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Explanatory foreword on the Low Carbon Energy Observatory

The LCEO is an Administrative Arrangement being executed by the Joint Research Centre (JRC) for the Directorate-General for Research and Innovation (DG Research and Innovation), to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind Energy
- Photovoltaics
- Solar Thermal Electricity
- Solar Thermal Heating and Cooling
- Ocean Energy
- Geothermal Energy
- Hydropower
- Heat and Power from Biomass
- Carbon Capture, Utilisation and Storage
- Sustainable advanced biofuels
- Battery Storage
- Advanced Alternative Fuels

In addition, the LCEO monitors future emerging concepts relevant to these technologies.

How is the analysis done?

The JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main deliverables?

The project produces the following generic reports:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Report on Synergies for Clean Energy Technologies
- Annual Report on Future and Emerging Technologies (information is also systematically updated and disseminated on the online FET Database).

Techno-economic modelling results are also made available via dedicated review reports of global energy scenarios and of EU deployment scenarios.

What's the timeline?

The LCEO produces its main reports on a two-year cycle. The first set was published in 2016 and the second will be available in 2018. A final set will be released in spring 2020.

Acknowledgements

We would like to express our gratitude to all the participants and contributors to this Workshop on the Identification of Future Emerging Technologies in the ocean energy sector. This report was made possible thanks to the contributions and review of the workshop participants, listed in Table 1.

We would like to thank Laura Rappucci whose assistance was fundamental in the organisation of the workshop.

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Table 1. Workshop Participants

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Introduction

As part of the European Commission's internal Low Carbon Energy Observatory (LCEO) project, the Joint Research Centre (JRC) is developing an inventory of Future Emerging Technologies (FET) relevant to energy supply.

A key part of the LCEO initiative is the consultation of external experts, addressing both those with in-depth experience in specific fields and those with a broad perspective on relevant science and engineering aspects. In this context, on March 27, 2018 the JRC organised a Workshop on Identification of Future Emerging Technologies for Ocean Enery, on it premises in Ispra.

The workshop was organised on the idea of a colloquium between international experts to discuss about future emerging technologies considering different aspects such as their technology readiness level (TRL)[1], the potential advantages and challenges affecting their development, and evaluating the possible speed of development.

A number of different technological solutions were discussed, identified directly by the invited experts on the condition that they respected the following criteria:

- To be a technology for energy supply/conversion in the field of ocean energy.
- To be a radically new technology/concept, not achievable by incremental research on mainstream technologies (this should match the concept of the Future Emerging Technology in the Horizon 2020 work program[2]).
- To be in an early stage of development: their Technology Readiness Level should not be more than 3.

Questionnaires were sent to experts for the identification of ocean energy FETs. The templates can be found in Appendix B. The structure of the workshop was builtupon the inputs received from the experts and on in-house analysis undertaken by the JRC.

The aim of this document is to gather, organise and highlight all the knowledge and information, provided by the external and internal experts, which were discussed during the workshop.

The ocean energy sector is still at an early stage of development

With only 17 MW of operating capacity installed in European water, mostly as demonstration or first-of-a-kind precommercial project, every technological solution proposed to bridge the gap between R&D and the commercialisation of ocean energy devices can be seen as an emerging technology. As such, given the input received from the experts in forming the basis for the workshop discussion, “technology families” have been created. Technologies families include components, parts, subsystems used by different developers and ocean energy devices that share a common application for FET or an underpinning technological principle of operation.

Experts have highlighted a general lack of design methodology in the development of ocean energy technology, as reflected in the European Commission report " Study on lessons for Ocean Energy Development" which identified critical issues that have affected and slowed the uptake of commercially viable ocean energy technologies. It shall not be surprising that there is wide consensus among experts that ocean energy technologies are considered "Future Emerging Technology", despite some of the most recent technological advances.

The sector needs a more holistic energy-system approach

The development of ocean energy technologies, and in particular wave energy converters, has followed a common path: optimisation of the hydrodynamics of an ocean energy absorber missing

[1] Detailed definition of Technology Readiness Level scale applied during the Workshop can be found in Appendix A.
[2] http://ec.europa.eu/programmes/horizon2020/en/h2020-section/future-and-emerging-technologies

a more holistic energy-systems perspective. Key aspects of the development where left out of initial design considerations and have later become expensive 'add-ons'. Key subsystems such the power take-off (PTO), control systems, Mooring and structural loading have not been considered from the off-sets .

Whilst it was noticed that most companies developing ocean energy technologies are small enterprises whit limited resources and expertise (computing power, testing) to explore design questions. Some practical aspects neglected at an early stage can become a problem if taken up at a later stage. It is a matter of system integration, as detailed in the recommendations below.

Technology families

The discussion on FETs for the ocean energy technologies was structured around nine different emerging technology families. First generation tidal, already at the pre-commercial stage, is also included in the overview.

- First generation tidal energy converters;
- Rotor innovation for tidal energy turbines;
- Floatig tidal concepts;
- Third generation tidal energy converters;
- Novel approaches tp first generation wave energy concepts
- Novel wave energy concepts;
- Innovative tidal and wave energy power take off;
- Control systems;
- Moorings and station keeping systems;
- Materials and components.

Technology families were created based on the input received from the experts prior the workshop and complemented by desk-studies undertaken by the JRC. Technology families group together wave or tidal converters, subsystems and components that are characterised by a common operating or design principle.

It shall be noted that a large variety of concepts have been developed for ocean energy conversion, with more than 200 different devices proposed. At EU level, information regading many of these different concepts are available through the Marinet Project[3], the Wave Energy Scotland program, the European Marine Energy Centre list of wave and tidal energy technology and the JRC's Ocean Energy Database.

Estimating TRL and speed of development

As part of the workshop, experts were asked to provide for each of the technology family an estimation of the TRL for each technology. The guiding principles of the European Commission were used as the reference TRL scale for the workshop. The report " Technology readiness level Guidance principles for renewable energy technologies : final report – Study" is publicly available[4]. Detailed descriptions of the TRL for ocean energy technologies are available in the annexes of the report[5], these are reported in Appenidx A.

It has to be noted that the use of TRL is a relatively new concept in the field of ocean energy technologies; and that sometimes a TRL cannot be unequivocally defined for a technology at the

[3] First supported under the EU-FP7 research program, and now through Horizon 2020

[4] https://publications.europa.eu/en/publication-detail/-/publication/d5d8e9c8-e6d3-11e7-9749-01aa75ed71a1

5 https://publications.europa.eu/en/publication-detail/-/publication/1da3324e-e6d0-11e7-9749-01aa75ed71a1/language-en/format-PDF/source-61073523

early stages of development. Different experts in one field can therefore have a different appreciation of the readiness level of a given technology.

The TRL evaluations appearing in this report are based on the general agreement between the experts that have participated in the workshop, yet they contained an intrinsic component of subjectivity due to the requirement to provide a TRL at technology family level and not on the specific ocean energy converter under discussion. Furthermore, TRL assessment is provided for technology family, since no data was available to provide an indepth assessement based on performance of the technology against the checkpoints (see Appenidx A for details).

It was recorded that experts expressed doubt about the use of TRLs as an indicator of technological development and seemed more prone to discuss it together with TPL – technology performance levels[6], as presented by J. Weber. This approach is based on the considerations provided above on the necessity for ocean energy technology developers to move towards a system-design rather than a sequential design.

Experts also highlighted the importance of verification of the TRL achieved, thorugh the implementation of stage gate metrics or other standardised model. Verification and certification processes were not part of the scope of the workshop.

The assessment of the TRL for each technology family was also coupled with an evaluation of the speed of development of the FET under consideration. An indication of the speed of development for ocean energy converters was presented by Weber et al[7], which identified as 13 years the time of development for ocean energy devices from TRL1 to TRL9 . Based on this analysis, the following scale was used to define the speed of development in the assessment of FET for ocean energy:

- Speed of development > 15 years, Slow
- Speed of development between 5-15 years, Medium
- Speed of development < 5 years, Fast

Recommendations

Design and system integration for mid-term deployment

Many recommendations put forward by experts concerned methodologies for system design and integration. For example, rather than sequentially, one should plan the PTO together with the system design.

The availability of a specific set of requirements would help addressing system design integration issues from the start. Some developers complain about having to look at functional requirements while still at TRL2. This is needed, however, to help conceive potentially deployable solutions from the early TRL stages. The push from a number of international organisations in developing a Stage Gate process for the development of ocean energy technologies is to be considered a positive step in this direction; and it may offer the paradigm shift that the sector has long needed.

Overall, a number of recurring technical issues were identified affecting all the technological families under discussion:

- Identification and development of new materials that are able to balance conflicting requirements (e.g. flexibility, structural and electrical robustness);
- Upscaling of materials and systems from lab to applications;
- Response to multiple forces in harsh ocean environments with non-uniform water profiles;

6 https://www.osti.gov/biblio/1365530
7 Cost, time, and risk assessment of different wave energy converter technology development trajectories (EWTEC 2017)

- More efficient energy harvesting and conversion;
- Costs of testing & demonstration ("one day testing at full-scale could pay for all low TRLs") and even computational modelling;
- Developing solutions also usable by other industries (for profitability);

Experts also stressed the need to first bring all (component) technologies up to similar and workable levels before combining them. Single units have to be developed far enough before making demo systems and building them in large numbers.

Assessment of R&D needs aimed at supporting future deployment

A second strand of recommendaitons arising from this work concerns how to gauge R&D needs.

Firstly, it is recommended to assess R&D needs per technology family. The present report discusses nine families identified by experts participating in this study.

Secondly, in addition to TRL, it is recommended to use the speed of development evaluation proposed in this report as a gauge of the R&D need of each technology family, considering also ancillary technologies.

Evaluation of the speed of development is dependent on the type of FET under evaluation as well on the interdependency between FETs and on technology development ancillary to ocean energy R&D. For example, recent advances in material science may accelerate the identification of suitable light material to be employed in ocean energy converters. Yet, their application in ocean energy implies that not only technical but also economical requirements are satisfied.

Structure of the report

The remaining ten chapters of this report are dedicated to detailed descriptions the technology families. Each technical chapter addresses one of the technology families presented above by offering:

- A brief technological description, highlighting areas of innovation and where FET could play a significant role;
- Advantages offered by the FET solution proposed;
- Limitations and challenges that may need to be addressed in order to bring the proposed technology to higher TRL;
- Project & activities that are currently exploring the potential of the FET, including where available relevant bibliography. In some cases further details are offered to enrich technological description;
- Assessment of TRL and Speed of development.

The authors would like to highlight that the report does not present a State of the Art review of ocean energy technologies, and thus some advance concepts may not appear in the report.

Projects and activities listed are to be considered selected highlights of FETs and do not represent the full spectrum of R&D activities on the given topic.

1 First generation tidal energy converters

1.1 Brief technology description

The term first generation tidal technology comprises all of those tidal energy converter that are normally characterised by 1) being fixed on the system by means of a foundation system and 2) employing either a horizontal axis tidal stream turbine, or a ducted turbines. As a consequence, second generation tidal technologies comprise tidal energy converter that are not bottom fixed, and thus employ a floating or semi submerged platform upon which one or multiple rotors are installed. Third generation tidal technologies comprise device that do not employ a rotor.

First generation tidal turbines represent some of the most advanced ocean energy technology developed so far and include technology developed by, Andtriz Hydro Hammerfest, Nova Innovation, OpenHydro/Naval Energies, Sabella, SIMAC-Atlantis, Tocardo, Verdant Power to name but a few.

Tidal energy is at the pre-commercial stage of technology evolution and market entry. Unlike other renewables, tidal energy can provide predictable and firm power aiding electrical network integration and management. However, there are techno-economic challenges associated with building, installing, operating and maintaining plant in energetic sub-sea environments in order to generate electricity at a price which can compete with current wholesale prices of electricity. Technology development not only needs to address the ability to capture and convert the hydro-kinetic energy efficiently and effectively, but also address the ease of installation, commissioning and maintenance. The latter also greatly influences and in some cases is the predominant factor in the costs of generated electricity from these technologies.

One of the key points of tidal energy is that it has currently reached a certain level of design convergence with the three-bladed horizontal axis turbine. This technological solution is widely employed in the current technology demonstrations. Nevertheless, new innovative designs can potentially help increase the performance of tidal converters.

The parameters influencing the capital costs of device, installation, commissioning and operation and the efficiency of power capture, conversion and take-off are:

- **Weight of device**. The device weight influences the material volume and cost. Savings on device weight results in similar saving on device capital costs and efficiency, ad helps reducing the costs of the station keeping systems. Station keeping system are designed for dynamic/snatch loading, which can be reduced when the device weight reduce. Reduction in device weight also reduces the size, complexity and costs of the installation vessels required. Heavier devices require more specialised, more expensive vessels to undertake the installation, maintenance and recovery. FETs presented in the "Advance Material" section of this report may provide a solution to decrease the weight of first generation tidal technologies.
- **Understand loads**. The thrust loading on tidal rotors will determine the maximum size of the blades. 25 m is pretty much the limit as the existing materials cannot sustain the thrust loads from bigger blades. Shedding peak loads for marine energy systems as soon as possible is the most impactful way of reducing the specification and costs of downstream components. The blade of a tidal energy turbine significantly affects the overall efficiency and design of the turbine system and therefore the costs. Flexible blades may address many of the challenges currently faced by the turbine blades. These are discussed in section 10.8.
- **Device Complexity**. The complexity in the design of tidal energy converts increases the risk of system failures and cost-associated with maintenance of the devices. In this context first generation tidal device may benefit from a simplified approach in the design of the power electronics infrastructure, control systems or sub-sea connections in the technology. High system complexity has been a common

failure mode for all technologies deployed to date. Possible solutions include rotor innovation and the development of water-gap power take off systems.

- **Minimise O&M**. In particular, given that first generation tidal converters are bottom mounted, innovations are welcome in order to minimise the need for divers to undertake installation or maintenance. Health and safety legislation limits the extent and duration divers can operate and restricts operations to daylight hours. This results in longer on-site time requirements needed for operations to be completed. In exposed sites, the likelihood of getting consecutive days of suitable weather to facilitate continuous maintenance operations can become challenging, especially in winter months. Similarly during the winter period, shorter daylight hours may restrict intervention to one tidal slack water per day.
- **Welcome breakthrough innovation.** First generation tidal technologies are at an advance stage of technological development, having demonstrated their reliability in generating electricity and achieving high capacity factors during operation. Nevertheless they are currently not cost-competitive with other renewable technologies. An in depth analysis of the R&D and market needs of current front runners is beneficial to accelerate the commercialisation of first tidal technologies. Step-change in the reduction of the cost of first generation tidal energy converters can take place thanks to new breakthrough technologies, FETs and 2nd and 3rd generation tidal, as discussed in the following sections.

To help first Generation tidal energy technologies accelerating commercialisation solutions for: i) lighter in components, ii) less complex and simplified station keeping system, iii) simplified mechanical and electrical connection-disconnection, iv) easily installable, accessible and maintainable when deployed need to be found.

1.2 Stage of development: TRL, size and speed

The TRL is high (7-8). The total installed capacity is circa 12 MW in Europe and the speed of development is medium, with device having reached maturity after 10+ years of R&D. Nominal rated power of first generation tidal technology ranges between 1-2 MW, could grow to 2-2.5 MW. Small-size converters with a power rating of 100-250 kW have also been developed and are operational in Europe and offer potential for upscaling in the longer term.

1.3 Main ongoing projects

First generation tidal energy technologies are deployed in the EU and worldwide in pre-commercial demonstration projects. Some example include:

- **Shetland Tidal Array** (Figure 1) – 3x100kW Turbines developed by Nova Innovation. First tidal energy array deployed.
- **Meygen** – 6 MW - 3x 1.5MW Turbines developed by AndritzHydroHammerfest (Figure 2)+1x1.5MW turbine developed by Atlantis Resources Limited. Largest tidal stream array currently in operation.
- **Sabella** D10 Tidal Turbine (Figure 3) - 1MW Tidal device developed by Sabella installed in Fromveur (FR)
- **Cape Sharp Tidal** Project (Figure 4) - 4 MW demonstration plant, with 2x2MW turbines developed by OpenHydro/Naval Energies
- Aflsluitdijk – 3x250 kW and Oosterschelde (Figure 5) – 5x250 kW projects employing turbines developed by **Tocardo**

Figure 1 – Nova Innovation turbine installed at Shetland Tidal Array © Nova Innovation

Figure 2 – Andritz Hydro- Hammerfest turbine installed at Meygen, ©Meygen

Figure 3 – Sabella D10. ©Sabella

Figure 4 – Assembly of OpenHydro turbine ©OpenHydro

Figure 5 – Tocardo turbines at Oosterschelde. ©Tocardo

2 Rotor innovations for tidal energy turbines

2.1 Brief technology description

A number of key innovations could provide significan step-changes in the development of tidal energy technologies, these include:

- Development of yawing turbines with variable pitch. Variable pitch allows changing the angle of attack to control absorption and power production
- Development of contra-rotating turbines. Contra-rotating turbines propose to solve the periodic reversibility of tidal current by designing rotors with high efficiencies in both directions. This is achieved either by rotating the entire turbine, by having two sets of blades on the same shaft or by having turbine blades with a special design that allows operation in both directions with same efficiency.
- Development of wet-gap turbines, which allow operation in flooded seawater conditions
- Development of direct drive PTO systems, aimed at reducing losses in the energy conversion. (Direct Drive PTO are discussed in more detail in Chapter 7)

2.2 Advantages

Rotor innovations can bring a number of key advantages in the development of tidal energy technology and thus provide a step-change towards the competitiveness of tidal energy converters, in particular rotor innovation offer:

- Increase in power capture and overall efficiency;
- Greater use of proven sub-sea engineering technology;
- Elimination of the gearbox, minimising the need of oil change and reducing problems with seals and bearings. It shall be noted that in both geared and gearless drive trains will be employed by the sector, like in wind turbines;
- Less complexity of design.

