Marine operations modelling to provide evidence-based results on the impact of novel dynamic cable design

A. Senar, S. Giorgi, B. Kennedy

Abstract— **The SEASNAKE project - an OceanERA-NET project – is aiming for developing fully dynamic cables for ocean energy. Through new design and application of novel coatings the project is designing a dynamic cable that better suits the conditions and user requirements. In order to fully understand the benefits, the Wave Venture TEMPEST™ techno-economic analysis software will be used to simulate the performance of a proposed wave energy farm with a special focus on the contribution of the dynamic cable subsystem. The results obtained from the simulations will not only provide a deep understanding of the reliability and cost-risk areas regarding the use of dynamic cables, but will also allow a comparison with a baseline scenario consisting of a more traditional cabling system. The latter will be key to identify the advantages of the SEASNAKE project and its commercial viability. KPIs (Key Performance Indicators) will include farm availability and power production downtime as a direct result of cable related issues. The reliability, maintainability and survivability of the cabling subsystem will be tested and the KPIs will give clear indication on the performance benefits and ultimately the impact on the LCOE will be of greatest consideration.**

Keywords—Dynamic cable, Wave energy, Ocean O&M

I. SEASNAKE PROJECT INTRODUCTION

SEASNAKE project, co-founded by SEAI and OCEAN-ERA NET, aims to research the development of a fully dynamic medium voltage cable, that will provide a step change in terms of overall performance, high reliability, and low risk for ocean energy applications. Under the project management from RISE, the cable solution will be developed by the cable company NKT, with the help of Chalmers University through CFD (Computational Fluid Dynamics) simulations. Wave Venture is responsible for the tasks involving simulating O&M (Operations and Maintenance) and Financial models on the SeaSnake, using inputs from the wave developer Sea Power Ltd.

Two of the main project outcomes focus on reducing the LCOE (Levelized Cost of Energy) for WECs (Wave Energy Converters) and proofing that increased availability is achievable with the SeaSnake solution.

The main objective of this paper is carrying out the Operation and Maintenance analysis and combining this with financial modelling in order to compare the novel SeaSnake cable with commercially available cables.

The objective of this analysis is to quantify the advantages and improvements that the new concept has over its competitors, both economically and from a marine operations perspective (e.g., faster/easier installation of the cable). Wave Venture has utilised the Wave Venture TEMPEST™ software to simulate full-scale wave farms to compare a baseline cable and the SeaSnake dynamic cable.

The focus of this paper is on analysing the benefits of using the improved SeaSnake cable as a solution for wave energy converters both from a marine operations and financial point of view. For the operations modelling, several tasks required in any wave energy project, such as, environmental surveys or, substation and export cable installation; have been left out of the scope of this project in order to have a more detailed focus on the impacts that the SeaSnake cable can have in future projects. For the financial simulation, and in order to calculate a project LCOE, CAPEX (Capital Expenditure) for the inter-array and export electrical cables, substation and project planning have been included in the calculations. These are assumed generic values and remain consistent across comparison simulations.

The simulations consider a whole system, whole lifecycle approach and outputs include the availability and energy yield together with statistics on vessel usage. To ensure a consistent environment the same WEC devices have been used for SeaSnake simulations and baseline simulations, without imposing any changes in

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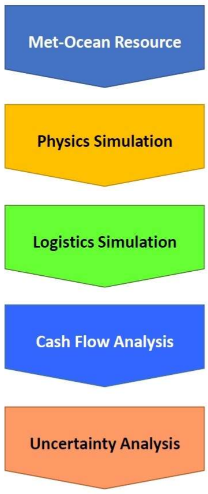

Fig. 1. Structure of the Wave Venture TEMPEST™ integrated techno-economic optimisation.

WEC dynamics, and hence the power matrix is identical in both cases. A full-scale 100 MW wave farm off the Irish west coast using the Seapower platform, rated at 1 MW, have been selected for the simulations.

II. Wave Venture TEMPEST™ Software

The Wave Venture TEMPEST™ software is an integrated engineering and financial analysis package, specifically designed for the needs of wave energy technology development. The software combines:

- Wave-to-wire simulation
- Installation, Operations & Maintenance model
- Cost model & simulated cash flow model
- Financial analytics
- Numerical optimisation

The Wave Venture TEMPEST™ software performs a time series analysis-based simulation. Weather resource data is input as a time series generating an hourly stepped logistics simulations and obtaining energy yield and cash flow outputs.

The logistics simulation responds to events in the farm lifecycle (Commissioning, device failures, scheduled maintenance, and decommissioning), through task sequences, actioning vessels, and other resources in the context of weather windows and other constraints. This approach gives a bottom-up assessment of operational costs and durations without making untestable high-level assumptions.

