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Techno-Economic Analysis Framework for Wave Energy Conversion Schemes under South African Conditions: Modeling and Simulations

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***Abstract*—**This paper presents a desktop study of comparing two different wave energy to electricity technologies (WECs) using a techno-economic approach. This techno-economic approach forms basis of a framework for rapid comparison of current and future technologies. The approach also seeks to assist in investment and strategic decision making expediting future deployment of wave energy harvesting in South Africa.

***Keywords*—**Cost of energy, tool, wave energy converter, WEC-Sim.

I. Introduction

IN South Africa (SA), Eskom is the largest power producer that generates electricity primarily from coal, approx. 92.8% [1]. This high dependency on coal has its disadvantages, such as high water usage, greenhouse gases produced and coal as a power generation resource is slowly getting depleted. With the national electricity demand is expected to double in next 15 years and as a result, Eskom is under considerable pressure to rapidly increase power generation capacity and address the aforementioned concerns [1]. These reasons led Eskom to embark on an investigation to determine if utility-scale of renewable energy, including wave energy power, is a viable supply-side option for Eskom and SA. A specific finding was made during the Eskom study which confirmed the availability of wave energy resource on the east and west coasts [1].

In order to determine technical performance of a WEC, its characteristics have to be determined. Output power matrix is one of the characteristics that are needed to predict the electrical power yielded, that in turn, contributes to the economic performance. The electrical power output of a WEC device is dependent on sea states representing wave resource.

In this paper, a wave simulation to give theoretical wave power available at the preferred location is performed so that wave characteristics can be matched to predetermined WEC power given by power matrix.

Two WEC devices are assessed for economic performance at the Western Cape coast location, using a COE Calculation Tool (COE_Tool) developed by a consulting engineer Julia F. Chozas in partnership with Aalborg University and Energinet.dk. The key outputs are Levelized Cost of Electricity, Net Present Value (NPV) for three different rates and the payback period. The currency used for the analysis is a Euro (€) and results are in US dollar ($) [2].

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II. Wave Climate

SA has an exposed coastline over 3000 km with average wave power levels well in excess of 30 kW/m. The chosen location for this study is Slangkop site, because it is one of the locations with high average power. It is located on the west coast in the Western Cape province of SA as shown in Fig. 1, and yields mean annual average wave power of 39 kW/m [3].

Wave parameters measurements from the wave measuring station CP01-Cape Point located at Latitude: 34.204 and Latitude: 18.28667 were obtained from Council for Scientific and Industrial Research (CSIR). The data comprises of significant wave height (m) and spectral peak wave periods (s) sampled every four hour from 01/01/2014 to 31/12/2014.

A. Wave Energy Scatter

Wave energy scatter diagram representing all occurring sea-states at Slangkop, shown in the Appendix, is the matrix defined in terms significant wave heights and average zero crossing wave period (T_z). It is assumed that there is a constant relationship between T_z and spectral peak wave period (T_P), thus, T_z is calculated using (1) [2]:

$$T_z = T_P / 1.5(s) \quad (1)$$

The bin resolution of 0.7 s x 0.5 m was used to populate the scatter diagram matrix, for both zero-crossing wave periods and significant wave heights respectively. Each bin of a matrix indicates the hours per year that a sea-state occurs, hence it was obtained by counting the number of times that a certain range of wave heights happen at a certain range of period. Some data where wave heights and periods had a value of 9999 were omitted in scatter matrix binning, and data omitted was equivalent of 100 hrs averaging on four days of the year. The reason for no record of wave data during those times could be associated with a measuring station being out service for maintenance or it could have been due to faults.