2.3 Limitations

A number of limitations currently witnessed need to be overcome to ensure that rotor innovations could provide a needed step change for tidal energy technologies:

- Addressing different hydrodynamic issues associated with potential rotor interactions;
- Lack of proven reliability and operational hours;
- Immature control of a counter rotating turbine with variable pitch due to high complexity;
- Ensuring transferability of technology so that seals, bearings achieve a similar lifetime as witnessed in ship-propeller (5 years).

Further more, some of the challenges encountered by first generation tidal turbines also pose limitation for the development of variable pitch, contra-rotating turbine:

- High thrust limits the blade size to max 25 m, with materials currently available;
- Lack of knowledge of the interactions of the rotor with wave forces;
- High maintenance due to weight, number of submerged parts and delicate parts.

2.4 Stage of development: TRL, size and speed

The development of variable pitch and counter rotating turbines has reached relatively high TRL (6-7), whilst wet-gap and direct-drive are at TRL 5-6. Power rating ranges between 100 kW to 2 MW (Magallanes). The speed of development is medium-slow with device reaching high TRL after 10 years of development.

2.5 Projects&Activities

Key projects exploring innovation in the rotor for tidal energy turbines include:

- Contra-rotating double turbine including:
    - **Magallanes**/CNV Naval Architects, 2 MW device expected to be deployed at EMEC in 2018 (Figure 6).
    - CoRMaT contra-rotating tidal generator with two closely spaced dissimilar rotors, moving in opposite directions by **Nautricity**. (www.nautricity.com/cormat/). It is developed in collaboration with Strathclyde University and employs a patented contra-rotating turbine. Nautricity claim suitability in water depths of 8-500m. Recently tested at EMEC (Figure 7).
    - **NEDO**, together with Kyowa Engineering Consultants Co., Ltd., EIM Electric Co., Ltd., Maeda Corporation, the Kyushu Institute of Technology, and Waseda University, have developed a counter-rotating propeller technology for tidal stream power generation. NEDO is also developing a floating solution for its turbines (Figure 8).
- **Tidetec** (Figure 9)that proposes a rotating tidal turbine to be implemented in a tidal barrage with attention to the unit design of the entire hosting caisson for easier maintenance and more efficient applications in bridges and transport infrastructures.
- Variable pitch and flapping blades, like **CarBine** project using a modify Savonius turbine (rotating flaps) (Figure 10).
- SIT turbine by **SCHOTTEL** (Figure 11) is lightweight, reducing turbine size leads to a better ratio of power and material use.
- **Ocean Renewable Power Company** (ORPC, Figure 12) is developing a multiple horizontal Gorlov turbines which comprise a horizontal shaft with paddle wheels and different bearing positions. As part of the Taoide H2020 project, they developing a fully-seawater flooded, "wet-gap" generator, capable of continuous and reliable operation in a marine environment. It is expected that a "wet gap" generator will enhance generator longevity, decrease repair times, and increase system availability .Similarly, **OpenHydro** has developed has a flooded architecture with seawater lubricated bearings (Figure 13).

Figure 6 – CNV Naval Architects. ©Magallanes Renovables

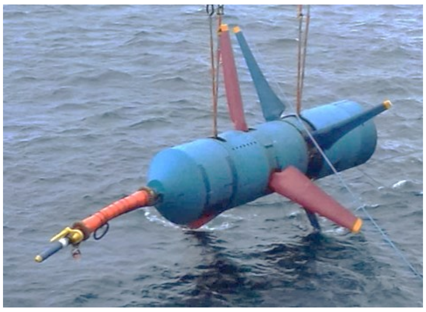

Figure 7 – CoRMaT ©Nautricity

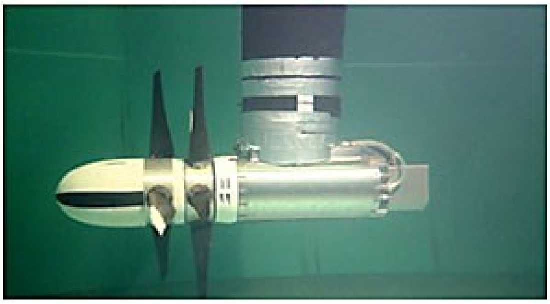

Figure 8 – NEDO. © New Energy and Industrial Technology Development Organization

Figure 9 – TideTec turning mechanism for barrages. ©Tidetec

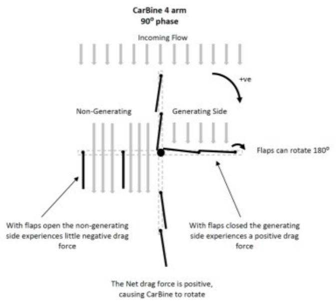

Figure 10 - Savonius turbine with rotating flaps

Figure 11 – SIT. © Schottel

Figure 12 - ORPC Gorlov Turbine. ©ORPC

Figure 13 - OpenHydro Turbine. ©OpenHydro

3 Floating tidal concepts

3.1 Key words

Floating tidal turbine, semi-submerged tidal turbine floating tidal, multi-structure tidal platform.

3.2 Brief technology description

Floating tidal devices are often referred to as 2nd generation tidal technologies. They differ from first generation through the use of a platform, which can be floating at surface level or semi-submerged, upon which one or multiple tidal turbines are installed. Different configurations are currently under investigation ranging from 100kW power rating (BlueTEC) to 2MW.

The general configuration of floating tidal systems ensures that the electronic components of converters (PTO, Frequency inverter) are located in the platform allowing for easy access for maintenance. This can take place directly in situ, by quickly taking the rotors out of the water if conditions allow, or by by taking the device back to a harbour.

3.3 Advantages

Second generation tidal technology offer a number of key advantages:

- These devices have the potential to reduce support structure costs. Compared to first generation tidal technology, they do not require heavy and costly foundation systems.
- Easier installation avoiding the need for heavy lift vessels.
- Floating tidal devices can be moved to ensure optimal power extraction in the upper part of water column.
- Easier maintenance and repair friendly, including the possibility of raising the turbines on the barge. Electrical equipment is easily accessible.
- No large crane ship needed. A small multi-purpose vessels can be employed for recover/installation

The technology would benefit from close collaboration with the ship building industry and programmes which enable such collaboration should be encouraged.

- Floating tidal structures could benefit from the knowledge developed in other sectors in terms of moorings so that they can be deployed in relatively close packed arrays.

3.4 Limitations

While floating structures can provide access for onsite maintenance, and quick connection and disconnection on to the station keeping, there are some limitations to their deployment, to include:

- Conditions at the sea surface are often more extreme and unpredictable than on the sea bed. Floating tidal technologies may have some advantages in terms of deployment, O&M costs etc., however this is weighed against the additional costs and design difficulties of a floating structure and additional off axis loading on a turbine.
- The floating structures have higher structural requirements to counteract overturning moment, which makes the converter less structurally efficient.
- Increased exposure to higher dynamic rotor loadings in sites with wave exposure, limiting the deployment potential.
- Similarly, submerged structures need to be large/very buoyant to enable the use of taut-moorings. Consequently also the anchor loads may become a challenge.

Anchors still have to be secured to the seabed, facing the same issues of bottom-fixed tidal structures.

- High loading and specialised station keeping systems, requirements larger/ heavier mooring systems to overcome increased combined thrust and heave loads. A semi-taut mooring system needs to be identified as a solution to deal with the reversing flow direction and forces.
- Floating structure may pose a navigation, further the presence of the device in the water column may result in unexpected environmental effects, and collisions.

3.5 Stage of development: TRL, size and speed

Some floating tidal platforms are already at an advanced stage of development, with the the SR1-2000 device developed by Scotrenewables having clocked over 2GWh to the grid as part of the Horizon 2020 FloTEC project (Figure 14). Sustainable Energy Marine has developed the Plat-O (Figure 15) device and later The Plat-I (Figure 16), deployed in Scotland at the end of 2017. The TRL is ranging 5-8, with semi-submerged structure still requiring further investigation. Maximum power rating is expected in the range of 2-2.5 MW, however this is dependent on addressing structural loading on the floating platform and rotor. Speed of the technology development is medium/fast, especially when employing advanced turbines.

3.6 Projects & Activities

- **Scotrenewables** SR1-2000 2MW device, deployed at EMEC since 2016, 3 GWh generated until august 2018. SR2-2000 2MW device under development. Turbines developed in house.
- **Sustainable Energy Marine LTD**, PLATT-I (surface floating tidal energy power station) rated at 280kW and PLAT-O (floating submerged tidal energy platform), employing SIT Turbines developed by Schottel.
- **Magallanes** (Figure 17) 2 MW floating device to be deployed at EMEC in 2018.
- Japan’s IHI Corporation has completed tests on a floating tidal turbine concept that uses 50kW 11-metre diameter rotors (Figure 18).
- Dutch developer **Tocardo** has deployed its turbine on the BlueTEC floating structure (Figure 19) and is currently developing a semi-submerged platform to be deployed at EMEC (Figure 20).
- **Capricorn** (Figure 21) and **GEM** (Figure 22) are testing a 50 kW and 20 kW devices respectively.
- **QED Naval** and **SCHOTTEL HYDRO GmbH** (Figure 23) are evaluating the installation of multiple turbines in semi-submerged platforms.

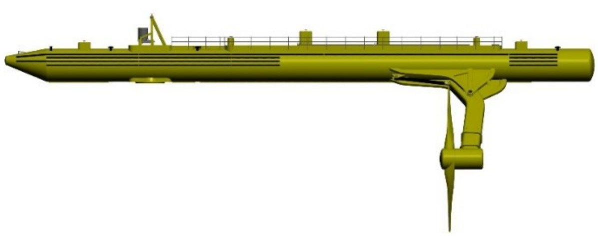

Figure 14- SR1-2000/Flotec. ©Flotec/ScotRenewable

Figure 15 – PLAT-O. ©Sustainable Marine Energy

Figure 16 – Plat-I. ©Sustainable Marine Energy

Figure 17 – Magallanes project. ©Magallanes Renovables

Figure 18 – Japan's IHI Corporation. ©IHI Corporation

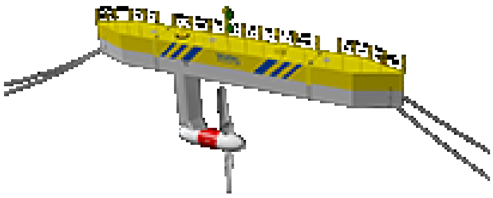

Figure 19 – Blue TEC. ©Bluewater

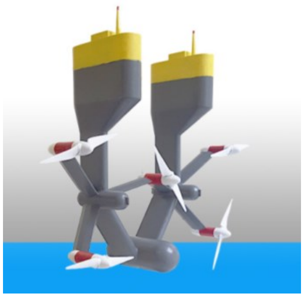

Figure 20 – Tocardo. ©Tocardo

Figure 21 – Capricorn Marine Turbine. ©Renewable Devices Marine Ltd

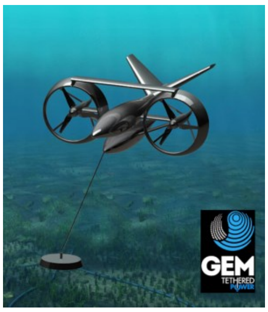

Figure 22 – GEM. ©Seapower Scrl

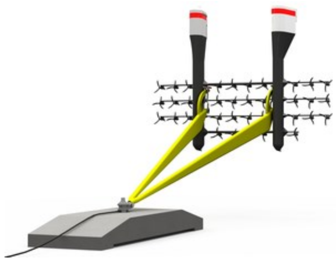

Figure 23 – Triton ©Schottel Hydro GmbH

4 Third generation tidal energy converters

4.1 Key words

Sails, kites, Bio-inspired oscillating hydrofoils'

4.2 Brief technology description

This category includes all concepts that were born as substantially different from the first generation rotor based tidal energy technologies. They extract energy from a tidal flow or water flow in a different way: inspired by fish swimming using the motion of an oscillating/flapping, through swings, sails or kites.

These technologies take a clear distance from the existing wind/tidal energy rotor based extraction methods. This is an important area of continued research: whilst current tidal turbines have adopted the 3 bladed, horizontal axis approach familiar in wind turbines, however the development of third generation tidal devices, currently at an earlier stage of development, may lead to a breakthrough in cost reduction. In particular, new technology may enable a step change in the overal efficiency of large scale array.

These devices offer the possibility of being deployed in areas with lower resoruces, and are therefore able to increase the market for tidal technologies once they become commercially viable.

Overall, it shall be noted that extracting energy from the water (a diffuse resource) is different to inputting energy which can be done in a concentrated way e.g. a fish/propeller. There are opportunities which combine engineering fundamentals with aspects observed in natural phenomena and which can lead to better overall solutions. As a low TRL technology category, bio-inspired technologies with cross-cutting aspects offer this potential, which to dat has has been little explored.

4.3 Advantages

- Applicable at lower energetic tidal flows/ areas depths where other tidal energy technologies are not possible.
- Operating at a low speed (some with start-up velocity as low as 0.4 m/s).
- Automatic orientation toward optimal direction.
- Low weight, reduced dimensions and less complexity compared to first generation tidal technologies.
- Maximum array efficiency for array shaped along the longitudinal direction of the tidal channel instead of across the channel (hence more environmentally and economically viable).
- High array efficiency: array's conversion efficiency is not limited to 2/3 (Betz's limit).
- Lower impact on large fish and sea mammals compared to conventional propeller type tidal turbines are expected, but further validation is needed.
- Low noise emissions

4.4 Limitations

- Understanding and proving the theoretical benefits in modelling and physical tests.
- For some concepts, the hydrodynamics and moorings are a challenge due to variability and induced forces, with consequent highly fluctuating efficiency.
- Some concepts may be particularly sensitive to plastics/sediments impact/pitting on the primary mover of the device.

- Control systems on devices like kites and sails are a challenge and may be a limitation on the deployment of such devices.
- Access to the devices for maintenance is a potential concern, especially if PTO is bottom mounted.
- Mooring systems and dynamic cable are reuired to address the challenges related with fatigue and robustness.
- Water column obstruction is also a concern as some technology: despite their limited dimensions, do not have a fixed position in the water column. When identifying tidal sites, it will also be required to check for migration routes for various species.
- Difficulties in the performance assessment and issues related to turbulence and its interaction with the installation: how to sense turbulence?

4.5 Stage of development: TRL, size and speed

Some of the more advanced concepts have already reached a medium high TRL 5-7, with other newcomers at TRL 3-4. The speed of development is medium/fast, and is affected by the development of materials/ancillary technology.

4.6 Projects & Activities

EEL Energy (Figure 24) consists of one membrane undulating in the tidal flow. The periodic motion of the membrane is transformed into electricity by mean of an electromechanical system running along the whole length of the membrane. A monitoring loop ensures optimised energy conversion in response to changes in flow conditions and power transmitted. The main ongoing research projects have been funded by BPI and Ademe and testing programme in current flume conducted at Ifremer.

Short bibliography: Trasch Martin, Deporte Astrid, Delacroix Sylvain, Drevet Jean-Baptiste, Gaurier Benoit, Germain Gregory (2018). Power estimates of an undulating membrane tidal energy converter. Ocean Engineering, 148, 115-124 . http://doi.org/10.1016/j.oceaneng.2017.11.002 or see http://www.eel-energy.fr/en/eel-tidal-energy-convertor/

Oscillating Energy Harvester Inspired by Fish Swimming (Figure 25). Tidal energy harvesters inspired by fish swimming have been developed, using the motion of an oscillating/flapping wing to drive a generator. This energy harvester is gaining attention as a new type of renewable energy converters due to several advantages such as its high array efficiency and operating at a low speed. The ability to control how vortices are shed in the wake allows to induce a flux of kinetic energy that enable compacted arrays with high energy extraction. Therefore, it is expected that installation of these energy harvesters as an array can be highly efficient occupying a small portion of the tidal channel, whilst extracting energy from all of the channel. The Main ongoing research projects have been conducted at the University of Edinburgh, University of Glasgow and University of Strathclyde. 2016-2017, Carnegie Collaboration, Research Grant [50349]: Investigation of flapping wings as a means of hydroelectric power generation.

Short bibliography: Kinsey, Thomas, and Guy Dumas. "Optimal tandem configuration for oscillating-foils hydrokinetic turbine." Journal of fluids engineering 134.3 (2012).

Minesto (Figure 26) deep green is one of the first concepct of tidal energy kite. Whilst employing a kite, however it still employs a small turbine located under the kite for energy conversion Deep Green produces electricity from slow tidal and ocean currents by a unique principle. By sweeping a turbine across a large area, at a speed several times the actual speed of the underwater current, could be suited for application in areas where tidal resources are lower compared to those where conventional first generation tidal device need to operate, thus with water current velocity 1.2–2.4 m/s compared to the 3.5-5 m/s. Minesto is currently developing a 10 MW farm in wales, also thanks to the support from Marine Energy Wales, the European Regional Development Funds and Horizon 2020 project DeepKite.