The financial simulation enables the user to analyse any cost on the model as a time series, to which uncertainty can be applied. The holistic nature of the Wave Venture TEMPEST™ analysis tool means that the economic or financial consequences of technical design choices can be assessed rapidly. Fig. 1 illustrates the structure behind the Wave Venture TEMPEST™ software.

The Wave Venture TEMPEST™ software has been already successfully used in previous technoeconomic projects featuring wave farms [1], [2].

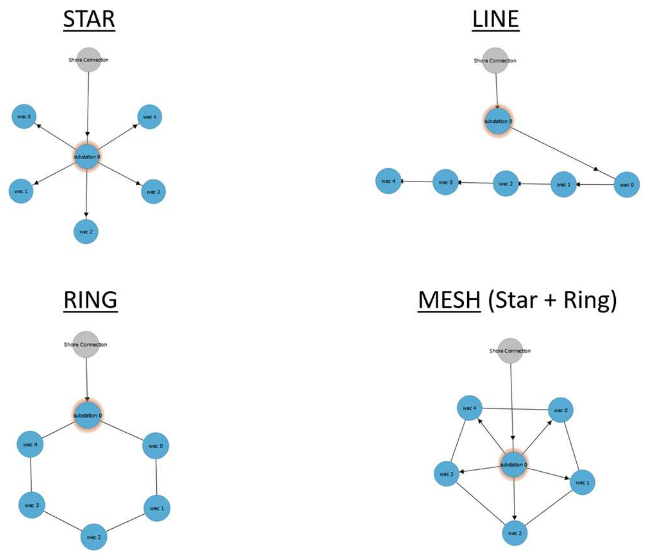

Fig. 2. Cable and converter layout base options

A very useful element for the Seasnake project is the powerful cable and electrical topology feature that has been developed to investigate the impact of cable failures within offshore renewable energy farms. This feature enables a detailed analysis of a cable's lifecycle and their effect on the offshore farm. In addition, the cable and device layout can be defined giving the user the ability to investigate the impact of cable failure and degradation on the availability and productivity of their project. Fig. 2 shows four example cable configurations to join wave energy converters together.

III. Methodology

The project uses evidence-based analysis and detailed simulation to model a commercial cable solution, used as the baseline, and the proposed SeaSnake cable to highlight the project level impact of the new cable design. This approach provides insight into the characteristics of the novel SeaSnake technology. Both cables will be modelled under equal conditions. The simulations run a marine operations and financial model of the lifetime of a 100 MW wave farm, including the commissioning stage, planned and unplanned operations and the decommissioning stage.

A. Cable technologies

The electrical infrastructure, in particular the cables, is an important component of an offshore farm, as it is responsible for transporting the generated electricity from the generators to shore. Typically, there are 3 main cable categories in a wave farm: the export cable, connecting the offshore substation with the electrical grid on the mainland, inter-array cables, joining the offshore substation with junction boxes, and umbilical cables, connecting the wave converters to junction boxes. The first two categories are relatively well understood and are commonplace in fixed offshore wind arrays, however the umbilical cables from the moving WEC to the junction box (or alternative) are less well developed. The SeaSnake, being a dynamic umbilical cable, belongs to the latter group and is where the main research is required. The export cable and inter-array cables have been included in CAPEX calculations for the purpose of LCOE modelling, but the marine operations and installation are not considered within the scope of the project. Installation and marine operations modelling analysis will be conducted on the dynamic (umbilical) section of cable.

For the dynamic cable simulations, a 200 m long unit has been proposed. Both the commercial cable and SeaSnake will be simulated under identical conditions to quantify the advantages of the novel design in a real-life scenario.

1) Baseline cable

The commercial cable used for reference, referred to as the baseline cable, is a dynamic armoured cable designed for MV (Medium Voltage) submarine applications. It is a 92.5 mm in diameter, 3 copper-conductor cable with a 24-core fibre optic unit. A 200 m dynamic cable weights approximately 3000 kg, with a cost of 21,000 € per cable unit.

2) SeaSnake dynamic cable

NKT has developed a thinner and lighter fully dynamic MV cable solution specific for Ocean Energy applications. The SeaSnake is a three-core cable with flexible conductors; it is triple extruded and includes an extra-strong polyurethane jacket and nano cable. With an outer diameter of 53.3 mm the novel cable stands at a weight of 3.1 kg per meter, making it more manageable than its counterpart. The SeaSnake not only aims to lower the LCOE by increasing performance and reducing cost, but its lighter design allows for easier installation, maintenance and decommission actions. The novel cable aims to cost in the range of 65-69 € per meter.

B. Sea Power wave farm

Sea Power Ltd is a progressive marine R&D (Research and Development) and engineering company located right at the world's most energetic wave energy resource. Driven by the realities of changing climate and the changing global energy market, Sea Power Ltd has in 2008, invented, designed, and developed a Wave Energy Converter device known as the Seapower Platform™ which is already impacting the wave energy sector [3].