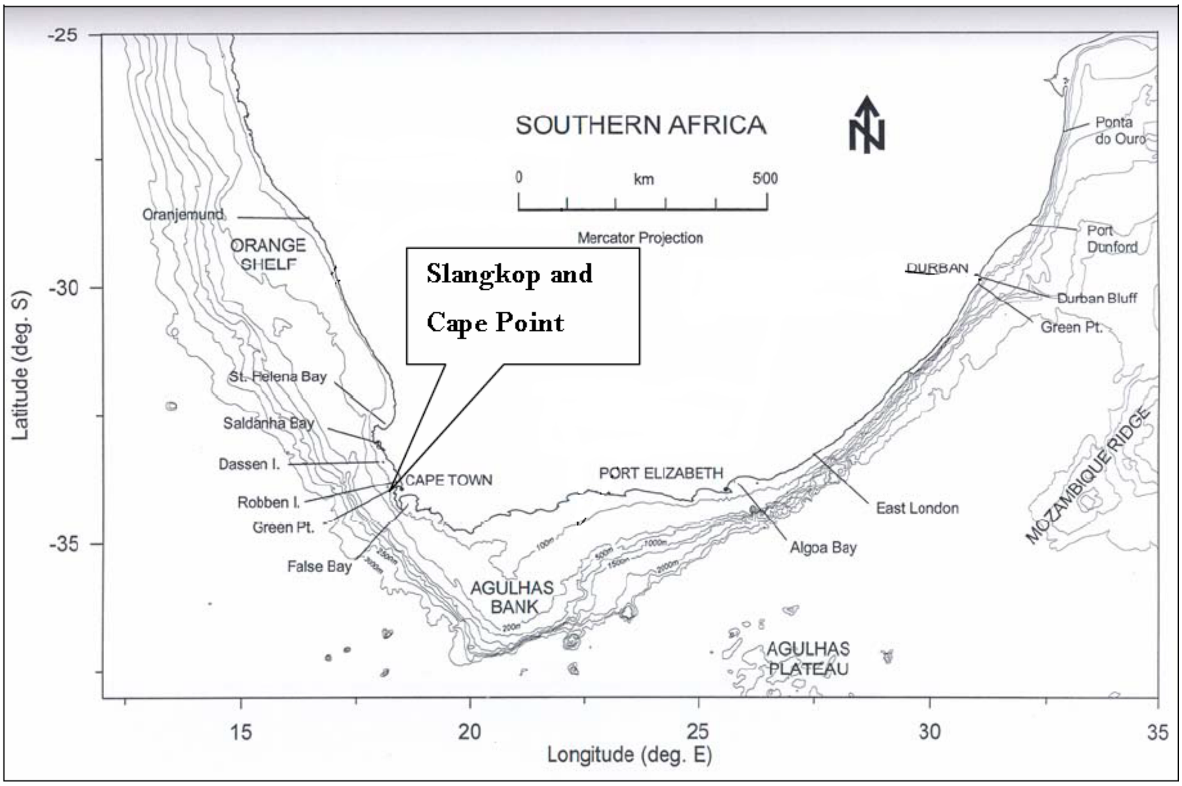

Fig. 1 Scaled diagram showing Slangkop site location [3]

The resulting wave climate matrix shown in the Appendix resulted in wave power density (P_{wave}) of 34.6 kW/m as a function of significant wave height (H_s) and zero crossing wave periods (T_z) as illustrated on (2) [2]. It should be noted that the power density calculated on a COE_Tool is slightly lower than the value previously approximated by [3], for the same location as mentioned in the beginning of this section. Although calculated power density is slightly lower than the power sated in [3], it is still above 30 kW/m determined as a minimum at the west coastline. The discrepancy in values may be associated with the missing data from the measuring station.

$$P_{wave} = 0.577 \times H_s^2 \times T_z \,(kW / m) \tag{2}$$

III. Analysis Approach

The economic analysis was approached by choosing two WEC devices to compare at the same site location, first device chosen was the Pelamis, chosen as a reference WEC because it is a device with most known data information, and it is also believed that a Pelamis was considered for SA and there were talks about investment in it on the Western Cape coast [4]. The analysis was done on a COE_Tool with parameters shown in Tables I and II. The Wavestar WEC device was a chosen as a second device for comparison to the Pelamis.

The analysis was considered for a single device instead of multiple devices or farms for each WEC technology, although results of studies [5], [6], [9] revealed that the project cost reduces with the use of multiple devices and the capacity factor increases. Table I tabulates Pelamis and Wavestar specification and assumptions used in the calculations.

TABLE I
WECs Specifications

Parameter	Pelamis	Wavestar
Length	150m [10]	12m [12]
Diameter	3.5m [10]	5m [12]
PTO Average Efficiency	80% [11]	70% [112]
Generator Average Efficiency	94% [11]	90% [12]
Generator rated Power	3x250kW [10]	600kW[12]
Availability	100% [11]	100% [11]

The approach for cost estimates is aimed at providing realistic yet conservative estimate for the conditions in SA for investors to make informed decisions and the authorities to consider WEC technologies.

A. Energy Output

Energy output is calculated by combining two matrices for a specific location. One matrix describes the probability of occurrence of sea states (determined by significant wave height and a characteristic wave period). This matrix is based on long-term statistics and is called scatter diagram. The power matrix describes the energy produced by the WEC.

IV. Feed-In Tariff

In SA, several policy instruments have been implemented to regulate and standardize trading of electricity while encouraging energy mix with deployment renewable energy technologies. In 2009, the government began exploring a Feed-In Tariff (FIT) higher than the market rate for non-renewable energy. It is also legislated that energy producers purchase these technologies from the manufactures at the higher price [4]. The incentive structure through FIT applied to renewable energy technologies was implemented under the Independent Power Producers Procurement Programme (IPPP) and is known Renewable Energy Feed-in Tariff (REFIT) [4]. Wave, tidal and geothermal energy conversion technologies were excluded in REFIT Phase I and II; because, these technologies were not commercially available and will be considered in subsequent years annual REFIT reviews [13]. Renewable Energy Power Purchase Agency is run by Eskom, who was appointed to be a single buyer office facilitated by National Energy Regulator of South Africa (NERSA) who awards tenders to Independent Power Producers (IPP's) [13].

REFIT was later rejected in favour of a most effective policy instrument to date known as Renewable Energy Independent Power Producer Procurement Program (REIPPPP). In 2014 a total of 64 projects were awarded to the private sector. Private investment of US$14bn had been committed, and these projects were to generate 3922 MW of renewable power. The implemented FIT across all renewable technologies deployed in SA after the bidding process ranges $143 /MWh to $336 /MWh [14]. Therefore, because there is no implemented FIT for wave energy technologies, it was decided to perform a levelised cost of electricity (LCOE) study using the maximum implemented REFIT.

