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CONSULTING ENGINEERS

RePOWER – Reinforced Polymers for Wave Energy

WES Structural Materials and Manufacturing Processes Stage 1 Public Report

Cruz Atcheson Consulting Engineers

This project has been supported by Wave Energy Scotland

1. Project Introduction

Wave Energy Scotland (WES) has commissioned the RePOWER (Reinforced Polymers for Wave Energy) project to Cruz Atcheson Consulting Engineers (CA). The RePOWER project aims to assess the use of reinforced polymers in the prime mover of point absorber wave energy converters (WECs).

The project brings together leading WEC developers (CorPower Ocean AB and Carnegie Clean Energy Ltd.), an independent engineering design team (CA, Arup Consulting Engineers and DNV GL) and materials & manufacturing experts (National Composites Centre, NCC), to complete a preliminary front-end engineering design (FEED) study that can assess the technical and economic viability of using reinforced polymers as a key structural material in WEC design.

A de-risking approach has been followed by the RePOWER consortium, defining and reducing uncertainties in the integration of reinforced polymers in the WEC design process. A detailed design methodology for load and structural analysis of WECs (following the WES Structural Forces and Stresses Landscaping Study) was implemented to analyse the use of reinforced polymers in WEC prime movers. Design iterations have been considered to refine the structural design and minimise the potential for significant over-design of the structure. This global design approach ensures a full investigation of the material in a representative WEC environment and was key in assessing material structural performance and device survivability. A cost model encompassing all the variables of the LCOE has been developed, leading to a definitive assessment of the material readiness and attractiveness while addressing step changes in CAPEX, OPEX and AEP.

A vast amount of key design / analytical questions have been addressed in one single project – with the potential to influence multiple Stage 2 / 3 projects.

2. Description of Project Technology

Unlike metallic materials, composites are more than a material: they are part of a design process. The type of polymer, the orientation of the reinforcement fibres and the fibre lay-up sequence are, among others, key design variables. Reinforced polymers are a composite design solution usually using fibres (e.g. glass or carbon) as the reinforcement and polymers (e.g. epoxy or polyester) as the matrix. The benefits of a high specific strength material that reinforced polymers provide are used in light weight constructions and have been demonstrated in applications such as wind turbine blades, pressure vessels and across the aerospace industry.

There is an intrinsic link between the material and manufacturing processes for the given environmental challenge, and for any given fibre / matrix combination there are a number of manufacturing processes that will provide different outcomes for product driven solutions. For offshore engineering applications, specific designs must take into account the manufacturing process, the use of materials with certified (or certifiable) specifications and the compatibility with the marine environment. In line with the R&D nature of a Stage 1 project, manufacturing options were investigated by the consortium from inception (design basis phase), noting that the WEC prime mover designs under consideration may, due to their own characteristics (e.g. symmetry), be more suited for specific manufacturing processes.

A summary of the anticipated advantages of composite materials and manufacturing processes and the relationship with key WES metrics is summarised in Table 1.

Table 1 Overview of the potential for composite materials to facilitate long-term LCOE targets