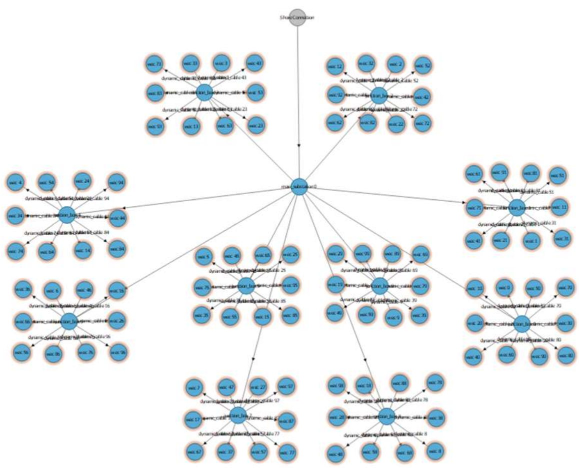

Fig. 3. Sea Power wave farm layout (exported from the Wave Venture TEMPEST™ software)

Fig. 4. Sea Power wave farm at AMETS B and nearby ports map

1) WEC and farm characteristics

The Irish engineering company is developing its own WEC known as Seapower platform. The hinged wave attenuator works by capturing energy from the relative movement between two floating pontoons. A 1:4 scaled version of the proposed device has already been tested in the sea with excellent results. The full scaled 1MW version of the WEC will be used on the simulation.

The 100 MW wave farm is composed by 100 Seapower platform units and have a proposed lifespan of 20 years before decommissioning. The WECs have been separated in groups of 10, where each group is connected to a junction box through a dynamic cable, in a star configuration. All 10 junction boxes are then connected to the offshore substation with inter array cables, and finally the offshore substation uses the export cable to transfer the energy to shore. Fig. 3 shows a visual representation of the wave farm layout, exported from the Wave Venture TEMPEST™ software.

2) Location and resource data

The site selected for the deployment of the wave farm powered by Seapower platforms was AMETS B in the northwest coast of Ireland. The closest port to the site is Blacksod port, roughly 35 km far from AMETS B, but its limited size does not make it suitable for the installation or decommission operations of the Seapower platform, hence it will be solely used as a servicing port for their maintenance and repair actions. For commission and

TABLE I
VESSEL CHARACTERISTICS

Vessel	Multicat with DP	RIB vessel
Tow capacity	1 WEC or 1 cable	N/A
Max speed	10 kts	30 kts
Towing speed	3 kts	-
Travel SWH limit	2.0 m	2.0 m
Working SWH limit	1.5 m	-

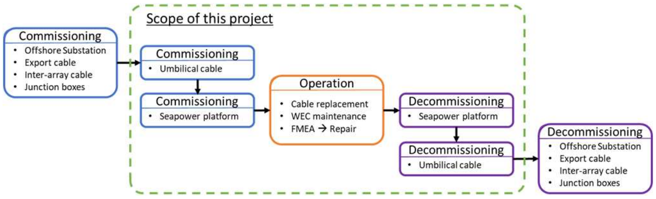

Fig. 5. Wave farm life cycle diagram

decommission stages Galway port was selected, located 175 km from the wave farm. Fig. 4 shows a map with the abovementioned ports and wave farm. The manoeuvrability and smaller size of umbilical cables, allow to use Blacksod port for not only the operational phase but also their installation and decommissioning.

AMETS B is part of the Atlantic Marine Energy Test Site (AMETS), that is being developed for the testing of full-scale wave energy converters and floating offshore wind technologies. The site has a 50 m water depth and total testing area of 1.5 km2 which is located 6 km from the Belderra Strand (54°13'37" N; 10°8'68" W). The area is known for its significant wave resource with an annual mean SWH (Significant Wave Height) of 3 m.

The resource data used to run the simulations regarding AMETS B, have been obtain from ECMWF's ERA-20C dataset [4], where the closest available point has been selected (54°00'00" N; 10°30'00" W). The downloaded resource includes measurements regarding wave and wind data with a 3-hour timestep for a 30-year period between 1980 and 2010.

3) *Vessels*

The marine operations for the Seapower WEC require a multicat vessel with dynamic positioning (DP) and hauling capabilities. This vessel is used for both umbilical cable related operations as well as WEC towing and installation. During the towing of the Seapower platform and its offshore tasks, a RIB (Rigid Inflatable Boat) is required as an additional support vessel. The characteristics of the selected vessels for the simulation are shown in Table I.

