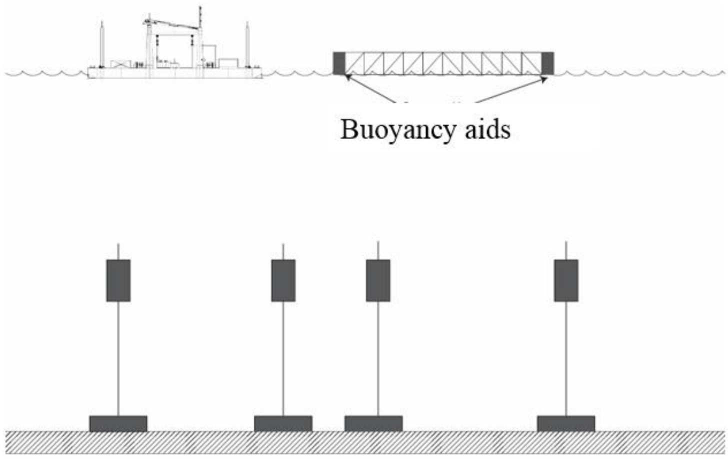
2 Transport and install moorings



Mooring lines are transported to site using an AHTS, which then lowers the mooring lines into place. A Remote Operating Vehicle (ROV) is used throughout the operation.

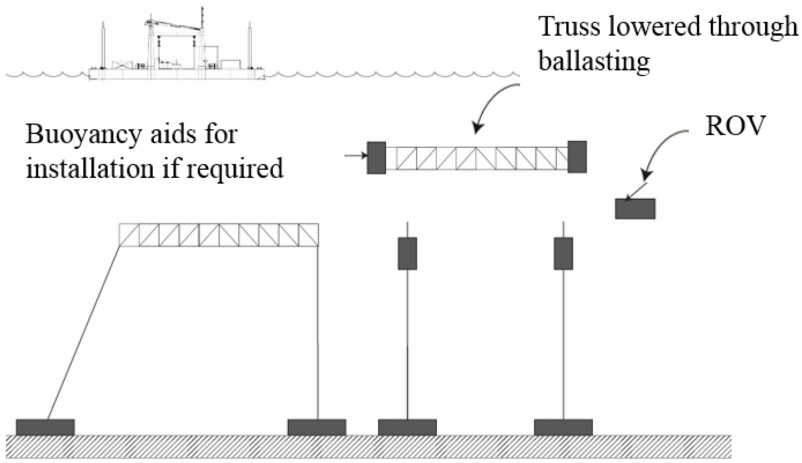
Temporary support buoys are attached to the upper end of each mooring line to provide buoyancy to ensure that the moorings are taught prior to connecting the device.

3 Tow-out trusses



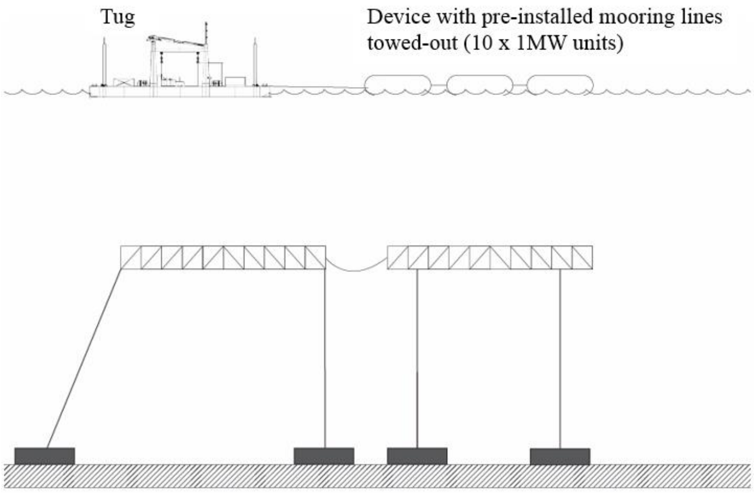
Each 60m single truss is towed-to-site using tugs. Buoyancy aids can be adopted to provide additional buoyancy during float-out operations.

4 Connect truss to mooring lines



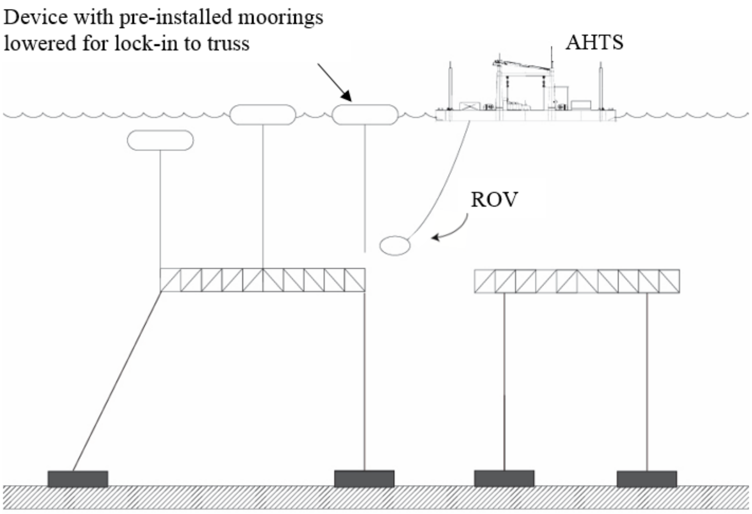
Each truss is ballasted to the required depth and connected to the mooring lines. The ballasting and connecting operation can be done using an ROV. The buoyancy aids used for transportation can be used if necessary.

5 Tow-out device with mooring lines attached to underside



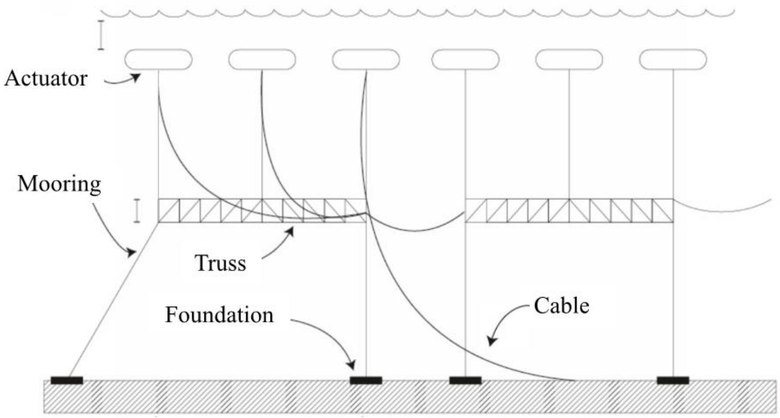
The devices, with pre-installed mooring lines, are towed to site for installation via tugs. It is evident that tow-out of multiple devices will lead to potential cost savings, but the feasibility of this operation with specific devices will need to be assessed.

6 Connect device to trusses



An AHTS is used for device installation, with the assistance of an ROV. Each device, with a pre-installed mooring line, is lowered and connected to the truss.

7 <u>Lay cables and connect to device</u>



Cables are laid and connected to each device, ready for commissioning.

Large Scale Marine Operations Examples

The ‘float-and-sink’ offshore campaign method is widely used for offshore transportation of large structures. Examples of these sorts of operations are shown in the figures below.