Metric	Description
Affordability	The Stage 1 RePOWER LCOE assessment shows that a reduction pathway towards £150/MWh is realistically achievable. A key opportunity offered by composite materials is the potential to extend the life of the prime mover structure. FRP composite prime mover estimates are similar or less expensive than current prime mover structures. Further reductions are envisaged in future stages of the project following detailed design considerations (e.g. reduction of material usage due to targeted reinforcement and optimisation of manufacturing processes). The impact in larger prime mover structures may also be assessed in subsequent stages of the RePOWER project.
Survivability	As a suitable representation of Scottish wave conditions, a characterisation of the long-term metocean conditions at the European Marine Energy Centre (EMEC) site was completed to define a metocean design basis. Fully coupled point and distributed load models were used to assess the loads, focusing primarily on ULS. The resulting loads were mapped in structural models prior to the structural assessment. Finally, finite element modelling was conducted allowing structural sizing of prime mover design options for both WEC devices (i.e. different material types and sectional configurations). The structural designs proposed for each WEC in Stage 1 of the RePOWER project passed the design strength checks. The results indicate that FRP sections using E-Glass/Vinylester are feasible for the proposed CETO 6 design and that FRP sections using E-Glass/Polyester are feasible for the proposed CorPower design.
Availability	Stage 1 RePOWER results have demonstrated that improvements in availability can be achieved via lower direct O&M costs, when the MTBF for minor prime mover maintenance events is increased. This finding provides one example of the potential of a composite prime mover to positively impact both the availability and the OPEX of a WEC farm, and consequently the overall affordability of a project.
Performance	MAEP estimates for each WEC were calculated considering net electrical power outputs and WEC availability (from the O&M modelling exercise). An uncertainty assessment considering potential performance enhancements (via e.g. the implementation of advanced controls) was considered in the calculation of the affordability metrics. The results demonstrate that increasing yield can have a significant impact on reducing the LCOE. Potential methods of improving the MAEP include the implementation of control strategies and/or improvements to the power conversion chain (PCC) efficiencies. Overall, a cross-cutting benefit of using composites in the prime mover helps to enhance performance (MAEP) by increasing WEC availability and the use of a lighter prime mover structure may be beneficial when implementing control.
Manufacturability	A material and manufacturing down-selection exercise was conducted by the NCC to identify the most suitable materials and manufacturing processes. Key material requirements defined in the down-selection processes include: costs, resistance to the marine conditions, structural weight, strength and durability. Vacuum infusion and filament winding processes were identified by the NCC as potential methods of manufacturing for RePOWER prime mover designs. These manufacturing methods offer the following key advantages: • Scalability • Repeatability • Manufacturing and supply chain readiness in Europe

3. *Scope of Work*

The RePOWER Stage 1 project was organised in six work packages. A front-end engineering design (FEED) report (D17, [1]) gathers all the Stage 1 findings. An overview of the tasks conducted in each work package and the associated key findings are presented in this section.

WP1 - DESIGN BASIS DEFINITION

An updated WEC design basis was developed in WP1 in close collaboration with all the project participants, namely the technology developers (Carnegie Clean Energy, CorPower Ocean), the independent engineering design team (CA, Arup, DNV GL) and the material and manufacturing specialists (NCC).

A brief overview of the Stage 1 design basis related deliverables is provided below.

- Design Basis Workshop Minutes (D01 [2]): A Design Basis Workshop involving all RePOWER participants was held at the project kick-off to allow project participants to jointly define key design basis features.
- Updated Design Basis Report (D02 [3]): Following the completion of the Design Basis Workshop (D01 [2]), an updated design basis was documented to allow its use throughout the project. The focus of the design basis is the prime mover WEC structure, to be constructed from the priority material(s).
- DLC Definition and Prioritisation Report (D03 [4]): Following the completion of the updated design basis (D02 [3]), a justification for the definition of appropriate design load cases (DLCs) was documented in D03 [4], including the environmental conditions and the design situations associated with each DLC. A guide to the calculation effort(s) to be conducted in RePOWER's WP2 was also provided, along with detailed recommendations regarding the environmental conditions, power take-off (PTO) settings, the type of analysis and the partial safety factors that apply to each proposed DLC.

Summary of the Key Features of WP1

- The general characteristics of two point absorber WECs were defined (CETO 6 WEC by Carnegie Clean Energy and CorPower WEC by CorPower Ocean). Emphasis was placed in the characterisation of the respective main structures, i.e. the prime movers.
- A site representative of Scottish conditions was identified and characterised (location close to EMEC). Thirty years of data from the National Oceanic and Atmospheric Administration's (NOAA) NCEP CFSR hindcasts was processed to create a site specific metocean design basis.
- A shortlist of priority DLCs was discussed and ranked, leading to the identification of the design situations to target in Stage 1 to quantify key loading and structural aspects.
- Along with addressing material/device specific questions, RePOWER Stage 1 also allowed the conceptualisation and initial assessment of key questions with potential industry-wide effects, namely:
    - The applicability of existing codes / recommended practices, and the necessity for suitable adaptions to be formulated (with a focus on load and structural assessment).
    - The influence that post-processing methods may have to derive long-term load estimates / characteristic values, and the need to quantify such uncertainty.

WP2 - STRUCTURAL LOAD AND STRESS ANALYSIS

The RePOWER Stage 1 load and stress analysis exercises were led by CA and Arup, with CA focusing on the load assessment and Arup leading the structural assessment of the proposed prime mover designs. CorPower have also provided load inputs for the CorPower WEC, obtained via CorPower's in-house loads model.

A brief overview of the Stage 1 structural load and stress analysis deliverables is provided below.