Seaqurrent (Figure 27) are also developing a tidal kite, whose operating principle is similar to the concept developed by Minesto, a tethered kite that react to the tidal flow by moving across the water column. The main difference between the two concepts is that in this case, the PTO is bottom based and is activated by the motion of the tether. (https://seaqurrent.com/#ourtechnology)

Tidal sails (Figure 28) The tidal stream cause the motions of the sail profiles which is connected in between two freely suspended direct drive permanent magnet generator stations. The device is exposed to a larger swept areas compared to conventional tidal technologies, and can therefore be employed in lower speed streams. The company is currently developing a 4 MW prorotype.

Figure 24 – Eel Energy. © EEL ENERGY

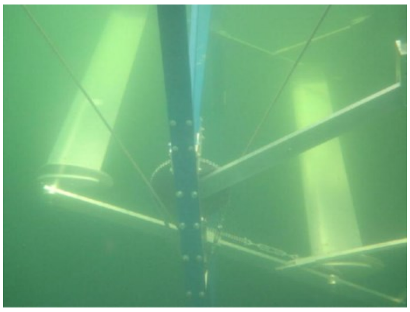

Figure 25 – Oscillating Energy Harvester (Thomas and Dumas, 2012)

Figure 26 – Minesto Deep Green. ©Minesto AB

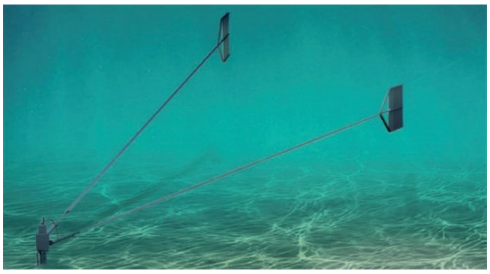

Figure 27 - Seaqurrent ©SeaQurrent Holding BV

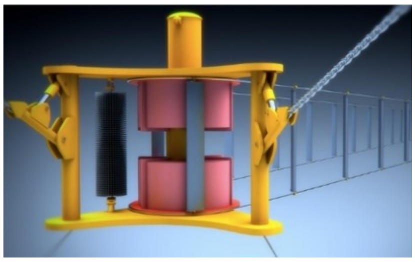

Figure 28 - Tidal Sails. © Tidal Sails

5 Novel approach to first generation wave energy concepts

5.1 Key words

Multi point absorbers, multiple OWCs, Integration with other offshore structures.

5.1 Brief technology description

The development of commercial wave energy technology started in the 1970s as a response to the oil crisis. The underpinning principle of wave driving the development of wave energy technology is based on the potential extraction of effectively the entire energy contained in the waves. Based on this mathematical analysis, more than 100[8] wave energy converters that respond differently to the motion of the waves have been developed. These are commonly classified according to the classification system presented by EMEC[9] which based on operational principle (e.g. reaction to the incoming waves) as well as on location (onshore, near-shore, and offshore). Whilst there is a huge diversity in the type of converters developed even within the same catergory, devices such as Pelamis (Attenuator), WaveBob, Salter's Duck and WaveSpring (Point Absorbers), AWRoller and Oyster (Oscillating Wave Surge Converters), Wave Dragon (Overtopping), and different Oscillating Water Columns devices (Pico, OceanEnergy, OceanLynx) are all to be considered first generation wave energy converters. A significant part of the current R&D on wave energy converters now focuses on overcoming the challenges encountered by first generation wave energy converters to developed commercially viable systems.

First generation wave energy concepts have typically been developed starting with a rigorous hydrodynamic optimisation of the power capture, often through high-end mathematical modelling and simulation. In this respect, the collector structural aspects are often well understood, yet they are not well developed as a complete wave energy system with other key components like the moorings, PTO and control systems integral to success but often not considered until late in the process. Therefore, the need to plan for the PTO and other subsystems within a system design has become obvious. Concept design at system level is essential to ensure the viability of wave energy converters.

There is a lack of convergence in design and consensus about the optimum design of wave energy converters, so further research and development is required to explore and identify the best solutions.

There is a wealth of research of wave energy going back 40 years, however the majority of device types have been around for decades. The availability of testing facilities and new computational tools are making research more accessible and opening up new opportunities. The advancement of artificial intelligence (AI) and learning algorithms offer an opportunity for developing designs which are more efficient - allowing a computer to make the design choices. This however leads to a trade-off between the optimal computer-generated design and manufacturability. New materials which can be moulded (plastics) rather than fabricated (steel) can be used along with computer generated designs to create more complex geometries.

It shall be added, that whilst new tools allows for the optimisation of the energy capture of wave energy devices, it is fundamental that standardisation and industrialisation of products are also addressed.

[8] http://www.emec.org.uk/marine-energy/wave-developers/
[9] http://www.emec.org.uk/marine-energy/wave-devices/

The main challenges faced by wave energy technologies include:

- High ratio of design/maximum loads (e. g. wave to wave) to average loads (e. g. annual)
- Poor efficiencies in the conversion from captured mechanical power from wave motion, to electrical (PTO, control and power electronics).
- Limitation of PTO loading during extremes (power electronics)
- Fluctuation of power output (power quality to the grid corresponding to grid-compliant electricity).
- Survivability (materials, components and moorings), with particular emphasis on extreme wave loads during storm events.
- Predominantly harness of energy from the vertical or surge motion in waves, while the combination of heave, surge and pitch motion modes is not developed (see tether section in Chapter 9).
- Heavy, generally high installation costs (vessels and complexity). It reflects also on loads (snatch) on the station keeping systems.

To overcome the limitations of first Generation technologies, a novel design approach has come into life. In this section we identify wave energy converters based on working principles and design of first generation technologies that have benefitted from innovations to optimise power capture and performance.

This section presents wave energy converters that have been inspired by the first generation wave devices and that has benefitted from structural and design innovations, to maximise power conversion, reduce intermittency and optimise costs, particularly focusing on multi-device FET solutions. In the next chapter, Chapter 6, novel wave energy or 2nd generation converters will be discussed.

It needs to be highlighted that other FETs and innovations addressing one single component and subsystems will be discussed in more details in the following chapters, in particular Chapter 7 will focus on PTO innovations, Chapter 8 will look into control systems, Chapter 9 will present innovative mooring and station keeping; and finally innovative materials are covered in Chapter 10

5.2 Advantages

- Better cost of energy and projected LCOE.
- Increased energy capture.
- Integrated storm survival mechanism in place This is achieved by : removing the main moving body from the waves, by reducing the overall forces on the structure by decreasing wave angle of attack, or by absorbing the main forces internally.
- Improved quality of power output.
- Optimised hydrodynamic efficiency and improved wave-structure interactions.

5.3 Limitations

- Single units need to be taken at the same level of development before combining in an installation.
- Overall efficiency is limited by the lack of adequate control strategies and PTO components.
- Moorings and mooring components have not been optimised due to the lack of clear standard guidelines (requirements are substantially different from the existing guidelines from shipping industry and oil and gas)

5.4 Stage of development: TRL, size and speed

TRL ranges between 2-5 (limited sea trials in full scale of the complete systems), potential for multi-MW installations. Development speed is medium-slow, as it requires optimisation of signle unit and of multi-unit structure.

5.5 Projects & Activities

WEPTOS (Figure 29). The Weptos wave energy converter is based on the Salter´s ducks concept. It is composed of 20 floaters, in 2 rows of 10 elements each, driving a common shaft. The innovative PTO allows for power extraction due to the pitching motion of the floaters. The whole structure has a storm-mode system implemented. The device adapts to incoming wave by reducing the angle of opening of the two rows of floaters. The strcture can therefore minimise mooring forces and structural loads by closing together the two rows of floaters (to 13°) compared to an open configuration (123°) employed for less energetic operational conditions. Currently, the device is being tested in large scale in real sea. The main ongoing research project is lead by Aalborg University, Denmark.

Short bibliography: Pecher & Kofoed 2017: Handbook of Ocean Wave Energy. Springer. ISBN 978-3-319-39884-4. Or see: http://vbn.aau.dk/da/publications/searchall.html?searchall=weptos for an extensive list of publications on the WEPTOS.

WaveNet (Figure 30). The wave net is a multiple point absorber developed by Albatern that allows power capture from 5 of the 6 degrees of freedom of wave energy: pitch, roll, heave, surge and sway. Innovation is centred around the Squid units, composed of aup of central riser tube connected to 3 buoyancy floats by linking arms, where the connections between each of these components is made by 6 identical, and fully articulated pumping modules. The rotating movement is converted into hydraulic power. Interlinked WaveNET units react against the rest of the array to deliver non-linear yield improvements as array dimensions increase. The Squid generating units feature a patented pumping module design, which avoids the use of mechanical end-stops. The latest projects are: Kishorn Hydrostatic Testing and deployment of the Squid on the Isle of Muck.

Symphony (Figure 31). The Symphony WEC is a novel approach to the Archimede WaveSwing originally developed by AWS, however it it contains in the end only two critical or key components: a are the structural membrane and the water turbine. Both are new patented technologies. The two key technologies replace a number of critical parts of the AWS, like bearings, endstops, hydraulic piston, the linear generator and the large air volume. Although the Symphony key components are novel, they are believed to be well designed and tested. The membrane is designed, build and tested by Trelleborg. The development and test of the key components are performed within the EU H2020 project WETFEET.

Short bibliography: https://symphonywavepower.com/the-symphony-technology/

CCell (Figure 32) is an Oscillating Surge Wave Energy Converter (OSWEC) developed by Zyba Renewables Ltd. The flexible curved guides of the CCell paddle focus the incoming waves towards a strong central core, driving the paddle forward and backward. Similarly, CCell's convex shoreward face cuts smoothly through the water, reducing energy dissipation from this face. This motion is consequently converted into electrical power.

Short bibliography:

https://www.sciencedirect.com/science/article/pii/S240589631733416X

KNSwing (Figure 33). KNSwing is an attenuator-type device, with wave energy absorbing sides. KNSwing wave energy converter investigates the use of concrete (see Figure 33) as construction material. The WEC is shaped as a ship with a central buoyancy volume and along each side is placed of Oscillating Water Column (OWC) chambers absorbing the wave energy converted via air-turbines. It has been tested in scale 1:50 at HMRC, QUB and AAU basins.

Short bibliography:

https://www.sciencedirect.com/science/article/pii/S2214166915000326#s0005

HACE (Figure 34) is another WE exploring the multi-chamber OWC concept. Its design is expected to bring three major benefits: it generates power from all types of waves, and operate almost all the time; the device is designed to be low weight and to reduce operating costs by simple maintenance. Finally it is designed to produce energy in a non-intermittent and stable way, avoiding massive destabilisation of the grid. The company has raised 850.000 Euro through the crowdfunding platform Happy Capital, that will be used for prototype construction, and has received support from the Foresea project.

Short bibliography:

http://hacewave.com/, https://www.youtube.com/watch?v=PUU3b6gqXSk

Seabreath wave energy MORE (Figure 35). MORE is a two-chamber oscillating water column device designed to generate a unidirectional and (ideally) continuous airflow. This kind of airflows allows the use of turbines with higher efficiency than the ones used in single-chamber OWCs. The MORE is based on the Seabreath's concept (Patent n. PCT/IB2009/051646). It has been validated by mean of tests carried out on scaled prototypes in wave flume, with regular and irregular waves, at the Department of Civil, Environmental and Architectural Engineering of the University of Padova.

Short bibliography:

http://www.seabreath.it/index.php/component/content/article?layout=edit&id=46

Hann-Ocean Energy – Drakoo (Figure 36). Drakoo is a twin-chamber OWC system that works by transforming waves into a continuous water flow driving a hydro turbine generator to produce electricity. The two chambers are connected by the hydro turbine, which exploits the flow of water generated by the water level difference between the two chambers to generate power. Step 1. An incoming wave increases the inlet chambers' water level. Simultaneously water is partly directed from the inlet to the outlet chamber, through a hydro turbine. Step 2. Once the water level outside the device falls, both chambers' water levels also fall, leading to a flow from the inlet to the outlet chamber and the outlet chamber to the outside environment. The two-step action of the water columns occurs continuously in waves. Meanwhile, the checkerboard valves regulatae the water flow. The water flow is nearly constant and one-directional resulting in smooth rotation of the hydro turbine which in turn generates stable electricity efficiently.

Short bibliography:

http://www.hann-ocean.com/en.php/products/drakoo.html,
https://tidalenergytoday.com/2018/03/23/hann-ocean-achieves-wave-energy-breakthrough/

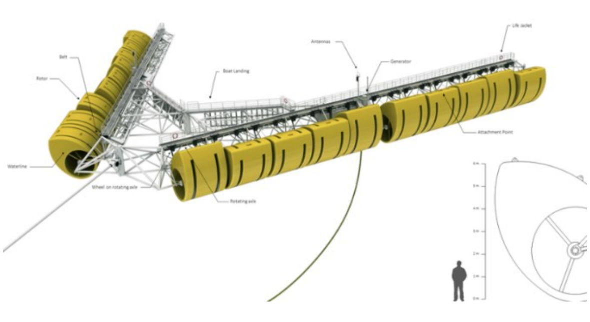

Figure 29 – WEPTOS. ©Weptos

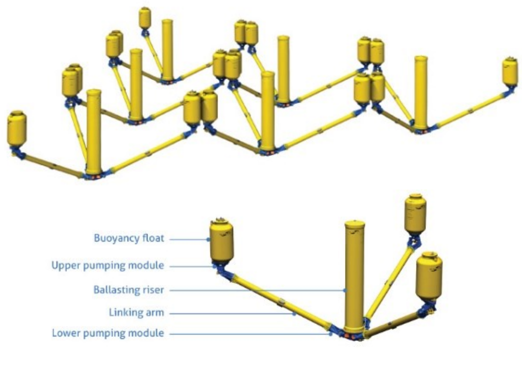

Figure 30 – WaveNET. © Albatern Ltd

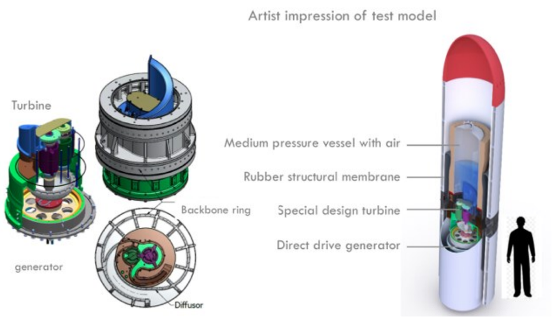

Figure 31 – Symphony. ©Teamwork BV

Figure 32 – C-Cell WEC © Engineering by Zyba Ltd

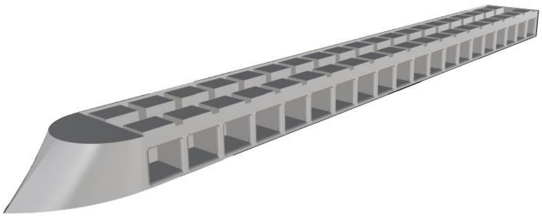

Figure 33 – KNSWING ©Ramboll

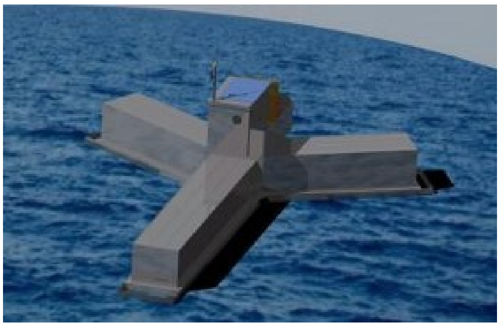

Figure 34 – HACE. ©Hace

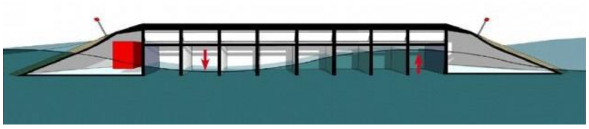

Figure 35 – MORE WEC – Seabreath ©Seabreath

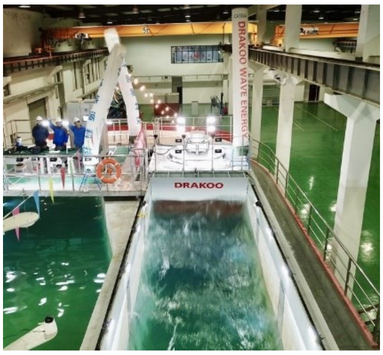

Figure 36 – Drakoo Twin Chamber OWC. ©Hann-Ocean Co.,Ltd

6 Novel wave energy converters

6.1 Key words

Carpets, membranes, tubes.

6.2 Brief technology description

This category includes all concepts that were developed as substantially different concepts from the first generation wave energy technologies. These technologies also attempt to take a distance from some issues experienced by first generation technologies. They extract energy from waves in a different way compared to mathematically inspired concepts following the pitch-heave-roll (point absorbers), pneumatic power (OWCs) or potential power (overtopping). They instead exploit the material-flexibility and the orbital velocities of water particles to convert wave power to electricity. As such second generation wave energy converters are characterised by an overall simplicity of design compared to first generation wave energy devices, though many concepts are still at a low TRL and have yet to provethe scalability of the device and of the PTO.

This, like for tidal energy, is an important area of continued research.

6.3 Advantages

- Fewer moving parts
- Passive system with reduced maintenance
- Reduction of wave loadings
- Elimination of complex mechanical and hydraulic components
- Light weighted and potential for cost reduction

6.4 Limitations

- Materials require further optimisation to perform optimally and extract interesting quantities of energy.
- Limitations modelling capabilities.
- Scalability.
- Integration of PTO at higher TRL to be proved.