1. The structure is built in a port, or on a dry dock Figure 53.
2. A tug is used for tow-out of the structure. For the port option, a lifting crane will be required to transfer the structure into the sea. For the dry dock option, the structure is brought out by filling the dock – a potential cost saving.
3. A tug (Figure 54), or multiple tugs (Figure 55), are used to transport the structure offshore.
4. The structure is then lowered into position through water or solid ballasting, removing the need for heavy-lift vessels.

Figure 53. A complete concrete gravity substructure built in a dry dock, awaiting float-out

Figure 54. Single tug float-out of a concrete gravity substructure (L21.5m x W2.75m x H4.65m)

Figure 55. Multiple tug tow-out of a ~180m truss-spar using multiple tugs

Appendix F: Stage III OPEX Model Inputs

O&M Simulation Tool Generic Inputs

Hindcast, weather and daylight data

The same weather data set is used in the assessment of each scenario. This is the data provided in the WES Case Study [24].

Vessels

A choice of three vessels have been identified: a Multicat, an Anchor Handling Tug Supply vessel (AHTS) and a Service Operations Vessel (SOV). The inputs are based on various datasets, including data for the MV C-Odyssey [26], MTS Vanquish [27]and Acergy Viking [28].

Table 49: Vessel inputs

Vessel Name	Average speed (kts)	Time to site, free (hours)	Time to site, towing (hours)	Fuel cost per hour (£)	Personnel capacity	Daily hire fees (£)	Vessel availability
Multicat	10	12.5	25	150	12	4,000	1
AHTS	12	10.5	25	380	12	20,000	1
SOV	14	9	25	200	60	30,000	1

The assumed towing speed is 5 knots for the vessels. Only the Multicat and AHTS are assumed to complete towing activities.

Operational limits

The operation limits inputs have been based on the vessel data above. A marginally higher operational limit has been set for the larger classes of vessels.

Table 50: Operational limits inputs

Vessel type	Significant wave height (m)	Wind speed (kts)
Multicat	2	20
AHTS	3	25
SOV	3	25

Labour

The baseload of labour has been assumed to be 12 technicians, likely to be organised as four crews each with three technicians, plus one site manager. The O&M labour has been assumed the same across all scenarios. This is consistent with offshore wind where the number of O&M crews on a project tends to scale with the total size of the project, with additional labour brought in as required. The simulation tool will account for extra labour as required. The cost of this extra labour is budgeted at £600 per day for all scenarios.

Power

The objective of this study is to compare OPEX and availability only. Hence a power matrix has not been entered to the tool. This does not affect the calculation of the failures or the OPEX associated with routine and unplanned maintenance. Nor does not affect the availability calculation.

O&M Simulation Tool Array Specific Inputs

Universal Inputs

The Inputs sheet in the O&M Simulation Tool requires Universal Inputs. This defines the inputs related to the WEC scenario and there are variations between these. The inputs are shown in Table 51 and the assumptions discussed below.

Table 51. Universal inputs for each WEC array

	100 x 1MW point absorber	**10 x 10MW point absorber**	**10 x 10MW grouped device**
Number of WECs	100	10	100*
Number of fault categories	3	3	3
Number of scheduled maintenance tasks	3	3	3
Array lifetime	20	20	20
Install ops limits type	1	2	1
Installation vessel	Multicat	AHTS	Multicat*
Install time (hours)	6	12	4*
Install technicians required	6	6	6
No. WECs allowed at base	25	6	50*
No. WECs allowed at base for maintenance	25	6	50*
Number of spare PTO unit	0	0	0
Number of spare instrumentation box	2	2	2
Delivery time (days)	42	42	42
Retrieval cost-benefit analysis	No	No	No
Onsite repairs cost_benefit analysis	No	No	No
CBA days allowance for maintenance	N/A	N/A	N/A
Night operations?	Yes	Yes	Yes
Array location	Same weather data and location for all WEC arrays		
Use current weather? (FPT-020-001)			
Choose specific dataset?			
Output format	£k	£k	£k

* Grouped device considerations

For the grouped device these entries are applicable to a single element of the grouped device i.e. one floating element, rather than the truss structure. For the purposes of the OPEX assessment it has been assumed that once the truss structure is installed, it has a 20 year lifetime and will not need to be returned to the O&M base for maintenance during this time.

Installation vessel and time

The selection of the installation vessel is based on the vessel required to tow the device. Typically, multicats such as the MV C-Odyssey have a bollard pull of 20 to 30 t and would be suitable for the 1MW point absorbers and for the individual floats of the grouped device. The 10MW point absorber and the main structure of the 10MW grouped device would require a vessel with a higher bollard pull rating such as a small AHTS.

The installation time has been estimated based on the assumed timing to install a 1MW point absorber – 6 hours. The 10MW point absorber is assumed to have twice as many moorings and connect points, and so the installation time has been estimated at 12 hours. The individual float of the grouped device is assumed to be simpler to install than the 1MW point absorber, demonstrating the advantage of the grouped device. As stated above the installation time for the truss has not been considered in the model as it is assumed that once this structure is in place it will not be removed throughout the life of the wave farm.

Installation technicians

In addition to any vessel crew, the number of WEC technicians is assumed to be the same for all three devices with two crews of three being required for the installation activities.

WECs allowed at base

The number of WECs allowed at the base has been calculated by considering an O&M base located at Arnish Head, south of Stornoway.

Figure 56. Arnish Head, potential O&M base location

Large Scale WEC Configurations

Details of the configurations investigated are provided in Section 6.2.2.

The 1MW Bref-SHB structural form and mass were based on design values from a leading submerged pressure differential device developer, described in [12]. This device was assumed for the grouped and individual 1MW arrays. The individual 10MW array was scaled based on this device. Energy performance and structural scaling assumptions are described in Sections 6.3 and 6.4 respectively.

Figure 57. Suggested O&M base layout

The approximate area of the O&M base available for buildings and a yard is 40,000m^2, approximately 200m by 200m. It has been assumed that 25% (10,000m^2) of this space is available to devices, leaving enough space to work around the devices and house the required equipment. The devices have been assumed to have a square or rectangular footprint for the purposes of calculations.

	Length & width/ diameter (m)	**Device area (m^2)**	**Devices allowed at base**
1MW baseline	20	400	25
10MW point absorber	40	1600	6
10MW grouped device (pontoon + floats)	230 by 30	6900	1
10MW grouped device individual floats	20 by 10	200	50

For the grouped device it has been stated in the universal inputs (see Table 51) that the O&M base can accommodate a maximum of 50 devices at a time. It has been assumed that the grouped device's truss structure would not be removed for maintenance during the life of the wave array.

Number of spare PTO units and Instrument boxes

These values are used by the simulation tool if it is determined that a fault can be fixed at the offshore site. The failure modes defined in the OPEX assessment include a minor failure where it is assumed a repair offshore is sufficient. Therefore, when running the O&M Simulation Tool, the failure action 'Replace instrument box' has been selected for this failure mode. The number of spares assumed is broadly consistent with what may be expected for offshore wind for a standard part. The lead time for the parts is consistent with relatively simple machined components that may be made at the O&M base or by a local supplier.

Cost benefit analysis

This has not been applied, as the desired outcome is a comparative assessment of the OPEX and availability for the three scenarios.

Fault Categories

Three fault categories have been defined for the scenarios. These fault categories and their inputs are detailed in Table 52.