- Priority Load and Stress Analysis Report (D05 [5]): Following the completion of the updated design basis in D02 [1] and the definition / prioritisation of the most relevant design load cases (DLCs) in D03 [2], D05 presents the methods and initial results from the priority load and stress calculations. D05 also presents a comparison between carbon/epoxy and glass/polyester material options for the proposed prime mover designs.
- Additional Load Analysis Report (D11a [6]): Building on the high-level performance assessment (WEC and material) documented in D06 [1] and following the completion of the high-level levelised cost of energy (LCOE) analysis documented in D07 [2], D11a presents the results from additional load calculations based on a range of supplementary DLCs and relevant load effects (e.g. global bending moments, characteristic tether forces).
- Additional Stress Analysis Report (D11b [7]): This Arup report provides additional structural design calculations based on the loads presented in D11a [6]. A detailed assessment of the impact of the expected loads on the prime mover, including the ability to withstand high-loading events (e.g. slap and slam), is conducted.

Summary of Key Features of WP2

- At a conceptual level (Stage 1), FRP sections using E-Glass/Vinylester are feasible for the proposed CETO 6 prime mover structure, and that FRP sections using E-Glass/Polyester are feasible for the proposed CorPower prime mover structure.
- Manufacturing the prime mover from reinforced polymers can address several key survivability metrics. The inherent ability to reinforce a structural design to a given strength target, in particular in features subject to stress concentrations ('*hot spots*'), is particular attractive in WEC design.
- Early engagement with a classification society (DNV GL) has ensured that a rigorous design approach was followed throughout. Multiple risks were continuously monitored and documented in RePOWER's risk register, to ensure continuity in the risk reduction process throughout subsequent stages of the RePOWER project.
- RePOWER Stage 1 also allowed the conceptualisation and initial assessment of key questions with potential industry-wide effects. For example, Stage 1 identified the need to assess in greater detail the influence that post-processing methods may have to derive long-term load estimates / characteristic values. Quantifying such uncertainties – both from the load and the strength / resistance perspectives – can be considered as suitable next steps.

WP3 - PERFORMANCE AND MATERIAL ASSESSMENT: KEY METRICS

Alongside the main load and stress analysis activities, WEC performance and material assessments were also completed in Stage 1 of the RePOWER project. A key aim of the such assessments was to estimate the WEC power performance at the target site, and examine, at a high-level, key metrics related to e.g. WEC survivability that may affect the practical limits for composite material utilisation in the prime mover(s).

A brief overview of the Stage 1 performance and material assessment deliverables is provided in:

- High-Level Performance Assessment (WEC and Material) (D06 [8]): A first assessment of key metrics related to the performance and loading affecting the WECs is presented in Section 4 of D06 [8]. The metrics were derived using data produced from the numerical model exercises described in D05 [5].
- Detailed WEC Performance Report (D12 [9]): The performance assessment is refined and expanded at the detailed assessment stage, as detailed in D12 [9]. In the detailed assessment, key WEC performance metrics (e.g. conversion efficiency) and the impact of a number of critical parameters (e.g. control) on WEC performance were investigated.

Throughout the performance assessments an effort has been made to recognise the uncertainties associated with the estimates made; however, it is recognised that subsequent stages of the RePOWER project should address the confirmation / validation of critical aspects via e.g. physical testing as presented in D17 [1]. An initial loads verification / validation exercise was conducted in D11a [6], with a comparison between WEC-Sim, OpenFOAM and experimental results. It should also be noted that all of the estimates presented should only be interpreted within the context of the Stage 1 RePOWER project.

Summary of Key Features of WP3

- Mean Annual Energy Production (MAEP) estimates for each WEC were calculated considering net electrical power outputs and WEC availability (from the O&M modelling exercise).
- The factor that has the potential to have a dominant impact on WEC performance is the implementation of an advanced control strategy. Connection to other WES programmes would be encouraged in subsequent stages of the RePOWER project, to ensure a holistic design approach.
- To allow the physical characterisation of the material response in subsequent stages, a detailed understanding of the loading affecting the prime mover is of paramount importance. Key load metrics assess in Stage 1 include:
  - Damage Equivalent Loads (DELs), suitable for fatigue analysis.
  - Survival functions, suitable for more detailed survivability assessments.

WP4 - MATERIAL AND MANUFACTURING ASSESSMENT

The National Composite Centre (NCC) led the material and manufacturing processes selection in the Stage 1 RePOWER project.