6.5 Stage of development: TRL, size and speed

Second generation wave energy technology are at a very low TRL(1-3), with no device tested nor installed in real sea. The maximum power rating for the device is yet to be identified, being dependent on the scalability of the material and PTO to utility scale. The speed of development could be medium-fast speed of development (e.g lower than 10 years) if chosen materials show little limitations and PTO performances are in line with expectations.

6.6 Projects & Activities

SBM S3 (Figure 37) SBM S3 is an innovative wave energy converter that features direct energy conversion from waves to electricity by means of electro active polymers. Electro-active polymers generate electricity once the membrane forming the converter is excited at the passing of waves. The flexible floater and its mooring system require minimum maintenance. Further detailes on electro active polymers can be found in section 7.5, where their application as PTO is discussed.

Short bibliography:

SBM S3: https://www.youtube.com/watch?v=LKHT5I9Xbjw&feature=youtu.be, https://www.sbmoffshore.com/wp-content/uploads/2016/06/Technology-Wave-Energy-Converter-FINAL-LOW-RESOLUTION.pdf

LILYPAD (Figure 38). The Lilypad WEC consists of a floating flexible membrane which follows the motions of the seas, and connected by ties to a submerged membrane which is "weighted and valved". The Lilypad is a scalable system that can exploit a very large wave front, and that can also be employed for coastal protection. Incominng wave move the upper membrane exerting a pull on the ties, whilst the lower membrane is designed to resist the upward forces. An extensible hose pump is used to create hydraulic pressure, that then activates a Pelton turbogenerator. Elastic tie elements are used to extend sufficiently, overcoming the hose pump's limitation, to facilitate the rise and fall of the upper membrane. These elements can be designed to resist extension at a constant force, which can then be transferred to a rotary system encapsulated in a surface mounted sphere, where electricity is generated. The Liliypad WEC is a patented concept.

Short bibliography:

LILYPAD: http://www.energyisland.com/projects/lilypad/lilypad.html

Costas Waves (Figure 39) Costas Wave is a WEC which employs water turbines activated by the waves. A system of flaps and chamber helps transforming the circular motion of the waves into a water flow that can be efficiently used by the turbines. It was tested under Marinet Program in 2013 at Aalborg University.

Short bibliography. https://www.youtube.com/watch?v=PKOfxV3WuwY

Anaconda (Figure 40)**.** The Anaconda, exploits the wave pressure in a submerged tube to drive a turbine. An entirely sealed structure, much designed like a trimaran, floats on the surface and converts ocean wave energy into electricity by utilising traditional hydropower plant and control methods. Wave motion is used to excite the power plant and causes an inner liquid volume to flow between the chambers via low-head vertical turbines. The turbines are connected to generators and electrical power quality is regulated using power electronics. Connected directly under the power plant is a conventional mooring system that is attached to the seabed. Electricity is exported to the shore via a standard marine cable, incorporating fibre-optic cable for communication and control. Produced electricity is delivered to the onshore grid or a local microgrid connected to power desalination plants onshore. A limitation to this type of wave energy converter is the identification of a sustiable type of PTO.

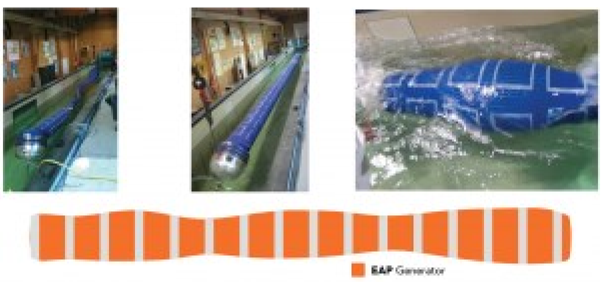

Figure 37 – SBM S3 Device. ©SBM Offshore

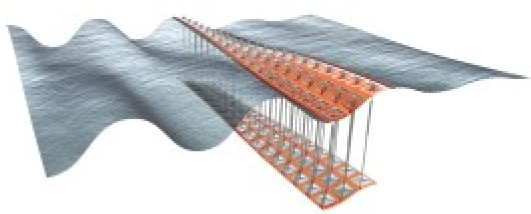

Figure 38 – Lilypad WEC. ©Energy Island Ltd.

Figure 39 – Costas Wave ©Aalborg University

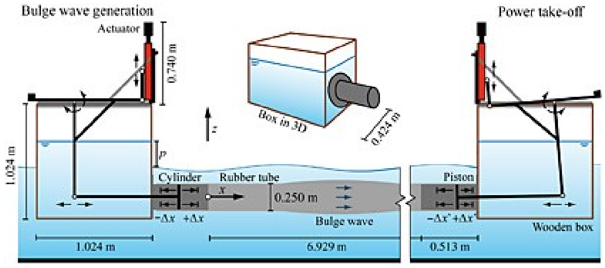

Figure 40 – Anaconda. ©Southampton University

7 Innovative tidal and wave energy power take off

7.1 Key words

Mechanical PTO, Dielectric Elastomers, Magnetic Screw, Bi-radial turbines, Very Low Head Turbines, Direct Drive, Self-referencing or Inertia, gearless power take off, generator.

7.2 Brief technical description

The Power Take off (PTO) is here discussed as a technology family that relates to both tidal and wave energy applications. While the PTOs are not necessarily the same, the issues and innovations are generally of common interest. Some of the PTOs here presented, even if so far have been applied to one or the other category, may find a different application in the future.

Figure 41 offer a schematic of power take off systems based on the principle of conversion of the incoming power to electricity.

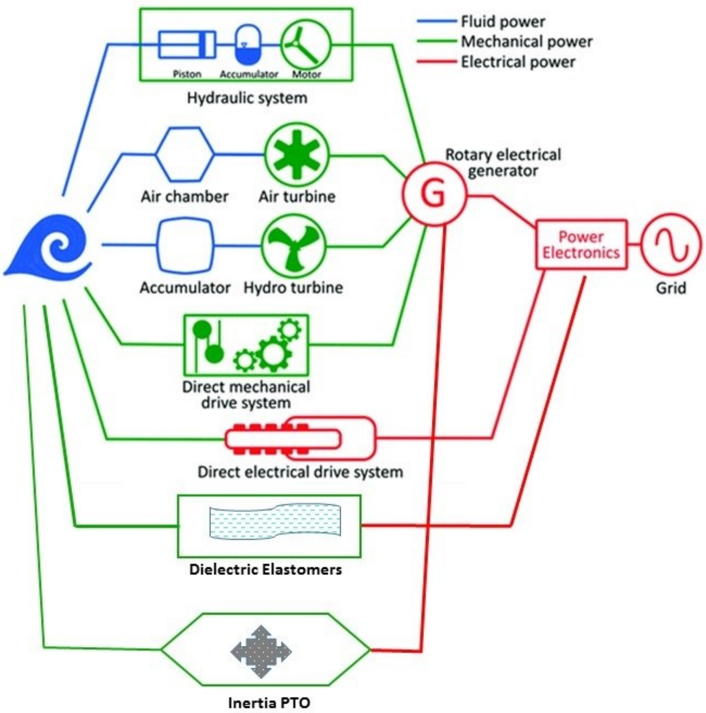

Figure 41 – Schematic of power take off systems based on operating principle. Modified schematics from: Têtu A. (2017) “Power Take-Off Systems for WECs” In: Pecher A., Kofoed J. (eds) Handbook of Ocean Wave Energy. Ocean Engineering & Oceanography, vol 7. Springer, Cham.

We will divide the PTOs in seven sub-families, each with a dedicated a subchapter:

- Mechanical;
- Direct Drive;
- Dielectric Elastomers;
- Hydraulic systems;
- Pneumatic;
- Hydro turbine systems;
- Self-referring or inertia PTOs;

7.3 Mechanical PTOs

Mechanical PTOs are those systems that translate the incoming energy by means of an extra mechanical system to drive an electrical generator, often by means of a gearbox. This process can take place in different ways:

- In the case of tidal turbines, the PTO transforms the tidal stream via blades into a horizontal rotor shaft application in a speed range of 10 to 80rpm depending on turbine and blade size. Low speed input torque then transferred via a gearbox to high speed driven generator. This is an approach similar to what is widely used in wind turbine application.
- In the case of wave energy, the mechanical energy of an oscillating WEC is transformed into rotational motion, which is coupled to an electrical generator.
- Novel applications are investigating the translation of non-rotary oscillating motions of a device into rotary motions before activating the generator. This option can be considered as a direct-drive mechanical PTO, offering the advantages of direct-drive systems (no gearbox) whilst employing a mechanical PTO. Overall it is expected that eliminating components such as gearboxes increases drive train robustness and compactness.

7.3.1 Advantages

Mechanical PTOs offer a number of advantages such as:

- Know how from many other sectors (e.g. wind turbine geared drive train, ship propeller shaft application).
- Well established technology.
- High speed inputs to generator reduce generators sizes and costs and increase efficiency.

The development of novel approaches to mechanical PTOs offer additional benefits such as:

- Increasing reliability, availability and efficiency of drive trains.
- Potential cost-reduction to allow for cost-competitiveness with offshore wind.
- Shorter energy conversion chain, and reduced number of components.
- Lower inertia, allowing quick reaction to varying conditions and adapting well to a wide range of control strategies.
- Magnitude of subsea power electronics and control systems and improve efficiency.
- Possibility to develop a "direct-drive configuration", which allows implement reactive control strategies (i.e. use the EMG in motor-mode) to be implemented.

7.3.2 Limitations

- Must allow the possibility to feed energy back to the system, for control purposes.
- Protecting the large size, low speed PMG generator against sea water is a big design challenge and there are limitations.
- In case the generator is open against sea water, debris and bio-fouling inside the generator is a big un-known point and developments and tests are needed.
- End stop problem (mechanical system moves with a certain stroke but can be destroyed if pushed too much by the waves).
- Tribology: different kinds of friction (and lubricant regimes) between components of the system need to be understood and addressed to avoid wear issues.
- Efficiency, as gears are sliding-friction components with intrinsic energy losses;
- Wear and sub-sequent metal particle dispersion in lubricant;

- The know-how from other sectors needs to be adapted to sea environment.
- Tolerances and assembly are very delicate for the magnetic screw type gears.

7.3.3 Stage of development: TRL, size and speed

The development of mechanical PTO has reached high TRL for geared tidal energy applications. Some of the more innovative PTOs innovation have reached medium TRL5-7. The speed of development was found to be medium-fast, with concept progressing quickly through the TRLs. The final size could range between 100 kWs to MW size.

7.3.4 Projects&Activities

WEPTOS has developed an innovative system to translate the up and down motion of its floaters into one directional rotation that is then fed to the shaft to the generator.

ResenWaves (Figure 42) is developing a spring based system able to optimise the energy capture of the buoy and translated into a rotating motion to the generator.

The **Magnetic screw** (Figure 43) converts the linear energy (coming from a buoy, for example) into rotations directly with a conversion efficiency of about 85 percent in the initial tests with a potential closer to 90-95 %. It is therefore classified as a Mechanic PTO as its motion can be fed directly into a generator. It was first designed to substitute the hydraulic PTO in WaveStar, no longer active, and despite the promising results, its development has stopped.

CorPower cascade gearbox (Figure 44) is capable of efficient conversion of linear-to-rotating motion with high durability. The amplified linear motion is converted into rotation using a proprietary cascade gear box, capable of efficient conversion of linear-to-rotating motion with high durability. The cascade gear has a design principle similar to a planetary gear box, dividing a large load onto a multiple of small gears, providing high power density. Compliant elements provide damping of transient loads, making it very robust. A dual set of flywheels/generators provide power absorption and temporary energy storage for power smoothing. Generators and power electronics are standard components known from the wind industry, enabling well known grid connection architecture.

Main project activities: WaveBoost in H2020 and HiDrive at EMEC and a Swedish Energy Agency funded full scale device test, commencing mid-2018..

The **Electro-Mechanical Generator (EMG)** is an innovative type of Power Take-Off (PTO) developed by UMBRAGROUP spa for wave and tidal energy applications, capable of converting slow speed, linear motion into three-phase electricity at high efficiency and reliability. Permanent magnets are integrated on the rotating component, which acts thus as rotor of the electrical generator. The rotor, spinning inside a bespoke-designed stator, induces a voltage on the stator windings thanks to the principle of electromagnetic induction. The frequency of the induced voltage is proportional to the number of poles of the generator. The technology is already widely used and well established in other sectors, e.g. robotics, machining tools or aircraft control systems.

Relevant projects:

- ReBaS (Figure 45) – Recirculating BallScrew,funded by Wave Energy Scotland (WES) under the innovation call for PTOs, Stage 2 (2015-2016):
- EMERGE funded by Wave Energy Scotland (WES) under the innovation call for PTOs, 2017-2019. GENERA (led by UMBRAGROUP spa, ongoing), funded by the Italian Ministry for Economic Development (MISE), 2017-2018.
- IMAGINE (led by UMBRAGROUP spa, ongoing), funded by the European Commission under the H2020 framework in the LCE-07-2016-2017 call.

- Short bibliography:

- "High performance mechanical actuators for aeronautical applications" project, PON Research and Competitiveness 2007-2013, National Operative Programme from the Italian Ministry of Economic Development.
- L. Castellini, M. Carmignano and M. D'Andrea, "Design and characterization of a 9.4 kW generator for wave linear reciprocating energy conversion," in International Conference on Clean Electrical Power (ICCEP), Alghero, Italy, 2013.
- G. Alessandri and L. Castellini, "Dry and Wet Testing of a PTO based on Recirculating Ballscrew Technology," in Asian Wave and Tidal Energy Conference (AWTEC) 2016, Singapore, 2016.
- L. Castellini, M. Martini, G. Alessandri, "Development and Testing of a Ballscrew Electro-Mechanical Generator (EMG) for Wave Energy Conversion", in European Wave and Tidal Energy Conference (EWTEC) 2017, Cork, 2017.

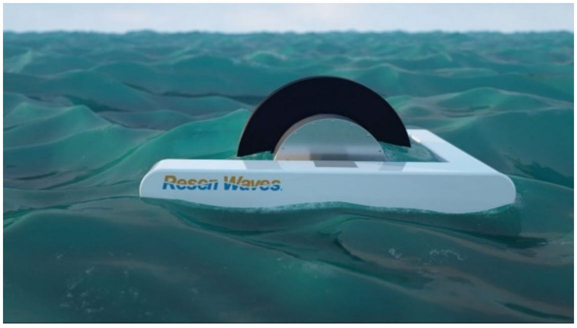

Figure 42 – ResenWaves. ©ResenWaves

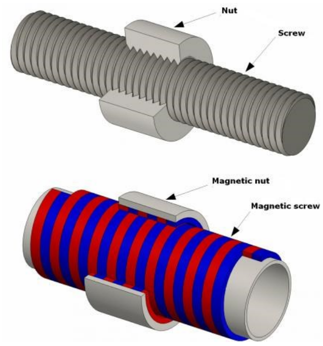

Figure 43 – Magnetic screw. ©Aalborg University

Figure 44 – CorPower cascade gear. ©CorPower Ocean AB

Figure 45 – ReBaS tests at Federico II, Italy. ©UMBRAGROUP

7.4 Direct Drive Systems

Direct drive, electrical PTOs are those systems where the incoming mechanical energy is directly converted to electrical energy at the generator without any intermediary stages. Direct drive systems include linear and rotary solutions, with both generally employing permenant magnet machines.

- Linear solutions have a larger application in wave energy devices due to the osscillatory nature of the energy source. The mechanical energy of the oscillating device is directly connected to the moving part of a linear electrical generator. In a point absorber WEC, for example, waves induce a heaving motion in the prime mover with respect to a relatively stationary stator equipped with coils, inducing an electrical current.
- Tidal systems generally employ rotary solutions, with leading technologies employing a similar topology to wind turbines, though a number of distinct types exist.

Good efficiencies in the range of 70-80% over a wide range of operating points are achievable and there are significant reliability and maintainability advantages. These machines tend to be physically large and heavy with significant structural and lubrication challenges. Various novel speed enhancing techniques exist to increase speed, such as magnetic gears or the use of springs and these would reduce the size of the machines and increase their efficiency as well as addressing excess loads.

The main development challenge: proving various aspects of the technology – operation in the marine environment, bearings, optimum machine architectures, scale-up and integration with WECs, reliable power conversion, cooling systems, magnetic gearing integration to improve efficiency, use of springs.

7.4.1 Advantages

- Direct conversion of ocean energy into electricity.
- Lower number of component.
- Decreased drivetrain losses due to reduced number of conversion steps.
- Multi-stage machines allow a fault in one stage to be isolated and the remaining stages can generate increasing availability, annual energy yield and hence reducing LCOE.
- High degree of modularity enables replacement of single faulty modules rather than the complete machine - improves maintainability and reliability.
- Reactive control capabilities.
- Systems which operate in seawater flooded environments avoid the need for sealing

7.4.2 Limitations

- Rectification needed before conversion into a sinusoidal fixed voltage and frequency waveform for grid connection. (Possible related O&M issues)
- Systems typically large and heavy due to the required high pole number without speed enhancement (typically more expensive - capital costs & installation costs)
- Operation in the marine environment.
- Linear systems have to overcome strict design requirements for air gaps between translator and stator.
- Cooling system.

7.4.3 Stage of development: TRL, size and speed

TRL 3-6, 25kW - 250kW size and medium development speed.

7.4.4 Projects & Activities

TAOIDE (Figure 46)is an H2020 project developing a direct drive permanent magnet generator capable of operating in a fully flooded condition. To provide reliable electrical generation it is critical to develop a generator that can withstand water intrusion. ORPC is designing and developing a high reliability electrical generator system for application in marine renewable devices, utilizing technologies already developed by ORPC vendors. This design comprises a fully-seawater flooded, "wet-gap" generator, capable of continuous and reliable operation in a marine environment. This design will maintain operability due to encapsulated rotors and windings. Such a "wet gap" generator will enhance generator longevity, decrease repair times, and increase system availability.