Table 52. Fault categories consistent inputs

Fault category	Relevance	Probability of failure	Action required	Description
Major failure PTO	WEC	0.0365 (1MW & grouped device) 0.3105 (10MW device)	Retrieve WEC	Fault with PTO that requires repair onshore (for grouped device, float removal required)
Major failure Other	WEC	0.0183	Retrieve WEC	Fault with another system that requires repair onshore (for grouped device float removal required)
Minor Failure	WEC	0.35	Replace instrument box	A failure, of any system, that can be repaired offshore

The failure rates are based on those estimated for offshore wind installations. A mean time between failures (MTBF) of just under 3 years for a minor failure is defined and just over 18 years for a major failure. The major failures have been split between PTO failures and other failures, in a ratio of 2:1. This split is based on failures observed in offshore wind, with 60% to 70% of major failures attributable to the nacelle power system components (e.g. gearbox, generator etc.), and 30% to 40% of major failures attributable to other components such as the blades, structure or foundation.

Device specific inputs

The other inputs required for fault categories are specific to the device concepts and scenario assumed. These inputs are outlined in Table 53.

Table 53: Fault categories device specific inputs

1MW point absorber					
Fault category	**Power loss**	**Vessel required**	**Time required offshore (hrs)**	**Time required onshore (days)**	**Technicians required**
Major failure PTO	0.01	Multicat	3	7	6
Major failure Other	0.01	Multicat	3	7	6
Minor Failure	0	Multicat	12		6
10MW point absorber					
Fault category	**Power loss**	**Vessel required**	**Time required offshore (hrs)**	**Time required onshore (days)**	**Technicians required**
Major failure PTO	0.01	AHTS	6	14	6

Major failure Other	0.10	AHTS	6	14	6
Minor Failure	0	Multicat	12		6
10MW grouped device					
Fault category	**Power loss**	**Vessel required**	**Time required offshore (hrs)**	**Time required onshore (days)**	**Technicians required**
Major failure PTO	0.01	Multicat	2	7	6
Major failure Other	0.01	Multicat	2	7	6
Minor Failure	0	Multicat	12		6

For major faults where WEC retrieval is required, the following assumptions have been made:

- The same vessel used for installation is required for the retrieval operation;
- The removal time spent on site, is half the installation time;
- The time required onshore is assumed to be 7 days for repairs to the 1MW and grouped device, and 14 days for repairs to the 10MW device; and
- Two teams of three technicians are required to complete all the operations.

For the 1MW device and the grouped device it is assumed that a major fault affects only a single device or a single float and so the power loss is 1/100th of the total array. For the 10MW device it has been assumed that the PTO is modular and that the device is still able to produce power if one PTO module fails. For the ‘other’ major failure, it has been assumed that power output from a whole device is lost.

For the minor failures it has been assumed that the repairs can be made during a 12 hour offshore operation, with two crews of three technicians.

Routine maintenance

Two routine maintenance tasks have been defined for the scenarios. These routine maintenance tasks and inputs are detailed in Table 54.

Table 54. Routine maintenance tasks consistent inputs

Maintenance task	Relevance	Carry out every…	Time of year	Action required
Routine inspection	Array	2	Summer	Moorings work
Major service	WEC	During year 10 and 15	Spring	Retrieve WEC

The routine inspection has been set up in the model using the ‘moorings inspection’ array task. This routine inspection and preventative maintenance activity is assumed to take place every two years. This may involve floating of the device and inspecting it at the surface and subsea inspection of various components.

A major service of the WECs is assumed to take place twice throughout out the array lifetime. In order to set this up in the model, two WEC maintenance tasks are defined as ‘major components refit’ and ‘routine service’. These activities involve retrieving the WECs and taking them back to the O&M base for a full service and overhaul. The events have been scheduled at year 10 and year 15 in the model, but are more likely to take place every 7 or 8 years.

Device specific inputs

The other inputs for the routine maintenance tasks are specific to the device and scenario assumed. These are outlined in Table 55.

Table 55. Fault categories device specific inputs

	1MW point absorber				
Maintenance category	**Vessel required**	**Inspection time per device (hrs)**	**Time required offshore (hrs)**	**Time required onshore (days)**	**Technicians required**
Routine inspection	SOV	12	300	N/A	24
Major service	Multicat		3	7	6
	10MW point absorber				
Maintenance category	**Vessel required**	**Inspection time per device (hrs)**	**Time required offshore (hrs)**	**Time required onshore (days)**	**Technicians required**
Routine inspection	SOV	24	60	N/A	24
Major service	AHTS		6	14	6
	10MW grouped device				
Maintenance category	**Vessel required**	**Inspection time per device (hrs)**	**Time required offshore (hrs)**	**Time required onshore (days)**	**Technicians required**
Routine inspection	SOV	8 + 24 for truss	260	N/A	24
Major service	Multicat		2	7	6

The routine inspection of a 100MW array requires a vessel capable of supporting offshore crews for a prolonged period whilst the inspection and maintenance is carried out. Inspection activities will likely require the use of divers and/or remotely operated vehicles (ROVs) to inspect the underwater elements. As offshore wind O&M operations are moving towards more capable vessels such as Service Operations Vessels (SOVs) it is reasonable to expect that a large array of WECs could use a similar vessel. As a larger vessel is being employed then there is the opportunity to take a larger crew and execute inspection operations on several WECs concurrently.

For the purposes of calculating the time required offshore, an inspection time per device is assumed, shown in Table 55. This is assumed to be the time for a three-man crew to complete the inspection. A crew of 24 would provide 8 three-man teams, with 4 teams working at any one time. An additional benefit of using a larger vessel for a shorter time is that there is more likely to be a suitable weather window for the maintenance operations.

For the major service, the offshore durations are based on those estimated for a major failure, and the same time has been estimated for the onshore works. The major service of the 10MW device is estimated to take twice as long as for the smaller 1MW and grouped device floats. It has also been assumed that two maintenance teams can complete the tasks. The vessels required are consistent with those required for installation and removal of the device.

Appendix G: Stage III Survivability & Performance Assessment

This appendix describes a quantitative assessment conducted using a more detailed numerical model, focusing on the effect of the control on the performance and loading affecting a large scale WEC. Essentially, the investigation considers three control strategies, and high-level performance and survivability metrics were quantified in one operational and one extreme sea states, respectively.

Methodology

The F-HBA WEC, a multi-body floating device composed of 10 heaving buoys (the floats) connected to a common submerged reference structure (the truss), was used as representative model. The device was modelled in WEC-Sim [38], considering the 10MW upscaled version as described in Stage II (see section 5.1).

WEC-Sim has the ability to model devices that involve rigid bodies, PTO systems and moorings. Simulations are performed in the time-domain by solving the governing WEC equations of motion in all relevant degrees-of-freedom, in a fully coupled format (i.e. simultaneously accounting for all relevant load sources). Further details regarding WEC-Sim can be found at http://wec-sim.github.io/WEC-Sim/.

The following subsections provide a more detailed description of the different features of the WEC-Sim models for the F-HBA WEC investigated in this study.

Structural Model

The WEC structural configuration was represented in WEC-Sim as rigid bodies with mass, inertia, PTO and hydrodynamic properties. The relative position of each body was defined by the location of each body’s centre of gravity in the global reference frame. The component connectivity was defined in the constraint and PTO classes that connect the bodies to the global reference frame. The locations of the constraint and PTO were also specified in relation to the global reference frame.