TABLE II
DYNAMIC CABLE INSTALLATION STORYBOARD

Task ID	Description	Type	Time
t_dc_i_01	Dynamic cable loaded on board	Work	1.5 h
t_dc_i_02	Travel from port to wave farm	Travel	-
t_dc_i_03	Vessel positioning	Work	0.25 h
t_dc_i_04	Cage lowering with winch/haul	Work	0.5 h
t_dc_i_05	Lift static cable end cage	Work	0.5 h
t_dc_i_06	Cable connection is made on deck	Work	2 h
t_dc_i_07	Static cable is lowered	Work	0.25 h
t_dc_i_08	Vessel return	Travel	-

TABLE III
SEAPOWER PLATFORM INSTALLATION

Task ID	Description	Type	Time
t_wec_i_01	Platform preparation for towing	Work	2 h
t_wec_i_02	Towing from port to wave farm	Travel	-
t_wec_i_03	WEC is moored into position	Work	3 h
t_wec_i_04	Dynamic cable end is retrieved	Work	0.25 h
t_wec_i_05	Dynamic cable connected to WEC	Work	2 h
t_wec_i_06	Vessel return	Travel	-

4) *Marine operations*

This section defines the list of tasks that are needed for the installation, maintenance and decommission for both the Seapower platform and the dynamic cable [5]. These are key inputs into the software and allow for the evidence-based analysis to be undertaken. Since the focus is on the dynamic cable, the following assumption has been considered: Offshore substation, export cable, inter-array cables and junction boxes are pre-installed on the offshore site at the beginning of the simulation. No marine operations modelling has been conducted for these sub-systems.

Fig. 5 gives a visual representation of the stages of the wave farms lifecycle that are included in the simulations.

It is worth mentioning that vessel travel durations are automatically calculated by the software based on the distance between locations, vessel speed, cargo, and sea condition (e.g., lower travel speed while towing a device or in larger waves).

a) *Cable installation sequence*

The first component to be installed during the commissioning stage is the dynamic cable. Table II details the action list required to install the dynamic cable, including the on-deck electrical connection and placement of a marker buoy to locate the cable end. The whole process is expected to take 5 hours (excluding travel duration).

b) *Seapower platform installation sequence*

Once all dynamic cables have been deployed Seapower platforms can be installed. Table III shows the storyboard regarding the Seapower platform preparation and connection, which takes a total of 7.25 hours. Note that the moorings are assumed to have been preinstalled.

c) *Decommissioning*

The last step in every ocean energy project is the decommission phase of the farm where the energy converters and their surrounding infrastructure are

TABLE IV
SEAPOWER PLATFORM DECOMMISSIONING STORYBOARD

Task ID	Description	Type	Time
t_wec_d_01	Travel from port to wave farm	Travel	-
t_wec_d_02	Dynamic cable disconnection	Work	1.5 h
t_wec_d_03	Moorings removal	Work	2.5 h
t_wec_d_04	Vessel returns towing the WEC	Travel	-
t_wec_d_05	Unloading of WEC	Work	1.5 h

TABLE V
DYNAMIC CABLE DECOMMISSIONING STORYBOARD

Task ID	Description	Type	Time
t_dc_d_01	Travel from port to wave farm	Travel	-
t_dc_d_02	Haul-up cable static end	Work	0.5 h
t_dc_d_03	Dynamic cable decommissioning	Work	2 h
t_dc_d_04	Vessel returns to service port	Travel	-
t_dc_d_05	Unloading dynamic cable	Work	1.5 h

removed from the ocean. The simulations presented in this paper have limited the lifespan of the wave farm to 20 years, after which the decommissioning process is initiated.

Just like for the installation, only the decommissioning of the dynamic cable and Seapower platform are included in the simulations, leaving the rest of subsystems out of the scope of the current work.

The decommissioning is represented by the same sequence of tasks utilised for the installation but in the reverse order. Decommissioning the Seapower platform takes up a total of 5.5 hours (see Table IV), while the decommissioning of the dynamic cable requires about 4 hours (Table V).

d) Planned maintenance

When the Seapower platform requires scheduled maintenance, the device is brought to the service port using the decommission sequence (Table IV), and then taken back to the wave farm following the installation task sequence (Table III). The platform is planned to return to port every 5 years for the periodic maintenance, where it will stay for 5 days while the onshore maintenance team fulfils the servicing on the device.

Umbilical cables' design life is lower than the wave farm's typical 20-year lifespan, so cable replacements are needed throughout the farm's lifetime. These cable replacements are carried out using the marine operations as shown in Table VI. A periodical inspection of the cables is also required to monitor the condition of the umbilical cables (see Table VII).

The baseline dynamic cable requires an inspection every 2 years before being replaced after 5 years of usage. The cable replacement and Seapower platform maintenance are carried out with the same frequency so each dynamic cable will be replaced during the maintenance of its corresponding platform. Due to the SeaSnake's special antifouling coating providing a reduction in biofouling and a load decrease on the cable, the SeaSnake cable will have a visual inspection every 4 years and a replacement after 10 years in the ocean.