Short bibliography: https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/ocean/taoide

TiPA (Nova Innovation, Figure 47) is an innovative direct drive Power Take-Off (PTO) for a tidal turbine. The focus of this project will be to replace the gearbox and conventional generator in the turbine with a PTO featuring a high-efficiency, low-maintenance direct drive generator. Successful development of a direct-drive PTO will significantly increase the commercial viability of tidal turbines. Reducing the cost of operation and maintenance of tidal arrays will increase Return on Investment for turbine customers, allowing turbine technology development companies to sell more devices into an emerging global market.

Short bibliography: http://www.tipa-h2020.eu/tipa-project/

PowerPod (Figure 48)technology by TRIDENT ENERGY: direct drive linear generator (for tidal and wave energy). Full 4-quadrant control capabilities, Trident's linear machine is more than just a generator; it is also a highly controllable, "damper" and "spring".

Short bibliography: http://www.tridentenergy.co.uk/markets/wave-and-tidal/

The **PECMAG PTO** system is a modular all-electric system with magnetic gearing that is being developed to suit a variety of WEC devices. The system can be configured as linear or rotary PTO options that offer flexible installation and deployment possibilities. There is no physical contact between the magnetic gears and so the system is able to 'slip' at high loads without damage. A project is being supported by Wave Energy Scotland[10].

Current projects include University of Edinburgh who are developing a 150kW linear generator **project Neptune** https://www.cgen.eng.ed.ac.uk/ under a £2.5m Wave Energy Scotland Stage 3 PTO fund. The **e-Ddrive project** (Figure 49) is developing linear and rotary systems with non-mechanical speed enhancement using magnetic gears for pseudo direct drive systems combining the advanatges of direct drive while reducing some of the limitations. This is currently funded by the EPSRC in the UK.[11].

Frictionless linear electric generators. The use of frictionless linear electric generators can prevent the use of mechanical-driven electric generators (e.g. endless screw). These are being investigated at Aalborg University[12]..

See for example: https://www.youtube.com/watch?v=f9Cs3daKT6o

[10] http://www.waveenergyscotland.co.uk/programmes/details/power-take-off/power-electronic-controlled-magnet-gear-pecmag/

[11] https://www.edrive.eng.ed.ac.uk/

[12] http://www.sdwed.civil.aau.dk/digitalAssets/97/97525_d3.2.pdf

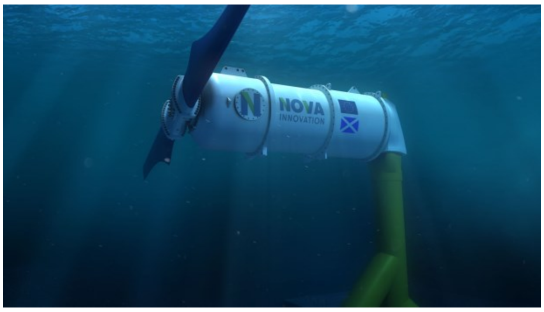

Figure 46 – ORPC device part of the TAOIDE project© ORPC, Inc

Figure 47 – Nova Innovation Tidal Turbine as part of the TiPA project. ©Nova Innovation

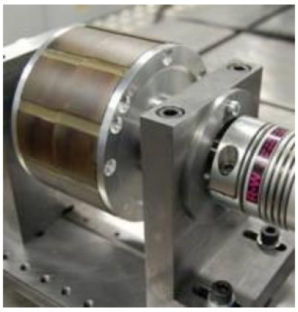

Figure 48 – Component of the PowerPod linear generator. ©Trident Energy.

Figure 49 – e-Drive project. ©e-Drive, University of Edinburgh

7.5 Dielectric Elastomers

Dielectric elastomers' working principle is based on the change in capacitive energy of a deformable dielectric. Dielectric Elastomer Generators (DEGs) are electrostatic generators, highly deformable solid-state capacitors that convert the mechanical work required for the deformation into stored electrostatic energy. This energy can subsequently be withdrawn from the capacitor at any time during and after the energy conversion phase.

Applied to wave energy, DEGs introduce a radical change in the traditional architecture of wave energy converters. Thanks to this functioning principle, DEG technology allows the merging of the primary mover and PTO components of Wave Energy Converters (WECs) into a single deformable body (typically a membrane), with the function of both capturing ocean wave energy and converting it into electricity.

7.5.1 Advantages

- Significant reduction in the number of components and consequently also maintenance costs. DEGs essentially reduce the entire drivetrain and PTO into a single stage.
- Good electro-mechanical conversion efficiency (60 - 90%) that is almost independent of load amplitude and frequency;
- Rather good mechanical toughness;
- Low weight and low mass density;
- Easy manufacturability, handling, assembling and recyclability;
    - Consequent easy installation and possible cost reductions;
- Good resistance to corrosive environments and biofouling;
- Silent operation;
- Integrated sensing functions;
- Solid-state monolithic embodiment with no sliding parts, no need of lubrication and low internal friction;
- Permits radically different and novel WEC designs.

7.5.2 Limitations

- Material has to be optimised to compromise between flexibility and durability: low flexibility limits power extraction, but high flexibility limits durability
- The capacity of the dielectrics may be an obstacle for scaling up the technology
- Issues related to the current manufacturing process: the large surface area of DEG-based devices, combined with the flexible nature of the elastomer film and possible friction between layers might induce reduced lifespan of the transducer. Furthermore, attention must be paid during the process so that air is not trapped in the interface, thereby causing a decrease in electrical breakdown strength.

7.5.3 Stage of development: TRL, size and speed

TRL 2. Can probably only achieve few kW in size, which requires further investigation. Fast speed of development.

7.5.4 Projects & Activities

Researchers from DTU Chemical Engineering (Denmnark), in collaboration with SBM France, have developed elastomers with high energy density, which means they can utilise the waves' movements and create electric energy (Figure 50). A simple scale model of EPAM-based wave energy harvesting system was tested in a wave tank over a range of wave periods from 0.7 to 3 s and wave heights from 2 cm to 6 cm. The energy output was found to be largely independent of wave period.

Potentially, SBM France will place a 500-meter long elastomer tube of the coast of France - five meters below the bottom of the ocean. It is expected that the elastomer generator will deform by the huge wave powers, and the mechanical deformations will in return turn into electric energy.

The Universities of Trento and Bologna and SSSUP (Pisa), in Italy, are actively investigating Dielectric Elastomers Generators through a range of FP7, H2020 and WES projects (Figure 51):

- **PolyWEC:** Future Emerging Technology FP7, EU Project. New mechanisms and concepts for exploiting electroactive Polymers for Wave Energy Conversion. http://www.polywec.org/
- **WETFEET:** H2020 Energy Project, Wave Energy Transition to Future by Evolution of Engineering and Technology. http://www.wetfeet.eu/
- **WES (PTO call) Stages 1&2:** Wave Energy Scotland funded project on direct contact dielectric elastomer wave energy converters.

AWS Ocean Energy Ltd are also developing their Electric Eel™. As stated by AWS, “it consists of a long elastic tube which is tethered below the surface of the sea. A passing wave causes a pressure or ‘bulge’ wave to propagate along the elastic tube. Power is extracted by smart electro-active polymer panels built into the sides of the tube. These panels are entirely flexible and produce an electric current when stretched.” Concept studies of the technology have now been completed with patents granted in a number a jurisdictions.

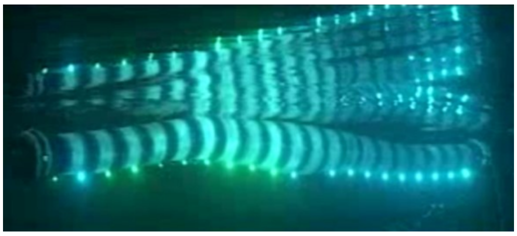

Figure 50 – Dielectric elastomers ©SBM Offshore

Figure 51 – PolyWEC tested as part of WES PTO project ©PolyWEC

7.6 Hydraulic PTOs

Hydraulic systems are used to interface the wave energy converter with the electrical generator since they are well suited to absorb energy from large forces at low frequencies. The movement of the body feeds energy into a hydraulic motor that then drives a generator.

7.6.1 Advantages

- Works well in low frequencies and high forces.
- The variability of the input can be accommodated with the use of different gasses and accumulators. It accommodates peak loads and smooths the energy conversion.
- Hydraulic pumps and motors may also be combined in a system that comprises fluid energy storage.
- Well established and understood technology with a mature supply chain making systems and components readily available.

7.6.2 Limitations

- Risk of fluid contaminant and environmental concern. Biodegradable fluids (e. g. synthetic esthers) could be an alternative. These fluids are already state of the art. Up to now mineral or synthetic oils were used since the amount of fluids was no big concern. And we are not talking about crude oil here. Need for environment-friendly oils and oil leakage containment measures.
- Large dimensions with a system comprosing of many components.
- Issues with the wear and seals of the pistons.
- Part load operation tends to have low operating efficinciences.

7.6.3 Stage of development: TRL, size and speed

The stage of development is medium high, above TRL 3-7. The size . Speed of Development: medium. Up to MW size.

7.6.4 Projects&Activities

WaveRoller uses hydraulics PTO. It has recenltly been awared the H2020 Megaroller project to investigate scaling up of the PTO to MW size.

WaveStar used Hydraulic PTO system in their device installed at Halstom (Figure 52). Similarly, **Pelamis** employed hydraulic PTO.

WavePOD developed by Bosh aims at developing an off-the-shelf standardised hydraulic transmission or power-take-off, without requiring customised components or fast control response times (Figure 53). (Support from the Scottish Government's Marine Renewables Commercialisation Fund (MRCF).

Wave Energy Scotland has funded a project by **Artemis Intelligent Power** and **Quoceant** to further investigate the development of hydraulic PTO for wave energy applications.

Figure 52 – Wave Star Piston ©Wave Star Energy

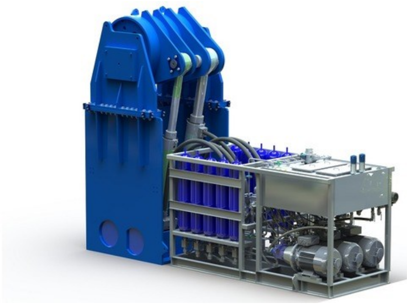

Figure 53 – WavePOD. ©Bosch Rexroth Great Britain

7.7 Pneumatic PTO

Pneumatic PTO are employed in Oscillating Water Colmun WECs for conversion of pneumatic power (pressurised air as a results of wave action) into electric power.

Bi-radial turbines, impulse and directional tubrines have been developed to improve the performance of OWC concepts. Following installtions in onshore OWC systems (e.g. Mutriku, Pico and Limpet), research is focusing on coupling turbines with floating OWC concepts.

7.7.1 Advantages

- Turbine is the only moving part in the whole system.
- Turbine is not in contact with sea which reduces loads, wear and damage risk whilst increasing maintainability.

7.7.2 Limitations

- Large dimensions.
- Must allow the possibility to feed energy back to the system, for control purposes.
- Depending upon the turbine type, impulse or reaction, the efficincy can be lower but is a trade off with complexity of the turbine.
- Turbines can be noisy during operation as they pass the oscillating air flows and exhaust these to the environment.
- Limited compatibility with a range of wave energy convertor types other than OWC wave type devices.

7.7.3 Stage of development: TRL, size and speed

TRL 6-8, more than 500 kW installed. Speed of development, slow.

7.7.4 Projects&Activities

Different OWC systems are currently being investigated, such as the OceanTEC Marmok device

Figure 54), the OceanEnergy Bouy (Figure 55), the Aquapower AirTurbine. R&D focus is on optimising the turbine shape and control system to increase power out.

OCEANTEC Marmok-A5 device is a point absorber oscillating water column (OWC) wave energy device whose generating system comprises two turbines located in the upper part of the device with a rated capacity of 30kW. The device generates power when the waves cause water column to rise and fall, compressing and decompressing the air above, which spins the turbines to drive an electricity generator . The device employs a vertical trubine, developed by Kymaner as well as one in-house developed turbine (SPOWCON). Turbines were dry-tested at Mutriku previous installation on the Marmok device. The deployment of the Marmok-A5 wave energy device at Bimep site, located 1.7 km off Armintza, took place in 2016, OPERA project.

Short bibliography:

- http://www.oceantecenergy.com/
- http://opera-h2020.eu/?p=1002
- https://www.researchgate.net/publication/319464897 (Open_sea_OWC_motions_and_mooring_loads_monitoring_at_BiMEP).

OceanEnergy Buoy. Siemens (Dresser Rand) are developing a next generation system – HydroAir which is being constructed at 500kW for deployment at the US Navy WETS test site in Hawaii on board the OE Buoy device. This is similar to the bi-radial turbine but has very high efficiency over a broad band. This power system has typical power electronics which makes the electricity produced fully grid compliant.

Short bibliography: A Novel High-Efficiency Impulse Turbine for Use in Oscillating Water Column Devices. Natanzi, S.; Amaral Teixeira, J.; Laird, Proceeding of the 9th European Wave and Tidal Energy Conference, EWTEC.

Figure 54 – Bi-radial turbine from Kymaner (Vertical). ©Opera H2020/Kymaner

Figure 55 - OceanEnergy OWC ©OceanEnergyIreland

7.8 Hydro-turbines systems

Hydro turbines, typically employed in overtopping devices or hydraulic pump systems using seawater as fluid have many years of design as propellers in the ship industry and for hydroelectric power plants. Nevertheless, despite being generally a mature technology, the working conditions for ocean energy are obviously quite different.

7.8.1 Advantages

- They operate at high efficiencies, above 90%.
- Well established and understood technology with a mature supply chain making systems and components readily available.
- Low maintenance.

7.8.2 Limitations

- Mechanism regulating the flow to the turbine with relative control must be designed: start and stop mechanism.
- New control of guide veins and pitch control.
- Efficiency drops for heads below 0.8 m.
- Limited compatibility with a range of wave energy convertor types other than overtopping machines or hydraulic machines.

7.8.3 Stage of development: TRL, size and speed

TRL 3-4. Size from few hundreds kW to 100s MW. Speed of Development, fast.

7.8.4 Projects & Activities

Ongoing projects on developing hydro-turbines for ocean energy development include the Gator PTO, The SDK Wave Turbine, the WaveSax and the Symphony Water turbine.

The **Gator** PTO (Figure 56)is based around a novel polymer 'spring pump' capable of pumping significant quantities of water at moderate pressures through conventional hydro-electric turbines.The hydro-electric PTO concept is based on a flexible compliant polymer spring tube. This polymer spring (or Gator) can be designed with a wide range of non-linear response curves allowing tailoring of the stress strain response. The first stage of this project looked at the viability of the thermoplastic spring (Gator) as a PTO system suitable for application in a range of wave energy devices. It's curently being support by Wave Energy Scotland.[13]

The **SDK Wave Turbine** (Figure 57) consists of a hydraulic turbine immersed in water within a resonance chamber. It was tested as part of the Marinet project.

The **WaveSax** (Figure 58), is a device based on the OWC concept, exploiting the flor of water contained in water-air chamber. The system howeer employ a hydro turbine which is activated by the the upwards and downward motion of the water column.

The Symphony water turbine (Figure 59), is the PTO of the Symphony WEC. As the device respond to the incoming waves it pressurised an internal fluids which operates a water turbine within the device activiang the generator. The fenerator is directly connected to the turbine wheel. As the magnets are on a large diameter and the velocity of the rotor goes up to almost 400 rpm, much less magnets and coils are needed and a large cost reduction is created compared to another option; the linear generator.

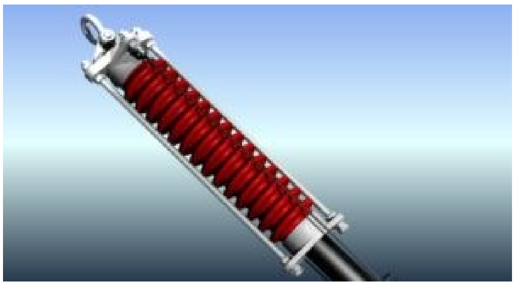

Figure 56 – Gator. ©Pelagicinnovation

Figure 57 – SDK Wave Turbine. ©Sendekia Ingenieria

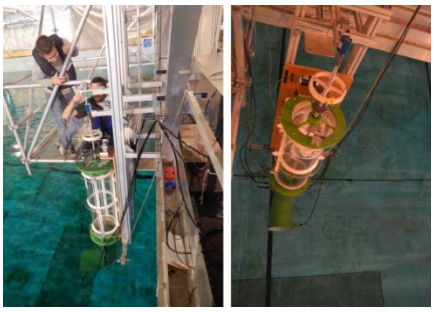

Figure 58 – WaveSax. ©RSE SpA

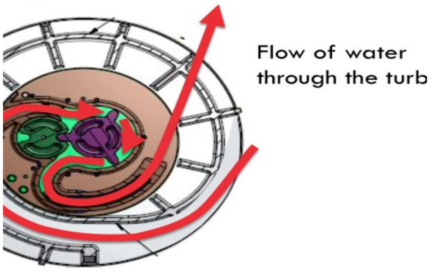

Figure 59 – Synphony water turbine. ©Teamwork BV

13 http://www.waveenergyscotland.co.uk/programmes/details/power-take-off/gator-a-compliant-seal-free-hydraulic-pto/

7.9 Inertia systems

Reacting body devices use the inertia of a large mass to generate the reaction needed by the power take off (PTO). Contrarily, in the case of a simple inertial mass, optimal control can adjust the dynamic parameters of the PTO (the spring constant and damping), to maximise energy absorption.