The two Stage 1 RePOWER deliverables led by the NCC were D13 [11] and D09 [10]. These respectively addressed:

- Material Limits Report (D13 [11]): In this report, the basic characteristics and properties of the remaining materials, as well as their most important limits, were presented. These limits will be critical in selecting a material from which to build the prime mover. Material selection was supported by a traffic light system, which indicates in clear visual form which materials could potentially be used to build the prime mover.

- Manufacturing Methodologies Review Report (D09 [10]): This report includes an overview of the manufacturing technologies for composite materials production. It provides information on the NCC's methodology for selection of the appropriate production method and information about the selection process of the appropriate production method for two different types of structures. The report concludes with the detailed description of the selected method of production and analysis of the costs of production that are associated with it.

Summary of Key Features of WP4

- The material option recommended by the NCC for the prime mover of both WECs is an E-Glass/Vinylester FRP, with industry standard protective coatings, due to its superior environmental resistance and fatigue performance qualities.
- Vacuum infusion and filament winding processes were identified by the NCC as potential methods of manufacturing for RePOWER prime mover designs [21]. These manufacturing methods offer the following key advantages:
    - Scalability
    - Repeatability
    - Manufacturing and supply chain readiness in Europe
- In coordination with WP6 (Risk Register and Testing Plan), the activities of WP4 have highlighted the necessity of conducting material characterisation testing in composite applications. The level of testing and the most appropriate priorities are discussed in detail in D17 [1].

WP5 - LCOE ASSESSMENT

The LCOE assessment for the target WEC designs was led by CA, with inputs from WEC developers and the NCC. A high-level LCOE assessment was conducted for designs that passed the high-level structural checks in D06 [8]. Following the high-level assessment, a critical review of the inputs and assumptions that feed into the LCOE estimates was completed in D10 [13]. Finally, an updated LCOE assessment for designs that passed the detailed performance assessment stage, and that take into account recommendations from D10 [13], was completed and presented in D14 [14].

A brief overview of the Stage 1 LCOE assessment deliverables is provided below.

- High-level LCOE Assessment (D07 [12]): This report presents the results of the high-level LCOE assessment including the presentation of CAPEX, OPEX and LCOE estimates.
- CAPEX and OPEX Assumptions Report (D10 [13]): A critical review of the main assumptions and inputs used in the high-level LCOE assessment is presented in this report.
- Long-term LCOE Reduction Potential Report (D14 [14]): Following the completion of the additional load and stress analysis (D11 [6], [7]), and the detailed performance assessment (D12 [9]), D14 presents the updated LCOE assessment, building on the work completed in D07 [12] and D10 [13]. A detailed assessment of the potential impact(s) of material usage on the WES metrics was also investigated.

Summary of the Key Features of WP5

- Through a combination of factors, the LCOE results demonstrate that a pathway towards the WES target of a LCOE below £150/MWh is achievable.
- A key finding of the high-level LCOE assessment (D07) was that the current prime mover CAPEX for point absorber type WECs equates to approximately 10% of the WEC CAPEX. This was verified independently both WEC developers involved in RePOWER Stage 1.
- Based on the LCOE assessment findings, a key objective of the Stage 1 updated assessment was to investigate ways that composites can amplify the coupled benefits in cost reductions across all key subsystems.
- The following list provides examples of areas identified in Stage 1 where potential improvements in affordability may be achieved:
    - The opportunity to extend the life of the prime mover structure. The LCOE assessment demonstrated that extending the life of a farm to e.g. 40-year improves affordability by lowering the LCOE and increasing the IRR of a project.
    - Reduced maintainability requirements for a composite prime mover, which can lead to improved WEC availability and lower O&M costs.
    - O&M results show that cost benefits may be achieved through the deployment of optimised farms (depending on the number of WECs considered for installation), via a more efficient use of O&M resources.

WP6 - RISK ASSESSMENT AND STAGE 2 TESTING PLAN

DNV GL was contracted by CA to provide third-party support across all RePOWER Stage 1 work packages (WPs), in topics related to Risk Assessment and Technology Qualification, as defined in DNV-RP-A203 and DNV-OSS-312.

The three deliverables led by the DNV GL were D04 [15], D15 [16] and D16 [17]. These are briefly described below.