A Simulink chart representing the multi-body structure implemented in WEC-Sim is illustrated in Figure 58. The F-HBA WEC was modelled as an array of ten floating bodies (the floats) each connected to a floating rigid body (the truss or truss) by a single translational freedom (heave only constraint). The moorings were modelled through a stiffness matrix constraining the truss displacements. Two additional non-hydrodynamic bodies, rigidly connected to the truss, were included to model the ballast.

The WEC dimensions (float diameter, submerged length, mass properties of the bodies) were scaled up from the NumWEC reference model and are summarised in Table 56. The main dimensions of the WEC are illustrated in Figure 59. Note that the original geometric, mass and power rating properties of the NumWEC devices are summarised in Table 3.

Table 56. Mass (tons) properties and moment of inertia (ton.m^2)

Body	Property		Value
Float	Mass (tons)		1964.7
	Moment of inertia (ton*m^2):	Ixx	348.4
		Iyy	348.4
		Izz	74.7
Truss	Mass (tons)		2520.5
	Moment of inertia (ton*m2):	Ixx	1227.6
		Iyy	3151.9
		Izz	2156.6
Ballast	Mass (tons)		1716.3
	Moment of inertia (ton*m2):	Ixx	31567.2
		Iyy	31567.2
		Izz	103.5

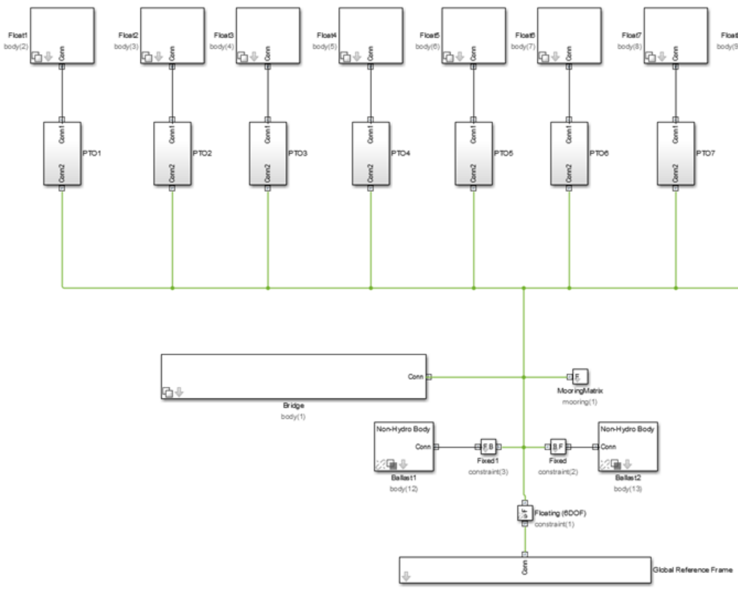


Figure 58 F-HBA WEC Simulink model schematic

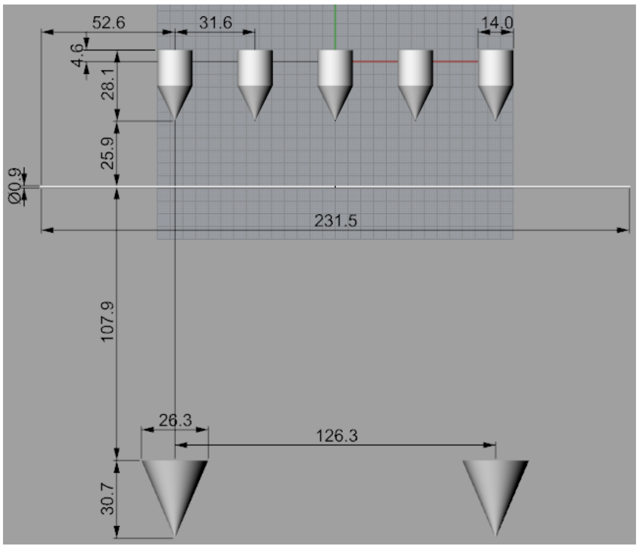


Figure 59 Main dimensions of the F-HBA WEC (in m)

Hydrodynamic Model

The hydrodynamic coefficients and the wave exciting force associated with the main floating bodies (floats and truss) were derived in NEMOH and loaded into the WEC-Sim model. The mean mesh for the wetted profile used in the NEMOH model is shown in Figure 60. The blue arrow indicates the head-on (0º) incident wave heading. The hydrodynamic interference (first order) between the multiple floats was accounted for.

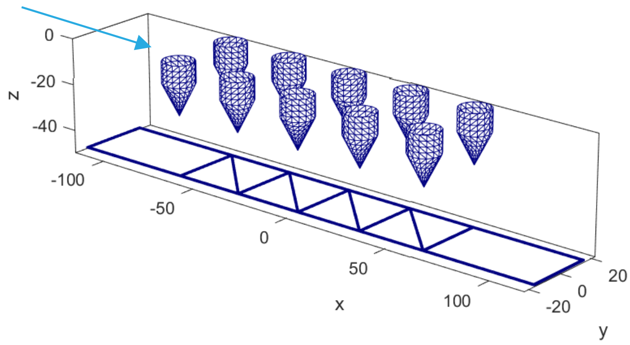


Figure 60 NEMOH mesh defined for the F-HBA WEC

Viscous Drag Force Model

In WEC-Sim, viscous damping forces can be included by using a Morison correction to account for additional force contributions.

$$F_d(t) = \frac{1}{2}\rho C_d D.u(t)|u(t)|$$

where, C_d is the dimensionless drag coefficient, D is the characteristic area of the device and u is the water velocity amplitude. Table 57 summarises the drag coefficient and characteristic area values used in the WEC-Sim model.

Table 57. Summary of the viscous drag properties used in WEC-Sim

Viscous drag properties		Value		
		x	y	z
Truss	C_d (-)	0.7	0.7	0.7
	D (m^2)	27.7	202.9	756.3
Floats	C_d (-)	0.5	0.5	0.5
	D (m^2)	231.0	231.0	153.0
Ballasts	C_d (-)	0.5	0.5	0.5
	D (m^2)	403.7	403.7	547.4

Mooring System Model

The mooring system was modelled by a stiffness matrix that limited the motion of the WEC in all degrees of freedom. The mooring properties are summarised in Table 58.

Table 58. Summary of the mooring properties used in WEC-Sim

Mooring properties	Value
Pre-tension (kN)	-27.3
Stiffness (kN/m)	3.5, 3.5, 9.7, 780, 550, 240

Power-Take-Off and Control Model Options

The F-HBA WEC is a multibody floating device composed of 10 floats connected to a common submerged reference structure (the truss). Wave power is absorbed from the relative motion between the floats and the truss, using hydraulic PTOs. Similar to the PTO system considered in the NumWEC study [2], the hydraulic PTO was modelled in WEC-Sim as a Coulomb damping force, acting in opposite direction of the relative velocity between the floats and the truss. The PTO force can be estimated by:

$$F_{PTO} = F_{mean} - \Delta F.sign(\dot{x})$$

where, ΔF is the force difference set in the hydraulic circuit and F_{mean} is the force required to hold the truss and ballasts, calculated as following:

$$F_{mean} = \left(V_{displ,floats} * \rho - M_{floats}\right) * g$$

where, $V_{displ,floats}$ is the displacement of the floats (in m^3) and M_{floats} their mass (in kg).