7.9.1 Advantages

- All the main moving parts are protected inside the floater body.

7.9.2 Limitations

- Big size is required to produce energy
- Relative large moorings required
- Large expected costs.

7.9.3 Stage of development: TRL, size and speed

TRL is 6-7, they can probably reach MW size but the cost would most likely be prohibitive. Speed of development, medium.

7.9.4 Projects & Activities

ISWEC. The ISWEC (Inertial Sea Wave Energy Converter) uses a gyroscope to create an internal inertial reaction that is able to harvest wave power without exposing mechanical parts to the harsh oceanic environment.

Whatever Input to Torsion Transfer (WITT). Contained within a sealed unit, a WITT uses two pendulums connected to a flywheel to generate electricity. Movement causes the pendulums to swing, and they are attached to a shaft that then turns a flywheel in one direction. The flywheel is connected to a generator, which produces electricity. The unit harvests chaotic motion, fast, slow or erratic, turning it into useable power. The company claims that no other device captures energy from all six degrees of motion (although Protean claim the same www.proteanenergy.com/Technology/Wave-Energy-Converter). WITT can be applied to harvest energy from both wave and tidal resources.

Short bibliography: Unaware of any scientific publications. Company website at http://www.witt-energy.com/howitworks.html.

8 Control systems

8.1 Key words

Latching control, passive control, phase control, reactive control, prediction algorithms.

8.2 Brief technology description

The extraction of energy by the PTO plays a significant impact on the hydrodynamics of ocean energy converter, and as such it needs to be included in the design of a WEC or a TEC from the early stages.

Control systems are fundamental for the operability of devices, in order to increase efficiency, to switch into safe operating mode in case of storms, and to increase survivability. This implies that the forces exerted on the device are monitored regularly. The control system acts on the phase and/or on the damping of the moving body, therefore improvements in the current methods of predicting short-term wave excitation are needed.

Many different type of control strategies have been developed,including:

- Latching control. Employed for phase control, requires a quick reacting PTO;
- Passive control, where damping adjusted based on sea state;
- Reactive control, the control system dynamically adjusts the spring constant i.e. stiffness, the inertia and the damping.

Developing control systems for ocean energy, especially for a floating WECs, has proven challenging. However necessary, control of the PTO system of ocean energy converters introduces complexity, which in return may lower the reliability of the system and increases maintenance cost. The influence of the control strategy on the structural fatigue must also be taken into account. For example: the moorings influence power capture and ideally could be controlled to have difference performances in operating and safety conditions; control of moorings as an integrated part of PTO systems.

The development of new technologies, and adaption of technologies from other sectors, is progressing however the unique challenge of building a realistic and reliable numerical model (including WEC) is rather elusive.

The identification of suitable control systems for applications in ocean energy conversion is subject to different research programmes worldwide, including:

- Wave Energy Scotland are currently funding 13 Control Systems projects covering development environments, model predictive control, machine learning, and DEG specific control.
- Some research groups working on Control algorithms and real-time controllers are: COER/Maynooth national university of Ireland and IFPEN, France.
- Sandia National Labs have a considerable work piece and have also been involved with the development of WEC-Sim.

The resources allocated to the development and implementation of control systems highlights the importance and the impact that the development of advance control system can play in optimising the performances of ocean energy converters. Advantages from the development of control systems are expected in the reliability, survivability and viability of TECs and WECs, through number of challenges need to be overcome to successfully develop control systems.

8.3 Advantages

- Increased power capture
- Increased efficiency (it can realistically change the average output by a factor of up to 2 as compared to the same WEC system without phase control)
- Increased survivability thanks to possibility to run “safe mode operation” during storms
- Control of moorings as an integrated part of PTO systems

8.4 Limitations

- Increased complexity
- Learning algorithms can take time, and need to experience the real conditions. Deploying such a strategy on a full scale device may take months to experience the right sea states to fully understand the optimal control action for any given set of conditions.
- Need for continuous monitoring of relevant parameters such as incoming waves, turbulence and forces on structural components.
- Survivability in the marine environment to be proven (corrosion, bio-fouling), and for high-number of cycles.
- Errors in the monitoring relevant parameters may lead to inefficient and faulty control (time domain evaluation of the control force on the main mover for example is a challenge, as much as the predations of the incident waves and relative induced oscillations).
- Demonstrate ability to cope with highly-reversible loads and to adapt to changing conditions of the device through aging or marine growth

Further challenges related in particular to the development of suitable control systems for wave energy can related to the following issues:

- Short-term perdition of random waves and induced oscillation on the body are necessary for correct functioning (prediction algorithms, in the order of 10-20 s horizons).
- Availability of suitable test platforms including Hardware-in-the-loop rigs or scale model WECs with equipment sophisticated enough to mimic full scale WEC behaviour.
- Challenges include availability of required hardware to run sufficient simulations to find the optimum control strategy for a WEC/PTO combination;
- Many of the control systems proposed in academia, require accurate model of the WEC/PTO/Moorings and future knowledge of the wave conditions. These are not attainable as all models will have errors and will diverge through aging of components and marine growth, and wave prediction, especially on a wave by wave basis is troublesome. Some of the emerging technologies are difficult to model, either alone or in conjunction with a WEC. The dynamics of the interaction between a WEC and its PTO is incredible important.
- The spring for reactive power control is very large and expensive.

8.5 Stage of development: TRL, size and speed

Control of Tidal and Wave energy devices as been tested in real sea and TRL varies from 2-7. Tidal, particularly, can benefit from a lot of technology transfer from wind and hydropower. Experts agreed that speed of development of control system could be high due to advances in AI and computational power, however application and testing in real sea situation are still required.

Short bibliography

Some of wave energy most relevant studies about control are:

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- Anderlini, Enrico & I. M. Forehand, David & Stansell, Paul & Xiao, Qing & Abusara, Mohammad. (2016). Control of a Point Absorber Using Reinforcement Learning. IEEE Transactions on Sustainable Energy. 7. 1-1. 10.1109/TSTE.2016.2568754.
- Wave Energy Scotland – Control Landscaping reports
- Ringwood et al – "A competition for WEC control systems"

8.6 Projects&Activities

WaveSpring. The Corpower C3 wave energy converter (shown earlier in Figure 44) is equipped with phase control system based on a negative spring arrangement that inherently widens the response bandwidth of point absorbers without the need for real-time wave information or prediction algorithms. The negative spring module acts directly on the linear mechanism of the buoy. This avoids the losses associated with transmitting large reciprocating energy flows through the PTO system, a challenge that has limited the practical use of phase control methods known as reactive control. Compared to other phase control methods such as latching, the WaveSpring principle offers similar amplification of power capture, but requires less than half the machinery force and therefore enables a smaller and less costly PTO. The device motion is continuous, avoiding the fatigue and wear challenges associated with more abrupt motion resulting from latching control. Half-scale C3 Wave Energy Converter installed at the European Marine Energy Centre (EMEC).

Short bibliography: http://www.corpowerocean.com/

AquaHarmonics. AquaHarmonics, winner of energy price, developed a device with priority the mechanical component and latching/de-clutching control system. The AquaHarmonics system can therefore be classified as a point absorber with latching/de-clutching control. Winner of the wave energy price:

https://waveenergyprize.org/teams/aquaharmonics

Short bibliography: http://www.cleantechconcepts.com/2016/11/wave-energy-prize-winner-floats-above-a-broad-sea-of-contenders/

9 Moorings and station keeping systems

9.1 Key words

Compliant moorings, synthetic moorings, load absorption

9.2 Brief technology description

Mooring for ocean energy have the challenge to keep different devices in place under the action of waves and tidal streams with often large ratios between design and operating loads. This high ratio is partially the reason for the high cost so far for moorings solutions. Additionally, in most cases, moorings need to limit the movements of the devices without preventing them to extract power in an efficient way, and allowing for orientation towards favourable wave direction. Design of mooring system for wave and floating tidal technologies is a new and challenging sector.

The following is a broad and non-exhaustive overview of the mooring challenges and opportunities for the marine renewable sector. There is a broad range of scale of marine renewables technologies being developed with displacement ranging from tens of tonnes to tens of thousands tonne displacements.

While there is significant cross-cutting overlap in mooring and foundation requirements between O&G, offshore floating wind, tidal and wave power, there is also significant diversity. This diversity is a largely due to the distinct environmental design and operating conditions associated with the different sectors. For example, mooring loads for floating wave power systems tend to be dominated by first order wave loads, whereas a tidal installation would have higher relative mean loads. Nearshore wave deployments on exposed sites, are subject to shallow water effects not experienced by deep water O&G deployments. A nearshore marine renewable development on an exposed coast, will often have a need for greater mooring compliance to reduce mooring and anchor loads which cannot be provided by catenary chain. Alternatives include axial compliance provided by low modulus rope or in line shock absorber e.g. TfI, Seaflex, Exeter tether.

There is also greater diversity in technologies being developed in FOWT, tidal and wave. For instance, if we consider wave power - there are systems which are designed to extract power in single, multiple and often different degrees of freedom. Consequently, the mooring requirements of a large pitching or heaving system are different from that of a ground referencing system. Some WECs are designed with PTO integrated into the mooring line. Not all mooring system require compliance and for example ground reference or TLP type structures, would normally require a high modulus mooring line (e.g. HMPE).

Conventional O&G mooring and foundation technology are not always transferable or economically viable for nearshore exposed sites, due to shallow water effects and seabed conditions. A large proportion of failure can occur at discontinuities in the system, such as top end fairlead connection, anchor connection (or touchdown) or other connection points such as in line buoys.

Mooring systems also require reliable tensioning and quick release/hook-up systems which impacts on system availability and costs. A number of new wave technology have a survival strategy to submerge in the water column during storm events. Such systems can require active winching and lines running through sheaves. Other challenges include the development of active weather vaning systems in order to improve the power capture in operating conditions or reduce extreme loads.

The variable nature of the seabed in the nearshore zone also presents a number of challenges for anchoring. Sediment for cost-effective drag embedment anchoring can be migratory and not always be relied upon. Fixing anchors to a rocky seabed can also be challenging to variable overburden of sediment. As the industry looks to more compact mooring systems to improve array densities and reduce impact on the other stakeholders this can present more challenges on the anchoring systems due to increase in their vertical load component. Counter to this there will be opportunities for anchor sharing at array scale. Large anchoring and foundation systems also can be expensive to install.

Ocean energy converters need to respond strongly to wave forces. Both slack -moored and taut-moored concepts may be prone to slack, with subsequent risk of large snatch loads. This may reduce life time or cause immediate failure of the mooring lines themselves or other components. Both research institutes and industrial companies are addressing this problem, which may also have some relevance for floating tidal stream converters.

Examples of mitigating solutions that have been suggested:

- Mooring lines with tailored rubber and/or spring elements for tailored stiffness characteristics that milden or avoid snap events
- Mooring legs that can take compression loads
- Buoyancy elements or weights that keep the line from going slack
- Winch systems that pull in line upon loss of tension
- More accurate simulation tools that can be used to accurately estimate snap loads

9.3 Advantages

- Improve efficiency and power capture.
- Decrease peak loads.
- Eliminate snatch loads, non-linear stiffness.
- Possibility of integration of PTO in the mooring line
- Possibility to allow the device to submerge in storm protection mode
- Good absorbing loads capacity (nylon).
- Low weight, low maintenance, increased fatigue life (for polymers).

9.4 Limitations

- They have to sustain high ratios of design and operational loadings.
- There is no standard for ocean energy mooring design.
- Limited technology transfer from other sectors.
- Discontinuities in the system and consequent more chances for failure.
- High compliance (case by case).

9.5 Stage of development: TRL, size and speed

The stage of development of mooring systems is high, yet the application of mooring systems to ocean energy given its different technologies and requirements is low, ranging between 2-7 as explained in the brief description. The size can scale up to multi-MW and the speed of development is fast.

9.6 Projects & Activities

Compliant moorings. This technology covers moorings system largely based on synthetic lines with a strong emphasis on the use of nylon. Short/shock absorbers are considered as a different technology. Synthetic moorings include moorings lines whose main body is made out of synthetic material: polyester, nylon, HMPE, and more…

Synthetic mooring ropes accessories: Tension Technology International (TTI) and its partners have developed a novel polymer line fairlead system. Advantages are low weight, low maintenance, increased fatigue life.

Dynamic Tethers, such as the one developed by Tfi Marine (Figure 60)**,** can be installed alongside existing mooring system. Their advantages include reduced operational costs, smaller footprint, minimised seabed scouring. Tether system can be employed in order to increased the total power absoroption of the system, such as the case of a **three-tethered wave energy converter** which utilises heave, surge and pitch motion modes to optimise power performance. For example, the **Nemos** WEC harvests energy from more than one mode of motion employing the dynamic tethers from Tfi. Dynamic tethers offer the possibility of developing A more efficient ways of extracting wave power.

Short bibliography:

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- Mooring Systems for Marine Energy Converters,John F. Flory, Stephen J. Banfield, Dr . Isabel M.L. Ridge, Ben Yeats, Tom Mackay, Dr. Pengzhu Wang, Tim Hunter, Prof Lars Johanning, Manuel Herduin, Peter Foxton.
- www.marinet2.eu/wp-content/uploads/2017/04/NEMOS-sea-tests_AAU.pdf

Anchor bags (Figure 61) are an innovative type of gravity based anchors (GBA) where the weight is provided by local aggregates filling bags. The bags are then grouped together in a synthetic net, which also provides the connection with the mooring lines. The design of the net and the use of polyester as its main material gives it good load sharing properties. The anchor bags mould to seabed to provide enhanced coefficient of friction and the they are significantly cheaper than equivalent steel or concrete gravity based structures. Anchor bags were originally developed by TTI and Vryhof as part of the Carbon Trust and Scottish Government funded projects including the Marine Renewables Commercialisation Fund (MRCF). TTI and Vryhof design anchor bags up to a dry weight of over 50T each and bags can be coupled together. As part of the MRCF project TTI conducted the design, testing and qualification of the bags in accordance to DNV-TP-A203 for new technologies. Only limited sea testing has been conducted to date. The main challenges are that the anchor bags require further testing to improve and TRL and the scalability of technology needs to be investigated. Main research project: MRCF project led under Innovate UK and carbon trust funding.

Underwater pulley (Figure 62) As part of the Nemos project, an underwater pulley and application-specific bearings based on MacGregor mooring system have been developed. The mooring system employs two fibre ropes for each approx. 20m long floating structure. These ropes are controlled by the MacGregor winches, which deliver the optimum degree of movement to maximise energy capture. Orientation of the floating structures can also be adjusted by the winches when wave direction changes. In extreme conditions, the winches can haul them down well below the surface to avoid storm damage.

Short bibliography:

https://www.cargotec.com/en/nasdaq/press-release-kalmar-hiab-macgregor/2016/macgregor-winch-expertise-employed-in-innovative-wave-energy-capture/

Taut mooring systems are usually connected directly or incorporate within the PTO of relative small devices so that the forces on the mooring line are translated into energy captured. Technologies proposing to use taut moorings include, ResenWaves DeepGreen from Minesto. The C3 WEC from CorPower Ocean consists of a heaving buoy on the surface absorbing energy from the combined surge and heave motion of the waves. The WEC is connected to the seabed using a taut mooring line. It has a pneumatic pre-tension module between the mooring line and the buoy.

Floatgen project developed by Ideol in France employs the first permanent nylon based mooring deployment. The **Demowind** project developed by EnerOcean in Spain will include Nylon based moorings.

Mooring for large wave energy converters. Mooring solutions for large wave energy converters is a Danish research project investigating solutions for large floating structures operating at intermediate water depths (30 – 100m) at commercial scale deployments. The project aims at investigating and comparing different mooring solutions useable for these large WECs. Other activities are under the University of Exeter university, UK and PAMSLIM project, Chalmers, Sweden.

Figure 60 – Dynamic tethers. ©TFI Marine

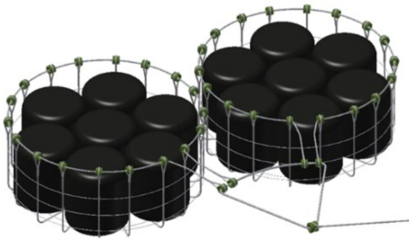

Figure 61 – Anchor bags and fairlead by TTI. ©TTI Ltd.

Figure 62 – MacGregor winches ordered by NEMOS ©Cargotec.

10 Materials and components

10.1 Key words

Fairlead, low friction seals, energy storage units, tribological, inflatable, concrete

10.2 Brief technology description

Materials and components are technology innovations that have gathered significant momentum in Ocean Energy, and are growing subject of R&D for the sector. . Materials and components for ocean energy have to survive the harsh marine environment often in new operating conditions and with high performance requirements.

There are great opportunities for materials/ hybrid materials which are lightweight, high strength, resistant to biofouling and corrosion, durable and low cost and allow mass production. In a futuristic prospective, self-repairing materials would find a perfect application in ocean energy.

In the following sections, we will describe some of the ongoing activities in Ocean Energy regarding components and materials. All subfamilies of technologies try to solve the common issues related to operating in marine environment with new operational requirements.

10.3 Energy storage units and power output smoothing

Energy storage and power output smoothing are important topics for ocean energy converters that might call for new solutions. Energy storage play a significant role in smoothing the power output accounting for daily, monthly, seasonal and yearly variabilities. The challenge is in identifying suitable size of the storage unit to be effective.