- Technology Assessment Brief (D04 [15]): This report presents the findings from the technology assessment carried out by DNV GL at an early stage of the RePOWER project. The document addresses the degree of novelty of the material and the applicable standards that are suitable to be used, as well considerations of the associated risks. It reports on the work providing the foundation for Stage 1 regarding identification and control of risk and the basis for strength assessments.
- Technical Risk Register (D15 [16]): This document records the risks and challenges associated with the forward development programme for material use and on the reference structures, identifying positive features and difficulties / challenges to be overcome prior to technology adoption, together with recommendations.
- Qualification Plan and Stage 2 Testing Plan (D16 [17]): This report forms the basis of the planning and costing for the next phase of technology development, with an immediate focus on Stage 2. In particular, a test plan for representative testing during Stage 2.

Summary of the Key Features of WP6

- One key reference – DNV-OS-C501 *Composite Components* - can be used a guidance document throughout all stages of the RePOWER project, and assist in the material characterisation process.
- A technical risk register was setup and maintained by DNV GL, with contributions from all RePOWER participants throughout Stage 1.
- In DNV GL's opinion, the Stage 1 results are indicative that the objectives of the RePOWER project are achievable. However, the results are not sufficient to reduce the risks levels initially identified in a demonstrably and comprehensive way, mostly due to the lack of physical testing (which is envisaged for e.g. Stage 2).
- However, it is important to highlight that in DNV GL's opinion the Stage 1 assessments were carried out with careful considerations on parameters used and that safety factor associated with a large coefficients of variation (COVs) were considered.
- Proposed activities for Stage 2 include:
  - Confirmation of material properties through the testing plan proposed in D16 [17] and structural design of critical regions.
  - Expansion of the DLCs to include other accidental, extreme loads (including local design) and a fatigue assessment.
  - Refinement / confirmation of the methodology used for loading derivation, with potential implications in the creation of a dedicated technical guidance note for WEC structural design.

4. Project Achievements

A detailed assessment of the impact on WES metrics of the material usage in the prime mover has been completed in Stage 1 of the RePOWER project, with particular attention given to affordability, survivability, and the related impacts on availability and performance (see Section 2). The results indicate that composite materials have the potential to facilitate the long-term LCOE reductions, through a combination of cost reductions and additional cross-cutting benefits (e.g. life extension of the prime mover structure) that positively impact the LCOE.

A summary of the key findings from the Stage 1 RePOWER project is provided below.

Composite materials offer the potential to extend the life of the prime mover

a. The prime mover can be seen as the 'primary driver' for life extension – in the majority of WECs, it is likely that at least one key-subsystem will be encapsulated / protected by the prime mover.

b. Should the prime mover fail, the integrity of the WEC and of its sub-system(s) may therefore be seriously compromised.

c. The inherent flexibility of the material, the relatively low contribution to overall WEC CAPEX, and the Stage 1 findings offer the potential to address structural *hot-spots* (e.g. joints, interfaces) in more detail in Stage 2.

d. At a conceptual level (Stage 1), FRP sections using E-Glass/Vinylester are feasible for the proposed CETO 6 prime mover structure, and that FRP sections using E-Glass/Polyester are feasible for the proposed CorPower prime mover structure.
   - The material option recommended by the NCC for the prime mover of both WECs is an E-Glass/Vinylester FRP, with industry standard protective coatings, due to its superior environmental resistance and fatigue performance qualities.

In addition to addressing material specific questions, RePOWER has the potential to tackle industry-wide generic questions, namely:

a. Early engagement with a classification society (DNV GL) has ensured that a rigorous design approach was followed throughout. Multiple risks were continuously monitored and documented in RePOWER's risk register, to ensure continuity in the risk reduction process throughout subsequent stages of the RePOWER project.
   - The early engagement with a classification society allows guidance towards the estimation of long-term extreme loading to be issued – extending existing guidance.

b. Along with addressing material/device specific questions, RePOWER Stage 1 also allowed the conceptualisation and initial assessment of key questions with potential industry-wide effects, namely:
   - The applicability of existing codes / recommended practices, and the necessity for suitable adaptions to be formulated (with a focus on load and structural assessment).
   - The influence that post-processing methods may have to derive long-term load estimates / characteristic values, and the need to quantify such uncertainty.

c. A comprehensive LCOE model, which accounts for multiple sources of uncertainty, was applied in Stage 1 leading to P10, P50 and P90 figures of LCOE. As further options are explored in RePOWER, these sources of uncertainty should be revised and updated, addressing relevant commercial roll-out scenarios.

d. The RePOWER Stage 1 project uses developer examples as case studies but aims to be applicable to wide range of scenarios – for example, the realisation in Stage 1 of the low percentage of prime mover CAPEX for point absorbers warrants a revision of the potential for composites to affect the prime movers of other WEC types.