TABLE VI
DYNAMIC CABLE REPLACEMENT STORYBOARD

Task ID	Description	Type	Time
t_dc_r_01	Cable loading and preparation	Work	1.5 h
t_dc_r_02	Travel from port to wave farm	Travel	-
t_dc_r_03	Haul-up cable static end	Work	0.5 h
t_dc_r_04	Dynamic cable replacement	Work	6 h
t_dc_r_05	Vessel return	Travel	-

TABLE VII
DYNAMIC CABLE SERVICING INSPECTION STORYBOARD

Task ID	Description	Type	Time
t_dc_s_01	Travel from port to wave farm	Travel	-
t_dc_s_02	Haul-up cable static end	Work	0.5 h
t_dc_s_03	Cable inspection	Work	1 h
t_dc_s_04	Vessel returns to service port	Travel	-

TABLE VIII
SEAPOWER PLATFORM FMEA

Failure ID	Description	Failure Rate	Repair time
PTO	Failure regarding the Power-Take-Off system, blocking the ability to generate power in a safe way	0.142	24 h
Control	Failure in the control and communication system of the device, WEC automatically shut down.	0.031	6 h
Mechanical	Repair or replacement of any mechanical components of the device (e.g., hinge, bearings, chassis, pontoon…)	0.060	4 h

e) Unplanned maintenance

When a WEC failure happens, the marine operations follow the same general procedure as the planned maintenance; in the case of the Seapower platform, the WEC will be brought to the port for the failure to be repaired. A failing dynamic cable is not expected to be repairable in a cost/time effective manner and will be replaced with a new unit.

Table VII shows a condensed FMEA (Failure Mode and Effects Analysis) for the Seapower platform with the probability of each failure and the estimated time for the repair. Cable failures can be gathered into a single input failure rate for preliminary analysis:

For the baseline cable an annual failure rate per cable of 0.182 (about 1 failures every 5.5 years) has been selected [2].

At the current stage of the SeaSnake project there is limited information to set a reliable failure rate, so two scenarios with different failure rates are used as input for the SeaSnake simulations. This approach will assist in the cable development process by highlighting the benefits and impact to for a wave energy farm, and by detailing the target reliability required to meet the stakeholder requirements. Two failure rates are selected to represent the reliability of the SeaSnake, a 25% improvement over the baseline failure rate (SeaSnake – 25%) and a 50% improvement over the baseline (SeaSnake – 50%).

- 0.137 annual failure rate (SeaSnake – 25%)
- 0.091 annual failure rate (SeaSnake – 50%)

TABLE IX
VESSELS HIRING COSTS

Vessel/Tool	Multicat with DP	RIB vessel
Mobilisation cost	8,000 €	-
Fuel hourly cost	150 €/h	15 €/h
Daily hire cost	5,000 €/day	200 €/day

TABLE X
CABLE HARDWARE COST COMPARISON: BASELINE VS SEASNAKE

Cable	Baseline	SeaSnake
Unit cost (Including connector)	135,000 €	90,000 €
CAPEX cable hardware cost (100 units)	13.5 M€	9.0 M€
CAPEX cable hardware cost reduction	-	33.3%

5) Sea Power financial inputs

The Wave Venture TEMPEST™ software allows for the financial modelling to be directly linked to the marine operations modelling. Several inputs, such as, vessel usage costs or replacement parts, are automatically allocated and calculated within the simulation. Any vessel or tool related cost will be calculated based on the cost list shown in Table IX. Other values, like, components costs or project management, can be input by the user. In order to respect the confidentiality agreed with Sea Power, the financial values shown in this paper will be kept at high level.

CAPEX gathers all the costs prior to the wave farm entering the operation/ production phase, including the unit costs for the Seapower platform, the dynamic cable, moorings, electrical infrastructure, and project planning expenditures. The costs related to the personnel and vessel usage during the installation of the Seapower platforms and dynamic cables are also included. Excluding vessel costs the total CAPEX for 100 units of the Seapower platform is €250M.

OPEX (Operational Expenditure) costs are related with the operating phase and maintenance expenditures. These costs will be fully simulated by the software and incorporate the vessel and tools hiring costs used during the planned maintenance and repair operations.

DECEX (Decommissioning Expenditure) costs include the associated cost to the decommissioning phase, where most of are vessel expenses (and disposal which is outside the scope of this project). The decommission of the substation, export cables and moorings are not considered within scope.

The new SeaSnake cable is expected to be competitively priced versus the baseline, as shown in Table X.