In order to assess the influence of the control strategy on the performance and survivability of the WEC, three different PTO models were implemented and are presented in this report (Issue A):

- In the baseline control strategy ("*Baseline*"), the force difference ΔF was set to the same value for all the floats. The force difference value was optimised such as to maximise the power output in the sea state considered (see *Simulation Setups* below)

- In the first alternative control strategy option (“*Option 1”*), the force difference ΔF was set to a different value for each row of float. The force difference values for each row were defined as a combination without repetition from five force values, namely (450, 550, 650, 750, 850)kN. The settings leading to the largest power output in the sea state considered (see *Simulation Setups* and below) were selected as the optimum.
- In the second alternative control strategy option (“*Option 2*”), a negative spring force was added to the Coulomb damping force. The force difference ΔF was set as the optimum combination from *Option 1*. Similar to the strategy for the force difference in *Option 1*, the negative spring coefficient k was set to a different value for each row of float, defined as a combination without repetition from five force values, namely (-0.5, -1, -5, -10, -15)kN/m. The settings leading to the largest power output in the sea state considered (see *Simulation Setups* and below) were selected as the optimum.

The power absorbed ($P_{abs,i}$) by the float i can be calculated as:

$$P_{abs,i} = F_{PTO,i}.v_i$$

where v_i is the velocity of the float i (in m/s) and F_{PTO} the PTO force (in N).

<u>*Wave Conditions*</u>

In a first approximation, two sea states were considered in this study as representative of operational conditions and extreme wave conditions at the EMEC site for performance and survivability assessment, respectively.

For the performance assessment, the environment conditions considered the most energetic wave at the EMEC site, i.e. the sea state contributing the most to the annual energy available at the site. Combining the scatter diagram of the site (see Figure 9) with the associated wave power flux (in W/m) in each bin, the energy transported annually by each bin can be derived, as illustrated in Figure 61 (with number marking the min/max of each cell). The peak of wave energy flux shows at H_s 3.25m and T_p 12s.

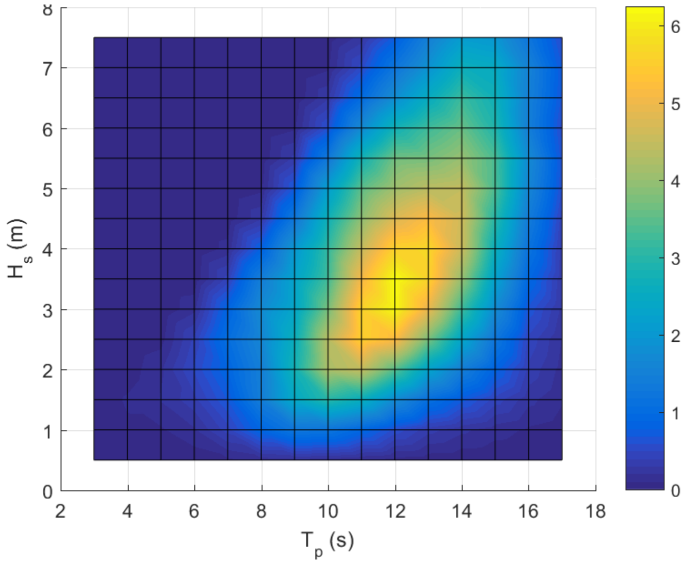


Figure 61 Scatter diagram of annual wave energy flux at the EMEC site (MWh/m)

For the survivability assessment, the environment conditions considered a 1-year return period extreme wave at the EMEC site. Figure 62 illustrates the 1-year environmental contour at the EMEC site, along with sample sea states selected on the contour.

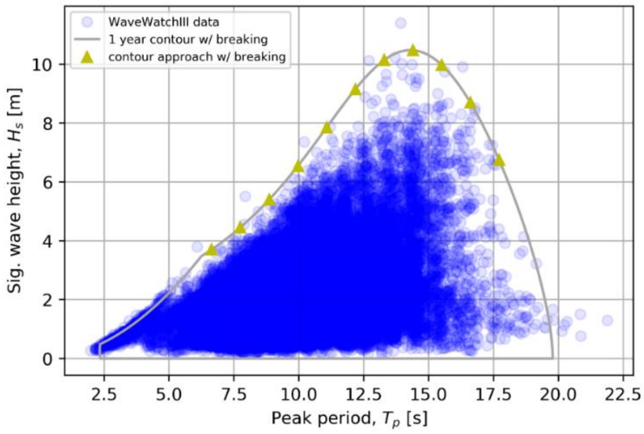


Figure 62 EMEC scatter diagram and 1-year return period environmental contour

The wave properties input in WEC-Sim, in both the performance and survivability assessment cases, are summarised in Table 59. It is noted that the wave direction also considered angled sea in the performance case with the *Baseline* control strategy in order to evaluate the impact of the wave direction on the performance. A head-on wave (0º wave direction – see Figure 60) was found to lead to the largest power output and was therefore used for the control strategy comparison and survivability simulations.

Table 59 Summary of the wave parameters used in WEC-Sim

Wave properties	Performance	Extreme
Wave class	Irregular	Irregular
Wave height (m)	3.25	9.32
Wave peak period (s)	12	12.18
Wave direction (º)	0, 45, 90	0
Wave spectrum type	JS	JS

Simulation Setups

The key input parameters required in WEC-Sim are summarised in Table 60.

Table 60 Summary of the simulation parameters used in WEC-Sim

Simulation properties	Value
WEC-Sim version	3.0
Convolution integral time (s)	150
Water density (kg/m3)	1025
Simulation length (s)	1950 (performance) 10950 (extreme)
Ramp-up time (s)	150
Simulation time step (s)	0.05
Nonlinear forces	Yes*

*Note that in PTO optimisation process the nonlinear hydrodynamic forces were not accounted for.

Metrics

Performance assessment

For the performance assessments, two key metrics were derived, namely:

- The mean power absorbed by each float (in kW);
- A ratio of the mean absorbed power to the RMS PTO force (in kW/N), as a measure of the PTO ‘reward’. This metric aims to assess how much power is converted per kN of PTO effort.

Survivability assessment

At the high-level, preliminary survivability assessment conducted in this study, the environmental conditions considered a 1-year return period extreme wave at the EMEC site. From the distribution of peaks in heave motion for each float observed during the three-hour simulation, it is possible to extrapolate the corresponding short-term extreme probability distribution.

In [39] details of the applicable short-term extreme analysis procedures are given, where the cumulative density function (CDF) of the extreme motion in heave $CDF_e(x)$ can be obtained as per the following:

$$CDF_e(x) = CDF_p(x)^q$$

where $CDF_p(x)$ is the CDF of the peaks in heave motion in the simulation considered and q the number of waves expected during the simulation time.

By extrapolation, the 50-year and 100-year return period excursion values can be estimated as the 98% and 99% quantiles of the $CDF_e(x)$ distribution, respectively. Essentially, the extreme analysis aims to assess the maximum excursions that will be faced by the floats, which can inform the design e.g. in terms of hydraulic ram stroke required for the hydraulic arrangement.

Results

The simulations were conducted in an operational sea state to optimise the PTO settings and to compare the WEC-Sim outputs with different control strategies. The results are presented, followed by the results for the survivability assessment in extreme wave conditions.