5. Applicability to WEC Device Types

The leading WEC developers chosen for the Stage 1 RePOWER consortium were CorPower Ocean AB and Carnegie Clean Energy Ltd. These developers provide a unique range of experiences of implementing innovative practices to WEC applications. The technologies being developed are of the point absorber WEC type and are at a medium to advanced technology readiness level (TRL).

At a conceptual level (Stage 1), FRP sections using E-Glass/Vinylester are feasible for the proposed CETO 6 prime mover structure, and that FRP sections using E-Glass/Polyester are feasible for the proposed CorPower prime mover structure.

The application of composite materials and manufacturing processes to other WEC types is also conceivable and may be further investigated in future stages of the RePOWER project.

6. Communications and Publicity Activity

Dissemination activities in Stage 1 of the RePOWER project focuses around WES events. In future stages of the RePOWER project, it is envisaged that wider dissemination of RePOWER activities will be made through participation in conferences and journal article publications.

7. Recommendations for Further Work

Following the completion of the Stage 1 FEED report, the proposed next steps in the RePOWER project include:

Risk Reduction

- The final Stage 1 technical risk register records the risks and challenges associated with the forward development programme for material use on the reference structures, identifying opportunities and challenges to be overcome in future stages of the project.

- Technical risks that are classified in the range of 'medium' to 'very high' have been identified in the risk register and methods of mitigating these risks are proposed in the Stage 2 testing plan.

Physical Testing

- Stage 2 of the RePOWER project will focus on risk reduction testing to demonstrate the Stage 1 findings and further investigate proposed hypothesis (e.g. life extension), to assess the cross-cutting potential of composite materials to reduce the LCOE. Potential Stage 2 tests and activities include:
  - Material characterisation.
  - Verification / Validation of the slap / slam empirical correction.
  - Validation of ULS metrics.
  - Test high risk areas in representative conditions under representative loading.
  - Links to structural health monitoring planning.

Additional Design Load Cases

- In Stage 1 a limited number of DLCs were shortlisted, focussing on design situations that are likely to affect the design of the WEC prime movers. The shortlisted DLCs were ranked to identify the priority cases for the initial, high-level load and stress assessment. In future stages of RePOWER additional DLCs should also be considered, e.g.:
  - Transport, installation, maintenance and repair, accidental / abnormal events, and damaged stability design situations.
  - In RePOWER Stage 1, DLCs were prioritised from a ULS and FLS perspective. However, it is acknowledged that accidental limit state (ALS) related events should be addressed in subsequent, detailed design stages, to consider e.g. prime mover compartmentation in damaged stability scenarios when transitioning from a ship impact situation (DLC 9.1) to a damaged stability scenario (DLC 10.6).

Design Methodologies

- Future stages of the RePOWER project will aim to extend existing guidance on design methodologies for estimating the loads on a WEC structure, namely:
  - No specific guidance exists on key aspects of the post-processing applied to calculate the ULS. The early engagement with a classification society allows guidance towards the estimation of

long-term extreme loading to be issued – extending existing guidance. A technical note in this regard is expected to be generated in Stage 2.

  - Detailed fatigue assessments, for example, additional conclusions may be drawn when assessing the evolution of DELs for increasing reference periods. The implications on cumulative damage may be assessed at a detailed design stage, as composites material may have the potential for extended life.

Detailed Design Considerations

- Future stages of the RePOWER project will consider more detailed structural design aspects, including e.g.:
  - Increase in the structural detailing with due consideration of joints and interfaces, for example composite to composite connections (e.g. those present on stiffened sandwich panels which may be generally relevant to all types of WECs).
  - Consideration of additional effects in the structural checks, e.g. swelling due to moisture uptake; creep due to sustained loading; fatigue and reliability.
  - Global design optimisation to lower CAPEX.
  - Detailed nonlinear modelling to enable design of connections and reduce the requirement for testing.
  - Confirmation of the reliability of the material offshore to enable LCOE reduction.