Solutions can be found in storage unit that store energy produced at sea for later application. Hydraulic/pneumatic/mechanical/chemical energy storage solutions of high round-trip efficiency are being investigated. Similarly, there is also scope for identification of system that smoothen the power output, especially for wave energy converters.

Storage solutions for tidal energy currently under investigations are evaluating the generation of hydrogen at sea, as a way to store the energy produced to overcome grid constraints.

Wave energy converters harvest energy from an oscillating flow. Both the wave-to-wave oscillation and the large power flow fluctuation due to wave grouping stands in contrast to the steady power flow and voltage quality required at the grid connection. Although the interconnection of many units can in principle smoothen the total power output there are still costs and regulatory complications driven by the power fluctuation of each unit.

Smoothing of power as early as possible in the conversion chain should be taken as a design goal. Conventional solutions such a flywheels and pumped storage may be used, but solutions must be tailored and optimised to fit the dynamics of wave energy converters.

10.3.1 Advantages

- Allows for longer exploitation of the resource, improving efficiency.
- Accommodates overproduction.
- Smoothen the power to the grid and overcomes grid limitations.

10.3.2 Limitations

- Added technological cost.
- Identification of optimal sizing of solution for power output smoothing, and its cost-effectiveness

10.3.3 Stage of development: TRL, size and speed

The TRL for energy storage applied to ocean energy is medium, but considerable technology transfer is expected from outer sectors. Speed of development is expected to be fast also because the correct application of storage will increase applicability of a highly variable and stochastic energy source. Several MWs size.

10.3.4 Project & activities

Hydrogen generation soutions are currently being investigate at the EMEC's tidal energy test side. An electrolyser is employed to generate hydrogen from excess power coming from the tidal devices (SR1-2000, Tocardo) connected at EMEC. Sabella is developing a project for deployment in Ushant where the 2MW D10 device is also used for the production of hydrogen in order to store excess energy and provide a smooth energy output to the island grid.

10.4 Sea water seals and lubricants

Ocean energy converters operating in the marine environment require increase reliability on components such as seal to limit losses, failures and the idenfication of lubricant to reduce friction losses.

In the case of tidal energy, especially large horizontal axis turbines, the rotor shaft application with nominal rotational speed levels between 10rpm (1.5MW turbine) up to 40rpm (0.1MW turbine) different proven sea water seals from ship propeller application are existing and used today. In a water level up to 30m, lip type seals are normally used. For deeper water levels, existing mechanical seal are more reliable. In case blade pitch actuation and nacelle yaw function is foreseen, individual seal designs are done today without long term experiences. Application-driven seal developments are needed to fulfil better technical and commercial requirements.

In the case of wave energy, most wave energy converters rely on components that have sealed connections between moving parts. It can be pressurised cylinders, rotational shafts or sliding rods. Such connections may cause considerable friction losses, especially if one side of the seal is pressurised. The details of seal design and choice of lubricant influence the economy of the whole converter significantly.

Identification, development of seals to meet the performance and cost-requirements for application in ocean energy conversion is needed to ensure long-term reliability of the devices.

10.4.1 Advantages

- Increased survivability of components.
- Lower friction means also lower wear and thus higher expected lifetime.
- Reduced maintenance.
- Long-term cost-reductions if increased reliability is proven.

10.4.2 Limitations

- Technology transfer from propeller applications need to ensure technical and commercial requirements of ocean energy are met.

10.4.3 Stage of development: TRL, size and speed

High TRL for other applications, such as propeller. Development can be fast, dependent on technology transfer.

10.4.4 Project & activities

Application-driven seal development is taking place as part of many EU funded H2020 projects, such as Tipa, Taoide and FloTEC, where PTO innovations are being developed.

10.5 Elastomers

There is potential to reduce the cost of wave energy through use of deformable fabric/elastomeric structures for wave energy conversion including rubbers. Developing WECs from these materials has the opportunity for improved survivability and reduced cost without compromising performance.

10.5.1 Advantages

- Allows for longer exploitation of the resource, improving efficiency, by having a longer resonance period than that of a heaving rigid body of the same size, because of the lower hydrostatic stiffness. This means that the device can be smaller and hence cheaper if a deformable body is used.
- Further advantages of fabric/elastomeric structures are that they are lightweight, they do not require as much material as rigid structures for the same given volume,
- They have very good fatigue properties.
- A flexible WEC is not only potentially smaller and lighter than a comparable rigid device but it does not assume its final volume until it is on-site. This means that transport and deployment costs are also reduced.
- Accommodates overproduction
- Smoothen the power to the grid
- Long life durability and fatigue proven in other marine applications

10.5.2 Limitations

- Scale up of manufacturing processes.
- Integration with other materials and components needs investigation.
- May lead to radically different WEC designs not currently under development.

10.5.3 Stage of development: TRL, size and speed

TRL 3, medium speed of development.

10.5.4 Projects

The ELASTO project led by the University of Edinburgh is investigating these materials as part of a WES funded project.

http://www.waveenergyscotland.co.uk/programmes/details/materials/elasto/

10.6 Advanced concrete

Concrete is fundamentally well suited to WEC structural applications as it has a low specific material cost, exhibits high stiffness and good fatigue properties, can be manufactured in generalised shapes to suit optimal hydrodynamic forms, and because light weight is not generally a primary concern for absorption.

10.6.1 Advantages

- Cheaper and faster to produce than steel.
- Better durability.
- Lower maintenance (less corrosion).
- Better resistance to fatigue.

10.6.2 Limitations

- Manufacturing process for complex shapes.

10.6.3 Stage of development: TRL, size and speed

TRL 3, application to multi-MW size, development speed:fast

10.6.4 Projects& activities

Concept for wave energy floaters produced in Ultra High Performance Fibre Reinforced Concrete (UHPFRC), such as the one shown in Figure 63. The main projects investigating concrete for Ocean Energy are FLOAT2 – New Flexural UHPC Application for Wave Converters 2, funded by ForskEL, Denmark and Advanced Concrete Engineering from WaveEnergy Schotland.

The Penguin device (Figure 64), developed by Finnish company Wello, employs concrete as a fundamental part of the devices, to ensure structural viability and reduced costs.

Short bibliography:

https://hi-con.blog/2017/11/08/considering-high-performance-concrete/,
http://www.waveenergyscotland.co.uk/programmes/details/materials/advanced-concrete-engineering-wec/

Figure 63 – WEC with UHPFRC. ©Wave Star Energy

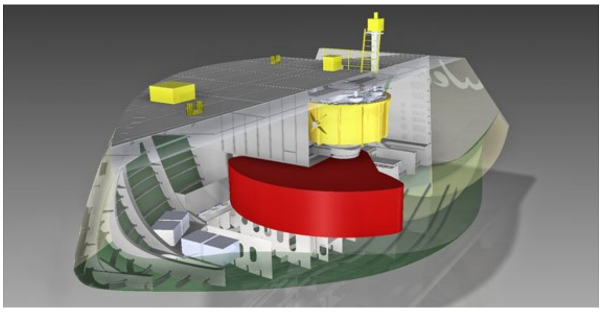

Figure 64 – Structure of Wello Penguin employing concrete. ©Wello Oy

10.7 Inflatable structure materials

Inflatable structure materials are being investigated in order to reduced the cost of technology and increase survivability of machines. Inflatable materials offer solutions in terms of redced weith and installation, however being at very low TRL they require signfincant R&D to assess full potential and scalability for ocean energy applications.

10.7.1 Advantages

- Step reduction in LCOE (light weighted material).
- Storm mode protection.
- Increased survivability.
- Reduced loads on the structure.
- Easily transportable and deployable at sea.

10.7.2 Limitations

- Scalability.
- Significant R&D needed.

10.7.3 Stage of development: TRL, size and speed

TRL is relative to tank testing (1-5), scalable to MW size, development medium fast.

10.7.4 Projects & activities

The **Automatically Inflatable and Stowable Volume ('AISV')** technology is intended to provide the economics of an otherwise unsurvivable machine with the survivability of an otherwise uneconomic machine. The novel concept to be developed in this project is intended to break this fundamental conflict between performance and survivability by introducing the ability to substantially change the machine hull volume on command. In the same way that ships reef their sails to deliver speed and survivability, selectable hull volume change allows a wave energy converter (WEC) to revert to a smaller robustly survivable form when the waves are extreme.

Main ongoing research projects:

http://www.waveenergyscotland.co.uk/programmes/details/novel-wave-energy-converter/aisv-automatically-inflatable-and-stowable-volume-for-step-reduction-in-wec-cost-of-energy/

Similar approach is the one chosen by TTI in the project **Netbuoy** (under the new material call of Wave Energy Scotland. Completed Stage 1.) The NetBuoy concept aims to significantly reduce the construction and installation cost of wave energy converter prime movers. A pressurised reinforced elastomer buoy is restrained within a rope net. The net provides the load-path between compliant buoy and machine room or PTO or mooring connection point. The system as a whole can be inflated at the deployment site, significantly reducing the space requirement for transportation from point of manufacture meaning lower cost vessels can be used and towing to site minimised. The Netbuoy concept has been developed around a heaving point absorber which can be attached to linear power take off and tether to the seabed using anchor but is envisaged to be applicable to many WEC technologies. [14]

10.8 Flexible blades materials

One of the key determining design parameters for tidal turbines is the effect of short-term flow variability inducing large structural loads on the turbine blades, PTO and supporting structures. The unsteadiness of the flow can vary significantly due to the shear layer in the current, turbulence, waves, etc.. These loads can be modulated and reduced through novel blade designs, in particular flexible blades which can dynamically alter their profile to shed these extreme loads and reduce

[14] http://www.waveenergyscotland.co.uk/programmes/details/materials/cargo-net/

loading on the rest of the system. This has the potential to reduce structural fatigue, overdesign, failure and cost whilst increasing lifetime, efficiency and reliability.

During the workshop it was emphasised that shedding peak loads for marine energy systems as soon as possible is the most impactful way of reducing the specification and costs of downstream components. In the context of tidal energy the first opportunity to do this is of course the blade. Flexible foil blades have the potential to passively and significantly reduce loads and thrusts entering the turbine structure and drivetrain, mitigating the effects of tidal shear, waves and turbulence.

10.8.1 Advantages

- Decreasing fatigue and extending lifetime
- Improving efficiency and costs
- Low weight

10.8.2 Limitations

- Reliability of these technology are still to be assessed
- Developing complete blades (to date only small sections developed) with this technology, scaling-up and testing in realistic conditions, including as part of scale tidal turbine prototypes.

10.8.3 Stage of development: TRL, size and speed

TRL is relative to concept design (1-3), scalable to multi-MW size, development fast.

10.8.4 Projects & activities

Among the Main ongoing research projects:

- 2018, Centre for Adv. Materials for Ren. Energy Generat. [EP/P007805/1], Morphing aero- and hydro-dynamic working surfaces. 2017-2018, EPSRC UKCMER (EP/P008682/1)
- MetaTide: A new meta-material for enhanced fatigue life of tidal energy converters. 2014 – 2015, EPSRC Newton Fund UK (Energy) [EP/M02038X/1], Mitigate fatigue load with flexible tidal turbine blades (FLEX-BLADES). 2012-2015, SUPERGEN Marine Challenge - Accelerating the Deployment of Marine Energy (Wave and Tidal) [EP/J010308/1], Increasing the Life of Marine Turbines by Design and Innovation

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- Susan Tully, Ignazio Maria Viola. Reducing the wave induced loading of tidal turbine blades through the use of a flexible blade. 16th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC 2016), Apr 2016, Honolulu, United States.
- Unsteady hydrodynamics of flexible submerged foils. Ignazio Maria Viola, Susan Tully, Gabriel Scarlett Institute for energy Systems, School of Engineering, University of Edinburgh, UK. 5th Oxford Tidal Energy Workshop. 21-22 March, 2016. Oxford, UK.

- Adjustable Camber for Extended Fatigue Life. Anna Young and Judith Farman. Whittle Laboratory, University of Cambridge, UK. 5th Oxford Tidal Energy Workshop. 21-22 March, 2016. Oxford, UK.

10.9 Hybrid Rotational Moulding

The rotational moulding manufacturing process offers a range of crucial benefits to WEC designers that could initiate a step-change impact in LCOE. The advantages of polymer-based design versus steel, particularly with fatigue and corrosion resistance, are becoming increasingly utilised in marine applications. Polyethylene products form the majority of low cost solutions, due to the low price and distinguishing plastic behaviour. Hybrid rotationally moulded structures have a concrete ballast material that contributes to the strength of the structure and innovative new design concepts for accepting point loads. Rotational moulding is the cheapest form of polyethylene moulding and the one that can output the largest end products, making it an attractive option for WEC designers.

10.9.1 Advantages

- Fast production and cost reduction (cheap materials).
- Possible to produce complex shapes.
- Improving efficiency and costs.
- Prevents bulking of the rotationally modules.
- Components resistance to corrosion.
- Fatigue resistance component.

10.9.2 Limitations

- Size of oven could be a challenge.

10.9.3 Stage of development: TRL, size and speed

TRL is relative to concept design (1-2), scalable to multi-MW size, development fast.

10.9.4 Projects & activities

Wave Energy Scotland is running a number of ongoing research projects aimed at identifying advanced rotational moulding techniques for wave energy devices

- http://www.waveenergyscotland.co.uk/programmes/details/materials/armwet-advanced-rotational-moulding-for-wave-energy-technologies/
- http://www.waveenergyscotland.co.uk/programmes/details/materials/advanced-rotational-moulding-for-ocean-renewables-armor/

10.10 Dynamic power cables

Dynamic power cables are under development for stable power transmission from floating offshore wind power generation facilities (that are subject to significant movement) for downfeed to static cabls which ensure connections to the shore. Technology transfer for application in ocean energy is significant, and would provide significant benefift to the the sector, especially for floating tidal and wave energy technolgoies.

A number of companies e.g. Hydro Group, produce flexible cables commercially but what is required are low cost high power connect/disconnect systems for removal of devices from an array.

10.10.1 Advantages

- Reduced number of components.
- Faster and cheaper installation.
- Reduction in maintenance costs.
- Better economics.

10.10.2 Limitations

- Long term impact of mechanical stresses on dynamic cables poorly understood and requires accelerated testing methodologies and rigs to be put in place.
- Application to ocean energy is dependent on the voltage size.

10.10.3 Stage of development: TRL, size and speed

TRL from floating wind tests is 7, and there is no reason to think that the technology should be different for tidal and wave energy. Scalable to multi-MW size, development fast.

10.10.4 Projects & activities

Bend restrictors and Dynamic power cables like HDPC4FMEC project were investigated during the Marinet Project by Norddeutsche Seekabelwerke GmbH and General Cable and CPNL Engineering GmbH. Other key developments are being undertaken by BPP, Prysmian and JDR.

Short bibliography:

- Leroy, Jean-Marc & Poirette, Yann & Brusselle-Dupend, Nadège & Caleyron, Fabien. (2017). Assessing Mechanical Stresses in Dynamic Power Cables for Floating Offshore Wind Farms. V010T09A050. 10.1115/OMAE2017-61630.

11 Conclusions and recommendations for futher work

The report presents an assessment of Future Emerging Technologies for ocean energy technologies (wave and tidal conversion), achieved following consultation and valdiation Workshop with different experts and stakeholders from the sector.

This has resulted in the identication of FETs for ten different technology families, with the potential to provide significant step-change to the sector. For each technology family, FET solutions are described together with an assessment of the TRL, of the speed of development and advatages and challenegs that may affect development.

Given the status of the ocean energy sector, as emerging and at a stage of market formation, a number of general remarks are necessary to frame the analysis of FETs in the ocean energy context:

- More advance technological solutions, such as first generation tidal energy converters, are yet to prove commercially viable. The development and integration of FET presented in this report could help significantly ocean energy technology lower their cost and become commercially attractive.
- In order to overcome failures previously experienced in the sector, an integrated systems approach is required to develop marine energy systems, subsystems cannot be developed in isolation.
- System capabilities and requirements should be properly defined and made transparent to increase the effectiveness of FETs development and applicability to ocean energy technologies.
- High TRL solutions from other sectors will in general be faster and lower risk to transfer and adapt compared with developing novel systems of low TRL.
- Industrial/ OEM collaboration should be involved early in the development of a technology.
- A market – without a market there is a major challenge in attracting developers and investors – identifying novel applications for marine energy, such as powering offshore installations, can be early markets creating demand in which to deploy and test technologies.

The FETs identified in the workshop offer both whole system solutions; such has the design of novel wave of tidal energy converters, or to specific components such as blades, mooring, PTO, seals and more.

As highlighted in the report, there is an underlying connection between the application or potential of FETs and the engineering challenges that need to be addressed in the development of commercially viable ocean energy converters.

The transferability of solutions from other sector,as well as the development of new technologies and materilas could impact significantly on the speed of development of FETs for ocean energy.

As a follow-up from this activity, it may be beneficial to contextualise the impact of the FETs presented in this report with the priorities for the ocean energy sector as identified through the Ocean Energy Roadmap, the SET-Plan Implementation Plan. A further analysis is needed to prioritise which options could have the greatest impact on the sector in achieving short-term goals (2025 targets) and long term ambitions (100 GW of installed capacity by 2050).

List of Figures

A. APPENDIX – Technology Readiness Level: Guidance Principles for Renewable Energy technologies

In this section we present the guidance principles for the TRL of ocean energy technologies based as defined by the European Commission. For each TRL the gudiance provide a description and checkpoints.