Control Strategy Optimisation

Baseline control option: Identical force difference for all PTOs

Simulations in the selected operational sea state with various force difference values were conducted, and the mean total absorbed power output was compared between all cases. Figure 63 shows the distribution of total absorbed power (in MW) with the force difference (in kN). The mean power output reaches a maximum for a force difference of $\Delta F = 650$kN, before decaying with a minimum reached at $\Delta F = 2157$kN.

The adjustment of the force difference to the sea state, using the same control strategy (i.e. identical value for all the floats), has a large impact on the WEC performance, with the mean power output varying from 738kW to 1,522kW (+106%). The importance of avoiding under- or overdamped regimes is clear from Figure 63.

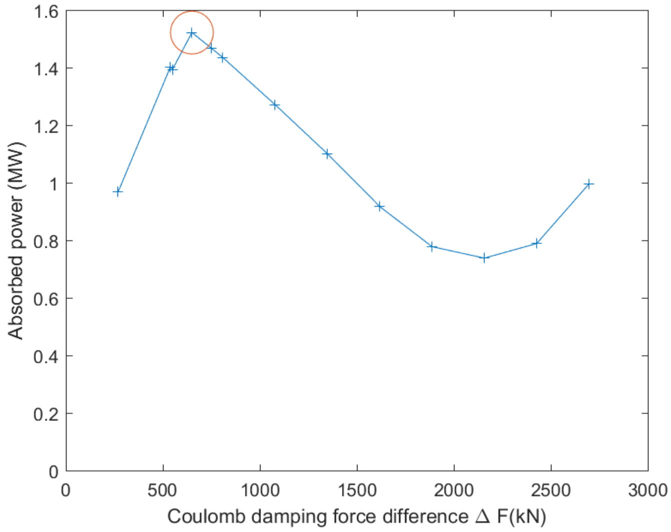


Figure 63 Distribution of total mean absorbed power (sum over the ten floats) with the Coulomb damping force difference ΔF

Additionally, an investigation on the influence of the device orientation on performance was also conducted, considering three incident wave angles (0º, 45º and 90º, where 0º represents waves propagating along the x-axis – see Figure 60). The mean total absorbed power outputs in each case are summarised in Table 61, showing a maximum at 0º. It was noted that the type of PTO damping greatly impact the results at 90º. In subsequent steps in this study, the optimum 0º angle was used for the device orientation, and the *Baseline* control strategy refers to a constant force difference of $\Delta F = 650$kN for all the PTOs of the WEC and is kept constant throughout the duration of the sea state.

Table 61 Total mean absorbed power output for each wave direction

Wave direction (degrees)	Mean absorbed power Pabs (kW)
0	1,521.9
45	1,205.3
90	389.9

Option 1: Force difference optimised per row of floats

Similar to the comparison of mean total absorbed power for various force difference values in the *Baseline* control strategy, the optimisation of the control strategy considered in *Option 1* involved the comparison of absorbed power for 120 different combinations of five force differences for the five rows of floats. Figure 64 illustrates the range of power output over the iterations considered, highlighting the maximum found for the following force difference setting: [750 650 450 550 850]kN, from the back row to the front row.

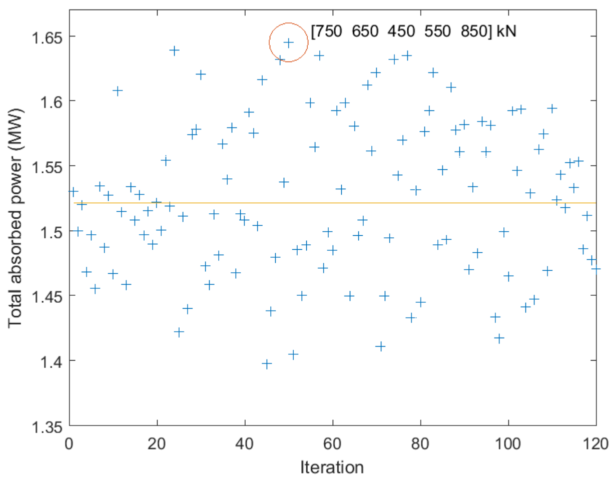


Figure 64 Variation of the total mean absorbed power (sum over the ten floats) with the optimisation iterations (blue crosses) and total mean absorbed power for the baseline control strategy (orange line)

Although the control strategy proposed with *Option 1* remains passive (i.e. not changed / optimised on a wave-by-wave basis), an improvement of 8% in power output compared to the *Baseline* option was found. Furthermore, varying the force difference settings for each row leads to a variation in WEC power performance of up to 18%, with the mean power output varying from 1.40MW for the least performing combination to 1.65MW for the maximum found.

In the rest of the study, the *Option 1* control strategy will refer to the optimum combination of force differences found, for all the PTOs of the WEC and constant throughout the sea state.

Option 2: Negative spring included and optimised per row of floats

Finally, and similar to the previous optimisation exercises, the optimisation of the control strategy considered in *Option 2* involved the comparison of absorbed power for 125 different combinations of five negative spring values (namely 0.5, 1, 5, 12 and 15kN/m) for the five rows of floats. A maximum absorbed power output of 1.65MW was found for a negative spring coefficient of -1kN/m for all the floats in the WEC. The negligible improvement when compared with *Option 1* can be directly related to the lack of active control. This suggests that to fully exploit the theoretical potential, wave-by-wave control is likely to be required.

Influence of Control on Performance

The optimisation of the PTO settings, presented in the previous subsections, highlights the impact of the damping parameters on the WEC performance.

This section describes the comparisons between the three different control strategies, set with the optimum values output from the optimisation exercises, in terms of WEC performance in the operational sea state considered.

Figure 65 displays a sample of the absorbed power and PTO force time-series output by WEC-Sim for the *Baseline* control strategy, along with the mean absorbed power and RMS PTO force calculated over the whole simulation duration (30 minutes).