Advanced Numerical Model Developments

- For the majority of the Carnegie CETO 6 WEC analysis (and DLC 1.4 for the CorPower WEC), a modified version of WEC-Sim was used for the priority load assessment. Using the nonlinear Froude-Krylov and nonlinear hydrostatics options available in WEC-Sim, and while adding the slap and slam contributions, distributed pressures across the WEC prime mover were estimated while considering the instantaneous wetted profile (noting that the equivalent linear quantities are estimated for a mean wetted profile). Previous CA code developments also allow the capability to account for the distributed diffracted pressure, contributing to an assessment of all the main linear and (weakly) nonlinear wave-induced load sources. Initial verification checks were also completed for specific DLCs using a RANSE solver. Future stages of the RePOWER project may consider:
  - Increasing the complexity of the numerical models used in the load assessment exercise.
  - Examine the effects of the fidelity of the underlying loads model and the potential of using global models at a high-level to identify areas of high local loading, which may allow the assessment of a wide range of DLCs from an early design stage. The influence(s) of additional parameters e.g. specific flow solver options, simulation length, etc. may be assessed in later stages of the RePOWER project via targeted verification and validation activities, with potential wide implications for the wave energy industry.

Detailed Assessment of Commercial Impacts

- Future work should address both technical / design and commercial scenarios. For example, future stages of the RePOWER project may consider:
  - Extended life assumptions carry implications for other key sub-systems. A closer connection to all WES programmes (e.g. PTO, Controls, etc.) is therefore recommended at the later stages, to ensure that realistic target reliability metrics can be derived across all key constituents of a WEC.
  - Further LCOE target scenarios should be considered – rather than a £150/MWh target, parity with offshore wind and nuclear could be considered (and the resulting assumptions to reach

such scenario detailed). Based on the Stage 1 findings, learning rates and life extension assumptions are expected to have a key role – thus warranting further investigations.

- The assessment of the impacts of the application of composite materials and manufacturing processes to other WEC types, namely those that rely on a wider use of structure material (when compared to point absorbers).
- Develop a robust manufacturing process for the material which can be implemented. Engage with the supply chain to identify potential manufacturing partners to ensure the supply chain readiness for a proposed prime mover design.
- Develop a technical roadmap which outlines the steps necessary to advance the material towards a commercial product, and which consider how the long-term technical challenges associated with material implementation can be addressed.

8. Useful References and Additional Data

[1] RePOWER's D17 Front End Engineering Design (FEED) Report. (05/02/18). Confidential.

[2] RePOWER's D01 Design Basis Workshop Minutes. CA Memo 1042-M-03-B (24/02/17). Confidential.

[3] RePOWER's D02 Updated Design Basis. CA Report 1042-R-01-A (10/03/17). Confidential.

[4] RePOWER's D03 DLC Definition and Prioritisation. CA Report 1042-R-02-B (21/04/17). Confidential.

[5] RePOWER's D05 Priority Load and Stress Analysis Report. CA Report 1042-R-03-A (15/05/17). Confidential.

[6] RePOWER's D11a Additional Loads Analysis Report. CA Report (04/10/17). Confidential.

[7] RePOWER's D11b Additional Stress Analysis Report. Arup Report (04/10/17). Confidential.

[8] RePOWER's D06 High-Level Performance Assessment Report (WEC and Material). CA Report (09/06/17). Confidential.

[9] RePOWER's D12 Detailed WEC Performance Report. CA Report (04/10/17). Confidential.

[10] RePOWER's D09 Manufacturing Methodologies Review Report. NCC Report NCC-TEC-1559 rev 0.1, dated 07/09/17. Confidential.

[11] RePOWER's D13 Materials Limits Report. NCC Report NCC-TEC-1559 rev 1, dated 15/11/17. Confidential.

[12] RePOWER's D07 High-Level LCOE Assessment Report. CA Report 1042-R-05-A (17/07/17). Confidential.

[13] RePOWER's D10 CAPEX and OPEX Assumptions Report. CA Report (15/09/17). Confidential.

[14] RePOWER's D14 Long-Term LCOE Reduction Potential Report. CA Report (05/01/18). Confidential.

[15] RePOWER's D04 Technology Assessment Brief. DNV GL Report PP176448-ERIGB316-01 DRR, Rev. 1, dated 20/04/17. Confidential.

[16] RePOWER's D15 Technical Risk Register. DNV GL Report (05/02/18). Confidential.

[17] RePOWER's D16 Qualification Plan and Stage 2 Testing Plan. DNV GL Report (05/02/18). Confidential.