IV. SIMULATIONS RESULTS

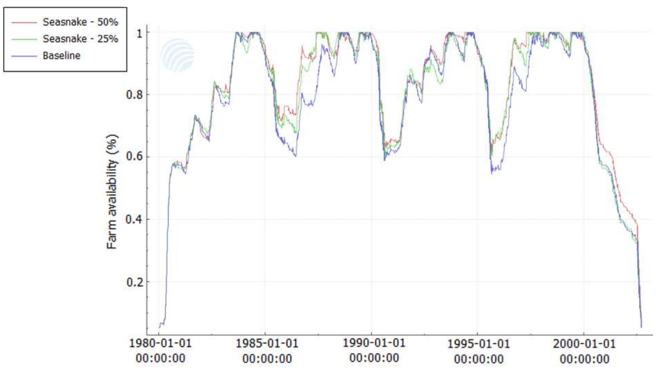

Fig. 6. Farm availability

The outputs of the simulations in the Wave Venture TEMPEST™ software proved evidenced-based results that highlight the impact the SeaSnake cable could have on future wave farm development.

Key objectives of the SeaSnake project are:

- De-risk and optimise the offshore operations.
- To proof that increased availability can be achieved with an improved design for reliability, maintainability, and survivability of WEC dynamic cables.
- To increase the economic viability of OWC (Oscillating Water Column) systems by reducing the LCOE.

To address the project objectives and quantify the impact several KPIs are considered:

- Installability
- Farm availability
- Losses due to cable failure
- Farm productivity
- Vessel usage
- Costs
- LCOE

a) Impact on installability and availability

There are various conclusions we can take from the farm availability shown in Fig. 6. Having a look at the installation phase, it can be seen that all 3 scenarios reach the fully commissioning of the farm pretty much at the same time, which is expected as the installation storyboards are identical for the bas eline and SeaSnake cable. A more detailed installation of the umbilical cables can be seen in Fig. 7, where it is noticeable the struggles to commission the cables during the winter months, installing just 6 cables between January and mid-April. The closeness between AMETS B and Blacksod port allow for timely umbilical cable commissioning during the summer months. The Seapower platform on the other hand, needs to be transported all the way from the port of Galway (175km from the wave farm), making their

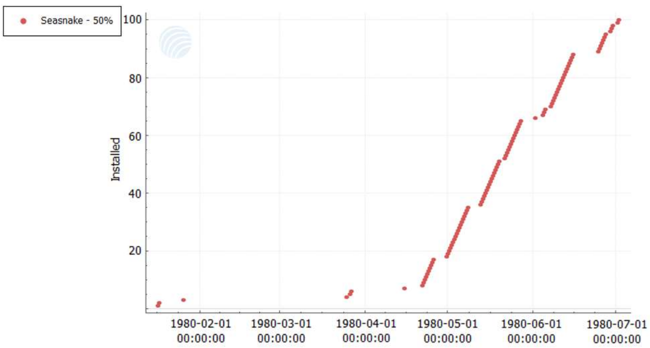

Fig. 7. Cable installation count

TABLE XI
AVAILABILITY IMPROVEMENT

Result	Baseline	SeaSnake 25%	SeaSnake 50%
Operating availability	86.77%	89.01%	90.94%
Availability improvement	-	2.24%	4.17%

TABLE XII
CABLE DOWNTIME LOSSES

Result	Baseline	SeaSnake 25%	SeaSnake 50%
Cable downtime losses	234.4 GWh	155.8 GWh	91.5 GWh
Losses reduction	-	33.5%	61.0%

installation not only slower, but pretty much unachievable during the months of winter. The winter months can be clearly identified during the commissioning phase as the availability increase stops due to the lack of weather windows, and it even decreases affected by the randomized device failures.

Apart from the winter availability drops, 3 big drops can be seen in the availability every 5 years due to the scheduled maintenance of the Seapower platform when the device is taken to shore. The lower failure rate of the SeaSnake cable can be identified looking at the availability drops, as the drops are more severe for the baseline cable than for both SeaSnake scenarios, resulting in over a 4% improvement on the operational availability of the whole farm (see Table XI).

b) *Impact of cable failures*

Fig. 8 gives the availability of just the umbilical cables through the lifespan of the wave farm. It can be seen that the drops in the baseline cable are more severe due to its higher annual failure rate. It is also very noticeable the effect of the greater life of the SeaSnake by checking the drops at 5 and 15 years from commissioning, when the Baseline cable is replaced but not the SeaSnake. Note that the drops in the SeaSnake lines are due to the scheduled maintenance on the Seapower platform, reducing the availability of vessels to repair the failed cables. In the 25 years of operation the losses related to cable downtime can be reduced by 61% (see Table XII).