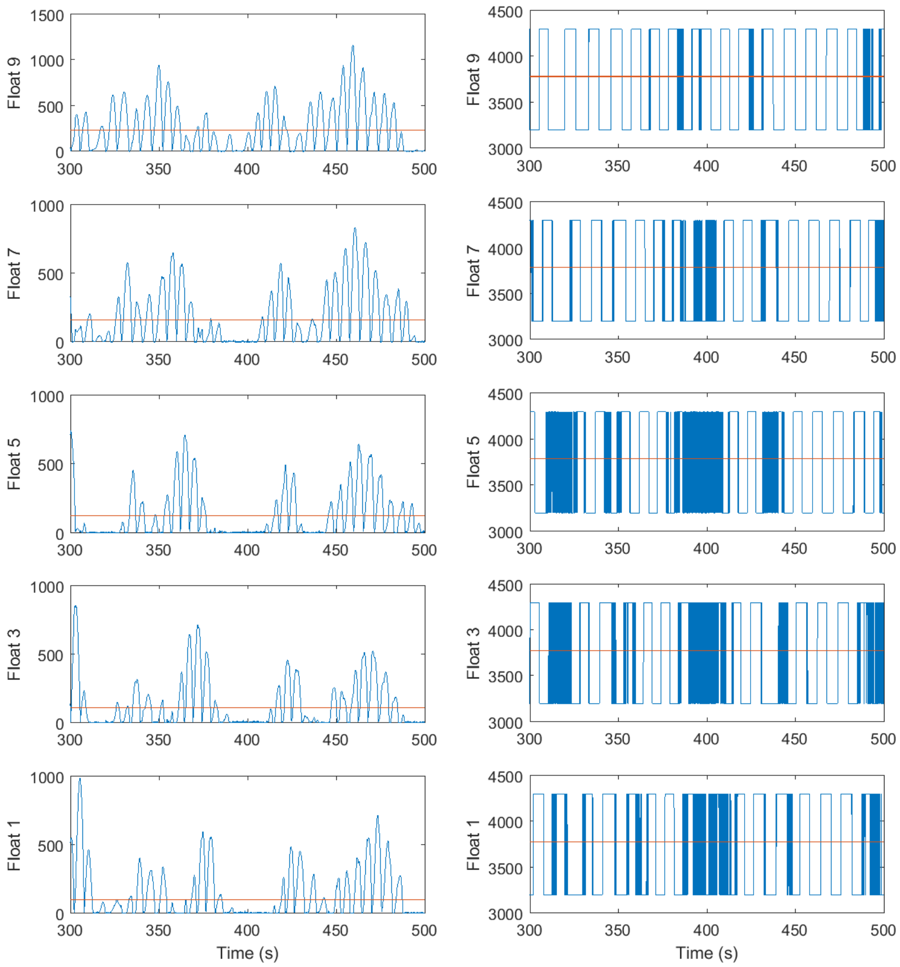


Figure 65 Sample absorbed power and PTO force outputs from WEC-Sim for each float in one row: time-series and mean absorbed power output (left); time-series and RMS PTO force output – *Baseline* control strategy case

Overall, the total power absorbed by the WEC increases by about 8% from the *Baseline* control strategy to *Option 1* and *Option 2*. Table 62 summarizes the mean absorbed powers at an individual float level, for each control strategy considered. Note that for symmetry reasons two floats in each row output the same absorbed power. The representative value for one float in each row of the WEC is presented. A significant improvement in terms of absorbed power can be seen in the front row (floats 9 and 10), with a 12% increase compared to the *Baseline* control strategy. However this increase leads to an important shadowing effect for the 2nd row, leading to a decrease in power output on that row. This finding is aligned with the outcomes of previous studies such as [40]-[41], where the variation of WEC performance in an array was investigated as a function of layout and control. The 3rd row shows a similar absorbed power output for the three control strategies. Finally, the two last rows (floats 1 to 4) present a large increase in absorbed power for *Option 1* and *Option 2* compared to the *Baseline* control strategy. Overall the global increase in power absorbed is 8%.

Table 62 Impact of control strategy (*Baseline*, *Option 1* and *Option 2*) on WEC performance: mean absorbed power per float

P_{abs}(kW)	Floats 9-10	Floats 7-8	Floats 5-6	Floats 3-4	Floats 1-2
Baseline	235.2	161.3	126.6	111.4	99.4
Option 1	262.5 *(+12%)*	119.3 *(-26%)*	123.2 *(-1%)*	162.6 *(+46%)*	133.5 *(+34%)*
Option 2	261.6 *(+11%)*	119.4 *(-26%)*	125.4 *(-1%)*	162.9 *(+46%)*	133.7 *(+35%)*

Table 63 summarises the mean absorbed power per RMS PTO force (in MW/kN) for each float and control strategy considered. Overall, the variation from the *Baseline* control strategy is similar to the variation observed in the mean absorbed power: about 10%, 45% and 33% improvement in 1st, 4th and 5th rows (floats 9-10, 3-4 and 1-2), respectively, and decrease of about 26% and 1%, respectively, in the 2nd and 3rd rows. Overall, the mean absorbed power per RMS PTO force increases by about 9%, indicating higher rewards from the PTO in this particular configuration.

It should be noted that the hydraulic PTO system represented by a Coulomb damping profile, selected in the NumWEC study based on the information from the concept developer provided in [2], presents essential characteristics that potentially limit the benefits of advanced control strategies in terms of mean absorbed power per RMS PTO force. In particular, and as can be seen in the right-hand plot in Figure 65, a Coulomb damping profile implies a quasi-binary PTO force alternating between a minimum and a maximum force value when the float's velocities change sign. The RMS PTO force presents limited variations between floats and between control strategies.

Similarly, the passive negative spring strategy evaluated in *Option 2* presents a limited capacity for improvement. It is expected that an active spring, applied at deterministic instances during the sea state, could further improve the performance.

Table 63 Impact of control strategy (*Baseline*, *Option 1* and *Option 2*) on WEC performance: ratio of mean absorbed power by RMS PTO force per float

P_{abs}/F_{PTO} MW/kN	Floats 9-10	Floats 7-8	Floats 5-6	Floats 3-4	Floats 1-2
Baseline	62.2	42.5	33.4	29.5	26.3
Option 1	68.3 *(+10%)*	31.5 *(-26%)*	33.2 *(-1%)*	42.9 *(+45%)*	35.0 *(+33%)*
Option 2	68.0 *(+9%)*	31.5 *(-26%)*	33.2 *(-0.5%)*	42.9 *(+45%)*	35.1 *(+33%)*

Overall, the cases presented in the operational conditions considered here highlight the significant impact of the PTO settings on WEC performance when optimising control.

Moreover, and noting the limitations due to the Coulomb damping profile and passive negative spring strategy, the improvement in control strategy from *Baseline* to *Option 1* and *Option 2* leads to overall increases in average power and in PTO effort reward (e.g. ratio of mean absorbed power to RMS PTO force).

Survivability Assessment

This section describes an extreme sea state case, investigating the effect of control on the extreme return values of float excursion.

Simulations in the selected extreme sea state using the different control strategies considered were conducted, and a short-term extreme analysis was applied to the float's excursion. The CDF of the peaks (in red) and of the extreme distribution (in blue) for each float are illustrated in Figure 66 for the *Baseline* (plain lines) and *Option 1* (dashed lines) control strategies. It should be noted that a Weibull distribution was fitted to the CDF of the peaks before the extrapolation to the extreme distribution. Other methods or distributions to obtain the extreme event probability function may be considered, as presented in [39].

As highlighted in the performance investigations, it was found that the Coulomb damping profile imposed on the PTO limits the impact of the control strategy on the WEC behaviour. This is particularly clear when observing the CDF distribution of the peaks, which remains fairly similar between the different control strategies investigated.

However, when considering the CDF of the extreme float excursion, significant differences are evident. E.g. Figure 67 displays the probability distribution of the extreme excursion of a front float (float 10) for both control strategies, close to the 50-year and 100-year return periods (i.e. 98% and 99% quantiles, respectively in orange and purple). A decrease of 1m (~8%) can be observed in the float excursion extreme value from the *Baseline* to *Option 1* control strategy. However, Figure 68 for a float in the second row (float 8) displays similar extreme values for both control strategies. At a high-level, these results illustrate the importance of control in non-performance, yet potentially critical, design aspects. Further work could explore more detailed metrics, potentially leading to layout specific systems or sub-systems in a grouped device context.