A.1 TRL 1 – Basic principles observed

Description: Basic research. Principles postulated and observed but no experimental proof available

Identification of basic principles, performers and interfaces.

The principles that underlie the technology are defined, and this analysis is supported by information that includes published research and/or other references investigating the identified principle.

The concept exists only on paper / software form, no hardware still exists.

A prime-principle based analytical model of the principles exploited (i.e. not representing the whole device), implemented into a first approximation model, should be developed based on the available published research. A set of relevant operating conditions should be considered.

Usually no mechanical/electrical efficiencies are included at this stage.

Interfaces (i.e. characterisation of the relationships) with other technologies (e.g. overall device or other subsystems) in the frame of system integration have been identified.

Checkpoints

Once readiness level 1 is achieved, the scientific concept is observed and documented. This means:

- definition of principles underlying the technology;
- evaluation of the benefit of the technology in comparison with other existing technologies;
- first identification of interfaces with other systems.

A.2 TRL 2 – Technology concept formulated

Description: Technology formulation. Concept and application have been defined

Definition of the technological concept and considerations about manufacturing aspects.

The practical application is defined. The analyses conducted in TRL1 are expanded toward considering the other necessary systems to convert the absorbed energy into electrical energy, at a level able to identify the main technological barriers.

At this stage, usually, it is not necessary to investigate the other sub-systems' performance.

In addition to the influence of monochromatic waves, irregular waves based on relevant sea states can be considered for WECs. For tidal devices, typical current velocity variation with water depth and typical turbulence levels may be considered.

The analyses are usually analytical/numerical, even if some basic experimental work to support the basic principles exploited could be carried out.

Published papers and patents may support the development of the concept.

Functional requirements are investigated and documented, and potential market has been identified.

Manufacturing approaches or capabilities needed to develop the concept are identified: it includes study of materials and processes approaches as well as modelling and simulation.

Preliminary installation considerations are performed.

A proof-of-concept integration of the systems should be carried out.

Checkpoints

Once readiness level 2 is achieved, the scientific concept is observed and documented. This means:

- Definition of application
- Identification of materials and suppliers
- Statement of interactions between technologies
- Identification of main technological and non-technological challenges
- Early consideration of commercial value of the technology.
- Operational environment: the environment is not simulated / is simulated to a limited extent

A.3 TRL3 – Experimental proof of concept

Description: Applied research. First laboratory tests complete; proof of concept

Analytical and first experimental proof-of-concept of the critical function/main characteristics, identification of manufacturability and compatibility

Ad-hoc and on purpose R&D is now initiated.

The main principles, characteristics, and performance of the concept are validated, using analytical studies and experimental campaigns at an appropriate scale level, in controlled conditions (laboratories). These laboratories should be able to reproduce the main wave (WEC) and tidal (tidal device) characteristics: small/medium ocean/wave basins, wave/flume tanks, and towing tanks are good examples. These studies focus on the main elements of the WEC/tidal system, and usually not on the integrated system.

Numerical modelling and simulations can be used to complement the physical experiments.

At this stage, it is advisable to explore as many relevant parameter ranges as possible in the design space, since it is still possible to change the main characteristic of the device at a relatively low cost.

An analysis to identify the manufacturability of the main elements using state-of-the-art commercial techniques is performed.

A preliminary value analysis is carried out.

A risk mitigation strategy is documented.

A compatibility analysis among the main energy-conversion elements is carried out.

Checkpoints

Once readiness level 3 is achieved, the scientific concept is observed and documented. This means:

- Analytical and experimental (lab scale, controlled environment) investigations of the main component/s of the device (i.e. absorber element, energy conversion elements if not available off the shelf, sub-components)
- Main energy-conversion elements manufacturability, installation, and operability analysis
- Compatibility analysis between main energy-conversion technologies
- Preliminary risk mitigation analysis
- Scale of testing: tests are conducted in a controlled environment (lab), and only on the main component/s of the technology (not the whole integrated system)
- Operational environment: the most relevant aspects of the environment (monochromatic wave height/frequency ranges, sea states' significant wave height and zero-crossing period for WEC, current speed and/or tidal ranges for tidal devices) are simulated in a controlled environment (lab).
- Fidelity: the main component/s of the system are reproduced and tested at a scaled level, to represent the main characteristics influencing the energy absorbed/transformed
- Confirmation of expected results estimated in the previous TRLs

A.4 TRL4 –Technology validated in Lab

Description: Small scale prototype built in a laboratory environment ("ugly" prototype)

Component and system validation in a laboratory environment, manufacturability and interoperability

This is a fundamental step of the development of WEC and tidal devices, focusing on the analysis and validation of the performance of the device in (lab simulated) real conditions, and assessing the performance sensitivities with respect to the main environmental condition parameters.

The separate components are now analysed from a whole-system point of view, therefore a system engineering approach should be adopted. This validation occurs at laboratory level, i.e. not in the field, measuring the relevant parameters linked to these main aspects: device performance, environmental loads (wind, waves, and currents), control strategy, support structure system (fixed or floating).

The experimental analyses, complemented by a range of analytical and numerical analyses, are conducted on a larger scale (~1:10-1:25), higher fidelity models, matching the overall configuration in the most important aspects, and using a more comprehensive set of environmental conditions. For WEC, a more comprehensive number of sea states and tidal condition ranges are considered. For tidal devices, typical current speed time histories, variation of current speed with depth, and typical turbulence ranges should be considered. For both, survival conditions needs to be considered.

Medium/large ocean/wave basins and/or large flumes and towing tanks are typically used at this stage.

The aim of these analyses is wider than TRL3, since their scope includes the definition of the power take off (PTO) control strategies, and the verification of the support structure design (fixed/floating support structure and mooring system).

A reference site/set of sites is chosen, or a representative generic site can be adopted.

Based on the analytical and experimental data: A) a first estimation of the operational and survival loads is derived, allowing a preliminary design and elementary costing, B) the measured power absorbed in a range of metocean conditions will allow and estimation of the annual energy yield.

Manufacturing processes requiring investments are identified. The manufacturing risks towards prototyping are identified as well as manufacturing cost drivers and Key performance parameters.

Needs for tooling, facilities, material and skills are identified.

Project risk management is integrated within project management.

Checkpoints

Once readiness level 4 is achieved, the scientific concept is observed and documented. This means:

- Testing and validation at laboratory level of technology gathering separate elements
- Validation of interoperability
- Manufacturing, installation, and operation investments/costs identified
- Risk management integrated in the project
- Scale of testing: tests are conducted in a controlled environment (lab), and integrating the main elements
- Operational environment: the relevant aspects of the environment are simulated in a controlled environment (lab).
- Survival load cases should also be considered

- Fidelity: some of the component/s of the system are reproduced and tested at a scaled level
- Detailed assessment of the commercial value is produced
- Confirmation of expected results estimated in the previous TRLs

A.5 TRL5 – Technology validated in relevant environment

Description: Large scale prototype tested in intended environment

Laboratory scale, almost-prototype experimental validation and in simulated environment

The major improvement from TRL 4 to TRL 5 consists in the enhanced model fidelity and environmental conditions fidelity of the experiments. The model tested is almost a prototype, allowing the quantitative measurement of the performance, but still tested in controlled (lab) or benign (sheltered sites) conditions.

The technological components are integrated with additional supporting elements (e.g. hardware and software) to be tested in a simulated environment.

The technology is able to establish, manage and terminate the integration with other technologies; this means there is a sufficient control between technologies.

Manufacturing component prototypes are created and a manufacturing strategy is defined.

Checkpoints

Once readiness level 5 is achieved, the scientific concept is observed and documented. This means:

- Testing and validation in simulated environment finished
- Control capacity towards integration at system level
- Manufacturing prototype completed
- Manufacturing strategy defined (including cost model)
- Scale of testing: tested in a relevant, but still controlled, environment.
- Operational environment: all the main aspects are represented in the lab, including not only the conditions influencing the power production level, but also those relevant for all the other sub-systems of the whole device.
- Fidelity: the scaled model configuration is similar to the full scale configuration in most relevant aspects (including balance of plant systems)
- PTO conversion efficiency (electrical) - Storm survival - identification of suppliers for TRL6 (relevant benign environment)
- Upscaling study based on test results is performed
- A refined detailed assessment of the commercial value is produced

A.6 TRL6 – Technology demonstrated in relevant environment

Description: Prototype system tested in intended environment close to expected performance

Technology application functioning, manufacturing and integration prototyped.

The major difference between TRL5 and 6 is the move from testing in laboratory conditions to a natural site, where the conditions cannot be controlled.

This is a fundamental intermediate step between the lab scale model and the intended final scale, to troubleshoot the technical issues and to reduce the financial risks, since a "benign" natural site is chosen. This site is closer to shore than an operational site (easier installation/maintenance), not exposed to the full open seas conditions (typically in bays), but still representing a relevant environment compatible with the scale of the prototype.

The device is fully operational, i.e. is able to produce energy, but since still at scale level and being only one device rather than an array of devices, the total power produced is limited, i.e. there is no need to connect the device to the grid (even if the main effects of the grid should be simulated).

The analytical and numerical models can be validated by the experimental data gathered, which could be considered at full scale level, i.e. not suffering from substantial scaling errors.

In order to test the device in a relevant environment, not only the maturity of the device but also the maturity of the company developing the device is proven.

It will be necessary to define in details the manufacturing, deployment, servicing, maintenance, certification, licensing and site permitting techniques and approaches, therefore substantially enhancing the personnel skills.

The technology is not only able to control information, but to specify what relevant data to exchange and also to translate information coming from a foreign/external data structure.

Checkpoints

Once readiness level 6 is achieved, the scientific concept is observed and documented. This means:

- Technology demonstrated in relevant environment
- Project management approaches are practised
- Servicing and maintenance techniques, even if at a smaller scale and for a limited amount of time, are practised
- Certification and insurance requirements, licensing and permitting challenges are satisfied
- Process and tooling mature
- Capacity of structuring information at system level
- Operational environment: the device is tested in a "benign" test natural site, i.e. the metocean conditions cannot be controlled, but these are suitable for a scaled prototype, avoiding extreme conditions
- Fidelity: the scaled model configuration is similar to the full scale configuration in all but minor aspects
- Details for intended final scale installation defined
- Design and manufacturing for intended final scale defined
- Simulation for energy production achieved
- An updated and refined detailed assessment of the commercial value is produced

A.7 TRL7 – System prototype demonstration in operational environment

Description: Demonstration system operating in operational environment at pre-commercial stage.

Application prototype integrated and demonstrated in field (operational environment), initial consideration and analysis at array level.

Prototype at operational level: the technology is demonstrated in an industrially relevant environment, at final scale, but still stand-alone (no array).

The location should represent the correct metocean conditions for the device scale used, and ideally should be placed near the proposed wave park site, but could still be a test centre. The device is tested over a comprehensive range of relevant conditions

The main focus at this stage is to gain operational experience for the WEC/tidal device, since in the previous TRL levels the testing time length could have been limited to few months, while at TRL7 continuous/discontinuous test for a period long enough to create confidence with respect to reliability and services can be envisaged.

The power production level and power quality is validated, and all the engineering aspects are proven.

Final scale decommissioning strategies need now to be defined and proven.

The economics aspects are proven at a near final scale/final scale level, even if for a one-off, bespoke design. By applying mass production estimates, a first estimation of the cost of energy produced by a park of tidal devices/WEC can be derived.

Manufacturing processes and procedures are demonstrated: production planning is complete.

The integration of technologies has been verified and validated.

Checkpoints

Once readiness level 7 is achieved, the scientific concept is observed and documented. This means:

- Pilot demonstrated in field (operational environment)
- Relevant operational experience in gained
- Reliability of integrated pilot
- Manufacturing and deployment techniques are proven
- Scale of testing: a pilot system at final scale
- Operational environment: the device is tested in a natural site with representative real sea conditions
- Fidelity: the prototype configuration is virtually the same as the full scale system
- All information for a commercial proposition are available
- Environmental aspects are considered and implemented in the final scale
- A certification roadmap is defined

A.8 TRL8 – System complete and qualified

Description: First of a kind commercial system. Manufacturing issues solved

System completed and qualified through test and demonstration

The technology is experimented in deployment conditions (i.e. real world) and has proven its functioning in its final form.

At this stage all the systems are verified from life-cycle point of view, i.e. the higher energy metocean conditions (more rare) experienced verify the fitness of the system in survival conditions, when maximum design load conditions can occur.

The environmental impact assessment performed in the previous phases is here refined and validated, and even if no long-term effects can be measured, the environmental impact of the manufacturing, transporting, installing, commissioning and decommissioning phases can be measured.

Array interactions should be analysed and estimated analytically and numerically, and ad-hoc tests in controlled conditions (lab), at scale level, may be conducted.

If it has not been done before, existing stakeholders and local communities should be contacted at this stage, in order to avoid potential future show-stoppers.

Manufacturing process is stable enough for entering in a low-rate production and all materials are available: manufacturing processes and procedures are established and controlled to meet design key characteristics tolerances.

Training and maintenance documentation are completed.

Integration at system level is completed.

Technology is deployed and operating in operational condition.

Checkpoints

Once readiness level 8 is achieved, the scientific concept is observed and documented. This means:

- Technology in its final form and under expected conditions
- Readiness for low-rate production
- Integration in operational environment
- Scale of testing: a pilot system
- Operational environment: the device is tested in a natural site with representative real sea conditions
- Fidelity: the prototype configuration is virtually the same as the final scale system
- Power matrix/function can be fully extracted according to IEC standards
- Number of hours/availability are maximised
- Health and condition are monitored
- Energy production is validated to confirm the economic plan
- Environmental impacts are contained
- Commercialisation plan is fully formulated

A.9 TRL9 - Actual system proven in operational environment

Description: Full commercial application, technology available for consumers

Actual array system operational – Economics validation

The tidal energy or WEC system is demonstrated at array level, even if it may consist of only few systems (3-5 devices). This will prove the economic feasibility (when extrapolated to the commercial farm level) of the system, making it a commercial product.

All the previous analyses, in all the disciplines (technological, economic, social, and environmental) are now expanded, verified, and validated at array level.

The hydrodynamics interactions between the devices are verified, as well as the array connection grid between the devices, the power conditioning equipment (substation), and the connection to the shore and the energy grid. This includes the aspects of their assembly, installation and decommissioning.

The quantity and quality of the power supplied to the grid is assessed over a long period of time, during which the array of devices is exposed to a full range of operational and survival conditions.

The economic feasibility is proven at a (mini) array level, and meaningful extrapolation can be derived for a large tidal/wave farm.

The consenting, licensing, permits, certification, insurance, health & safety procedures are further defined and expanded at array level, reaching full maturity.

The system is ready for full rate production: materials, manufacturing processes and procedures, test equipment are in production and controlled.

Performance and reliability of farm are demonstrated.

Checkpoints

Once readiness level 9 is achieved, the scientific concept is observed and documented. This means:

- System fully operational, including the inter-device energy grid, the substation, and the connection to the shore energy grid
- Integration of technology proven in operational environment
- Full-rate production
- system ready for commercialisation
- Scale of testing: 1:1 (final scale), an array of 3-5 (or more) devices
- Operational environment: the devices are deployed in a real commercial site, exposed to the full range of operational conditions
- Fidelity: the device is identical to the commercial product (apart from the necessary adjustments for the different location conditions)
- Failure report/log
- Farm power matrix/curve
- Business case for commercial technology sales

B. Templates for the identification of FETs sent

B.1 Future Emerging Technology template

Please fill-in this template with a potential Future Emerging technology

Technology (or research area) name:

Keywords:

Brief technical description:

Degree of development, potential and challenges

(Why this technology should be considered FET/innovative, estimation of TRL, potential relevance, applications, what are the challenges, etc.)

Relevant parameters

(Identification of parameters characterising this technology – e.g. efficiency, power, …)

Short bibliography

(reference to a few scientific papers/reports)

Main ongoing research projects:

(e.g. Project X developed by University Y in Country Z)

B.2 Emerging technologies identified by the JRC in the ocean energy

Please comment trends and challenges for the research areas of your competence:

1) New generation of Tidal Energy Converters

2) Floating tidal structure

3) Innovative Tidal Energy Power Take Off (water gap)

4) New generation of Wave Energy Converters

5) Innovative Wave Energy Power Take Off (Dielectric elastomeric, magnetic screw, non-resonance, polymeric spring)

6) Innovative Moorings (Synthetic materials, anchor bags, dynamic tethers)

7) Innovative Materials for Ocean Energy (polymers, concrete, rotational moulding)

8) Cross cutting issues with offshore wind

C. List of abbreviations

AI	Artificial Intelligence
EMG	Electro-Mechanical Generator
FET	Future Emerging Technology
FOWT	Floating Offshore Wind Turbine
GBA	Gravity Based Anchors
JRC	Joint Research Centre
LCEO	Low Carbon Energy Observatory
LCOE	Levelised Cost of Energy
MRC	Marine Renewables Commercialisation Fund
O&G	Oil and Gas
O&M	Operation and Maintenance
OSWEC	Oscillating Surge Wave Energy Converter
OWC	Oscillating Water Column
PMG	Permanent Magnet Generator
PTO	Power Take Off
R&D	Research and Development
TEC	Tidal Energy Converter
TLP	Tension-leg Platform
TPL	Technology Performance Level
TRL	Technology Readiness Level
UHPFRC	Ultra-High Performance Fibre Reinforced Concrete
WEC	Wave Energy Converter
WES	Wave Energy Scotland
WITT	Whatever Input to Torsion Transfer

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