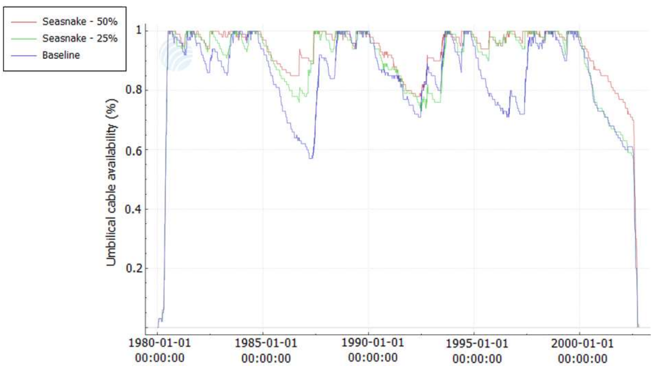

Fig. 8. Umbilical cable availability

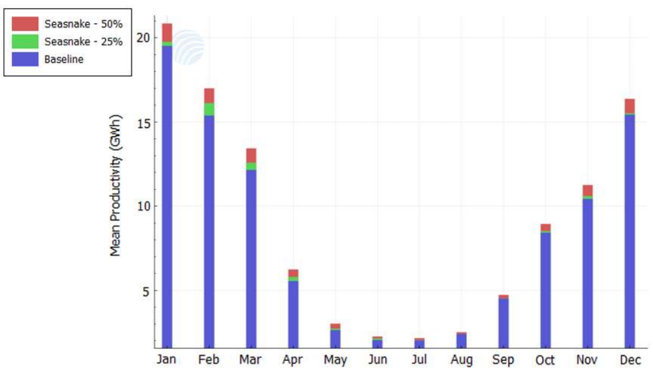

Fig. 9. Mean monthly productivity during operational phase

TABLE XIII
PRODUCTIVITY INCREASE

Result	Baseline	SeaSnake 25%	SeaSnake 50%
Total productivity	1,918 GWh	1,998 GWh	2,069 GWh
Productivity increase	-	4.17 %	7.87 %

c) *Impact on productivity*

The increased availability of the farm (especially during the winter months), has a direct impact in the productivity outcome of the wave farm, reaching an improvement of nearly 8% with the most optimistic SeaSnake cable (see Table XIII). Fig. 9 shows the average power generation per month during the operational phase (excluding installation and decommissioning), showcasing the importance of a high availability during winter months where the mean productivity can surpass the 15 GWh, or even 20 GWh for the month of January.

d) *Impact on Costs*

Putting the focus on the financial results, Table XIV and Fig. 10 show the major costs breakdown of the wave farm in each scenario. CAPEX and DECEX values remain very similar, but in the OPEX costs is where the advantages of the SeaSnake cable can be seen. The longer lifetime and more spaced inspections for the SeaSnake have a direct impact on the planned OPEX costs, achieving a 37% reduction of the expense. Planned OPEX costs gather the expenses linked to predictable operations, such as, cable inspection/replacement, periodical WEC maintenance, and management costs during the operational phase. Unplanned OPEX, expenses that are a result of WEC and cable failures, which are lowered by up to 29% when the SeaSnake is the selected choice for the wave farm. Since the SeaSnake

TABLE XIV
COST BREAKDOWN

Result	Baseline	SeaSnake 25%	SeaSnake 50%
CAPEX	279.7 M€	276.3 M€	276.6 M€
OPEX	302.7 M€	208.2 M€	198.5 M€
Planned OPEX	203.1 M€	126.8 M€	128.2 M€
Unplanned OPEX	99.6 M€	81.4 M€	70.3 M€
DECEX	12.0 M€	11.8 M€	11.9 M€
TOTAL	594.4 M€	496.3 M€	487.0 M€

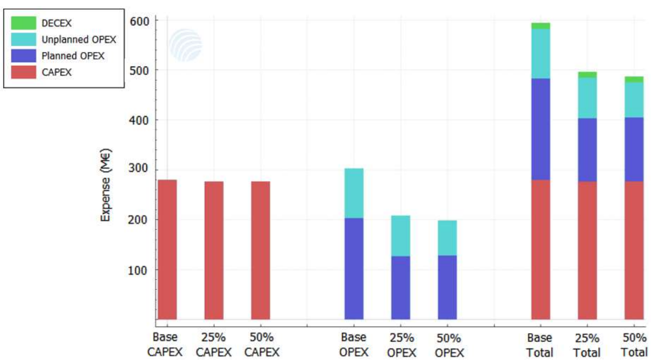

Fig. 10. Major cost element comparison

TABLE XV
"SEASNAKE – 50%" CABLE UNCERTAINTY EFFECT IN OPEX

Result	P10	P50	P90
OPEX	210.0 M€	198.5 M€	187.5 M€
Planned OPEX	137.7 M€	128.2 M€	119.0 M€
Unplanned OPEX	72.3 M€	70.3 M€	68.5 M€

TABLE XVI
MULTICAT VESSEL WORKING HOURS AND COSTS REDUCTION

Result	Baseline	SeaSnake 25%	SeaSnake 50%
Multicat working time	19,908 h	17,163 h	16,363 h
Multicat working costs	19.1 M€	17.4 M€	16.9 M€
Costs reduction	-	8.9%	11.5%

cable is still under development, some uncertainty should be applied to the unit cost value. In Table XV, the percentiles of the operational phase expenses values are shown for an uncertainty of ±15% (normal distribution) on the SeaSnake unit cost, where the total OPEX values reach 210.0 M€ and 187.5 M€, for P10 and P90 respectively.