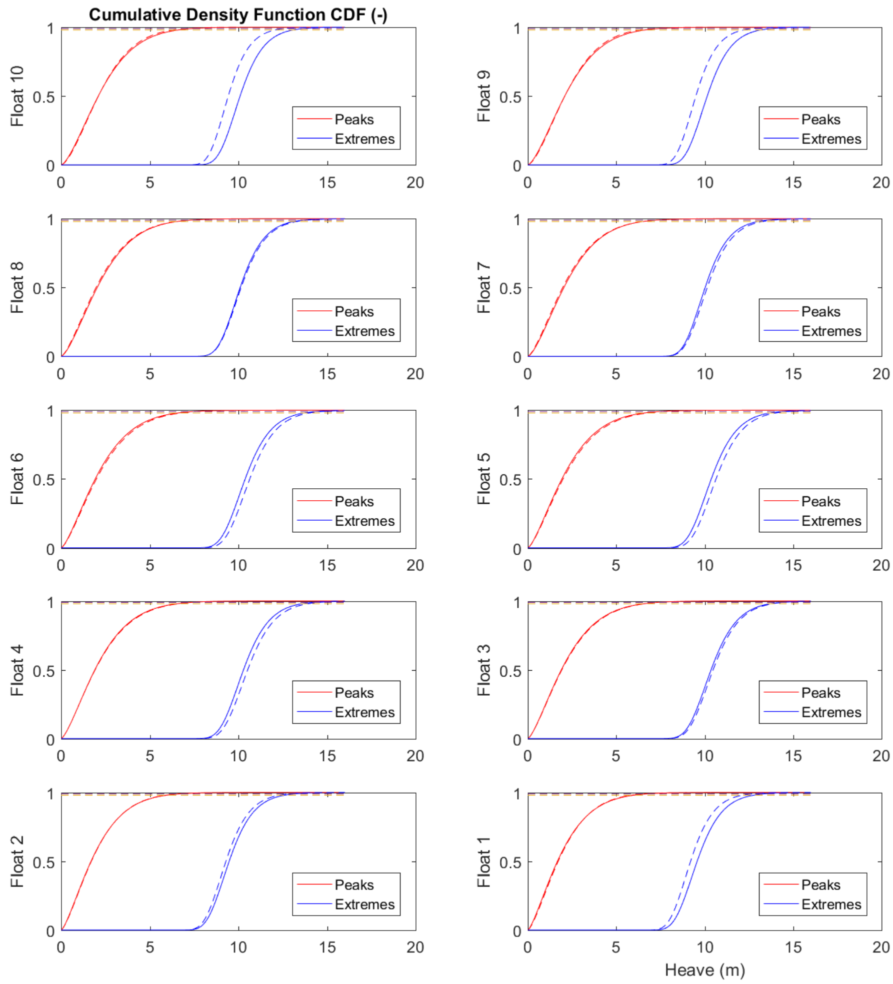


Figure 66 CDF of peaks and 1-year extreme float excursions for the *Baseline* (plain lines) and *Option 1* (dashed lines) control strategies.

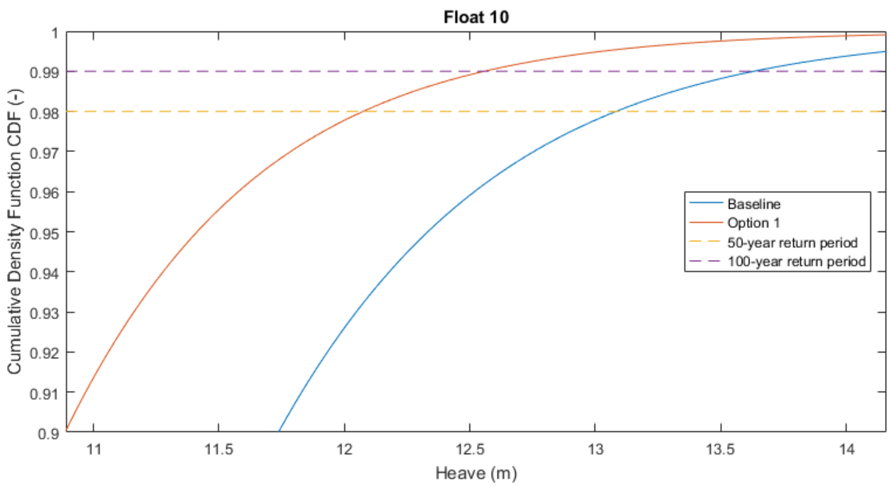


Figure 67 CDF of extreme excursion for float 10 for the *Baseline* (in blue) and *Option 1* (in red) control strategies. The orange and purple dashed lines mark the 50-year and 100-year return periods, respectively.

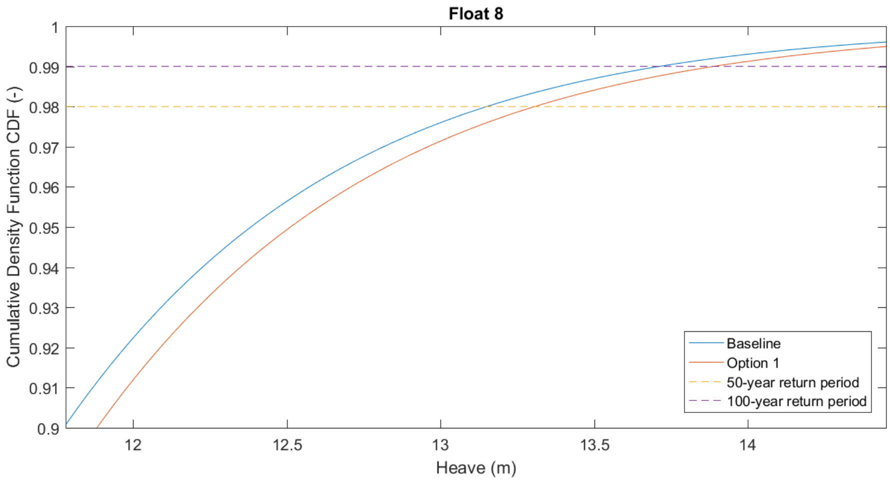


Figure 68 CDF of extreme excursion for float 8 for the *Baseline* (in blue) and *Option 1* (in red) control strategies. The orange and purple dashed lines mark the 50-year and 100-year return periods, respectively.

Conclusions

Following the high-level investigations regarding the role of size / scale and control to reduce the gap between the baseline WEC energy yield estimates and the theoretical maximum, a refinement of the opportunity assessment of upscaling was conducted, looking at both performance and survivability aspects.

This additional study focused on the effect of the control on the WEC performance and loads, quantifying high-level performance and survivability metrics in operational and extreme sea states, respectively, using the F-HBA WEC as an illustrative example.

In terms of performance, and noting the limitations mostly associated with the Coulomb damping profile, the improvement in control strategy from *Baseline* to *Option 1* or *Option 2* led to overall increases in average power and in PTO effort reward (e.g. ratio of mean absorbed power by RMS PTO force). It should be noted that *Option 1* and *Option 2* are sub-optimal strategies (passive by nature), and that further significant improvements with active, wave-by-wave control strategies can be expected.

In terms of survivability, the metrics considered the extreme excursion of each float. The study compared the variation in extreme value associated with the change in control strategy from *Baseline* to *Option 1*. Noticeably, the change in control strategy lead to variation of up to 8% in extreme excursion for the front floats. The results presented should be seen as an illustration of the potential impact of the control methodology for design in survival conditions, rather than a representative quantification of the WEC survivability.

To enable further conclusions to be drawn, future work could consider additional control strategies (see e.g. [42]), and also extend the investigations to a long-term extreme response. Such additional level of detail, more related to the transition between concept and detailed design, is intrinsically dependent on more a detailed definition of the WEC(s), and may in turn impact e.g. the design of the prime mover itself and / or the key supporting structures.