An important cost to analyse in depth in offshore renewable energy projects is the usage of the hired vessels. In the Sea Power wave farm a Multicat vessel is used for both the WEC and cable installation; the WEC operations remain untouched in all 3 scenarios, but the work required to repair and replace umbilical cables varies, having a direct impact in the costs associated to vessel usage. Table XVI summarizes the vessel usage and the costs associated to fuel and daily hire, showcasing up to 11.5% cost reduction, the reduced annual failure rate is the main reason after this result.

e) Impact on LCOE

Wrapping up with the results, let's have a look at the LCOE, which is reduced from the 310.0 €/MWh on the baseline simulation to 235.0 €/MWh on the most optimistic SeaSnake scenario (see Table XVII); that computes for a 24.2% reduction on LCOE. The discount rate utilized on the calculations is 10%, and the maturity of the Seapower platform is assumed to be 100MW installed capacity. The uncertainty on LCOE shown in Fig. 11, is solely a product of the uncertainty applied to the "SeaSnake - 50%" cable unit cost.

V. CONCLUSIONS

The simulations carried out using the Wave Venture TEMPEST™ software have quantified the advantages of the novel SeaSnake dynamic cable over a commercially available equivalent umbilical cable, by comparing them in a realistic future wave farm scenario using Sea Power's Seapower platform as the wave energy converter.

The expected lower unit cost (135,000€ vs 90,000€) has

TABLE XVII
LCOE REDUCTION

Result	Baseline	SeaSnake 25%	SeaSnake 50%
LCOE	310.0 €/MWh	248.7 €/MWh	235.0 €/MWh
LCOE reduction	-	19.8 %	24.2 %

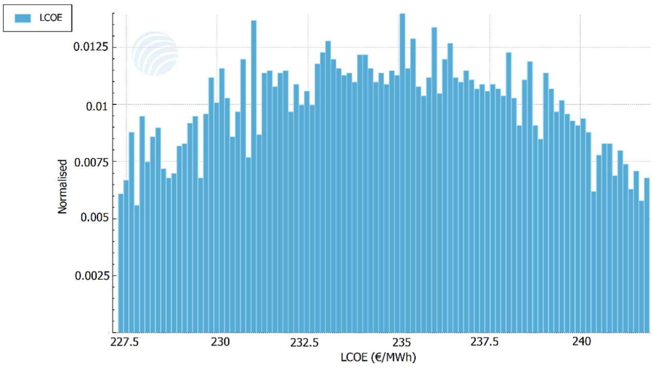

Fig. 11. LCOE uncertainty distribution (Seasnake – 50%)

a positive impact in the financial results, but the real game changer is the durability that the SeaSnake can offer due to its design and antifouling coating, allowing for up to 10 years of lifetime with visual inspections every 4 years and a significantly lower failure rate than its competitors. Some of the most interesting outcomes that are directly related with this feature are:

- Operating availability and productivity number have risen by 4.17% and 7.87%, respectively. The impact is very significant in high energetic zones like AMETS test site, where the weather windows are scarce.
- Vessel usage, and its associated costs, have dropped significantly. This has a direct impact in the OPEX costs and hence in the overall project costs, which have been lowered by up to 34.4%.
- The LCOE of the project has been reduced by 24.2% for the Sea Power wave farm.

A. Impact of SeaSnake

Despite being at an early development stage and more testing and analysis being required, the novel SeaSnake dynamic cable, steps up as a promising solution for wave energy. With a more than competitive expected price and a strong design making it a light and durable cable, the SeaSnake will allow offshore renewable energy projects to reduce their cost of energy and make them competitive on the energy market.

B. Future work

The ongoing testing and analysis on SeaSnake will provide us with higher quality data around the dynamic cable that will be used as an input for higher accuracy result. Two of the main inputs that need to be studied for the posterior techno-economic simulation are the survivability (cable failures and maintenance strategies) and the advantages that a lighter cable might have on offshore operations (e.g., lower task durations, connection in tougher sea conditions…). Also, an enhanced scope including a discussion around moorings, or higher detail in tasks such as electrical connection will help towards higher quality outputs

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