V. Assumptions for Calculations

The economic analysis was done on a LCOE-Tool as mentioned in Section IV. Pelamis unit costs were gathered from [5]-[8] and adjusted by applying indices of certainty as discussed and illustrated in [15]. Table II tabulates parameters used for cost analysis. The analysis and costs is done based on a wave data of 2014. The discount rate shown in Table II is assumed to be constant because NERSA stipulated a constant discount rate for all other renewable technologies in the IPPP. Project life time is assumed to be 20years because all renewable project economic life time existing in SA are considered for 20 years [13].

A. Capital Expenditure (CapEx)

The calculation of the CapEx is directly related to physical parameters specified in the design specifications such as, WEC's structure, the Power Take-Off (PTO), the grid infrastructure and the installation and mooring.

B. Operation Expenditure (OpEx)

The OpEx is a representation of Operation and Maintenance (O&M) costs, as a cost per unit of energy produced. Annual OpEx comprises of:

- Operation and maintenance cost per year, assumed to be 6% of CapEX [2].
- Site lease and Insurance, assumed to be 2% of CapEx [2], [6].

TABLE II
Assumed Parameters for LCOE Analysis

Parameter	Pelamis	Wavestar
Power Conversion Module	€1,623,127 [15]	-
Steel per tonne	€6,000 [15]	-
Mooring	€552,165 [15]	-
Admin, Planning and Consenting	€5,682,925 [15]	-
Pre-Assembly and Transport	€35,228 [15]	-
Electrical Connections/Cables	€386,301 [15]	-
Total CapEx	€9,933,000 [15]	€24M [6]
Insurances	2% [2],[6]	2% [2],[6]
Discount Rate	12% [14]	12% [114]
Project Life Time	20 years	20 years

VI. Results

A Technology Readiness Level (TRL) of 6 was selected for both Pelamis and Wavestar; this implies that testing is at full scale at test sited, and the majority key performance characteristics and cost drivers satisfy potential economic viability under distinctive and favourable market and operational conditions [16]. TRL level of 6 comes with an uncertainty between -20% and 20% in calculations of this analysis.

A. Technical Results

Figs. 2 and 3 show a bar chart for annual power produced by a Pelamis at Slangkop for different wave heights and wave periods. The energy production indicates the performance of the WEC throughout its lifetime at Slangkop location.

It is noted that the predominant power is produced by waves with heights between 2 m and 2.5 m and periods of 7.5 s. For a Wavestar, waves with heights of 2 m and periods of 7 s produce predominant power as seen on Figs. 4 and 5. Fig. 5 shows that there is significant wave power on waves with heights above 3 m but not utilised for production of electricity because a Wavestar engages a storm protection mode ceases operation, this has an effect on a capacity factor.

The Pelamis was predicted to be 53% efficient and to have a Capacity factor of 9% as tabulated in Table III, this implies that this device with the assumed specification does not generate electrical power from most sea states but more than half of its rated power is generated when favourable sea states occur. It is apparent that the Wavestar performs better as compared to a Pelamis with same sea states; Table IV shows a Capacity factor of 15% percent hence the Wavestar has more favourable sea states than a Pelamis as Slangkop.

TABLE III
Pelamis Technical Results

Capacity factor	9%
Annual electricity production	563 MWh/y
Average annual electricity production	64 kW
Average wave-to-wire efficiency	53%

TABLE IV
Wavestar Technical Results

Capacity factor	15%
Annual electricity production	808 MWh/y
Average annual electricity production	92 kW
Average wave-to-wire efficiency	53%

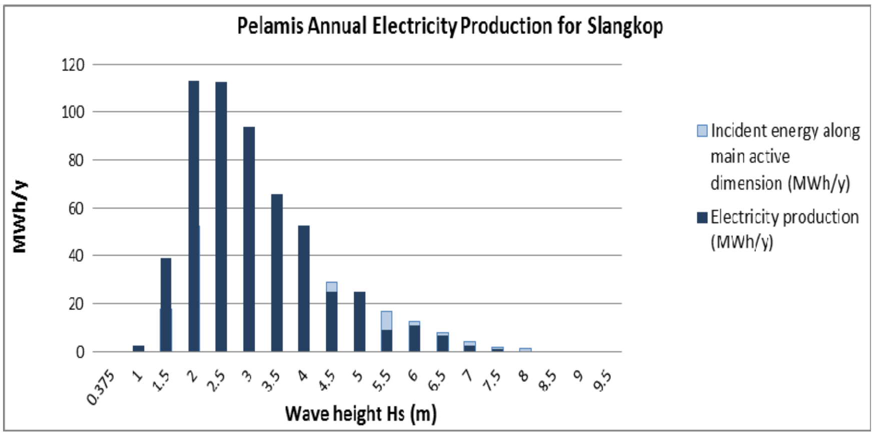

Fig. 2 Pelamis power production at specific wave heights simulated for Slangkop site

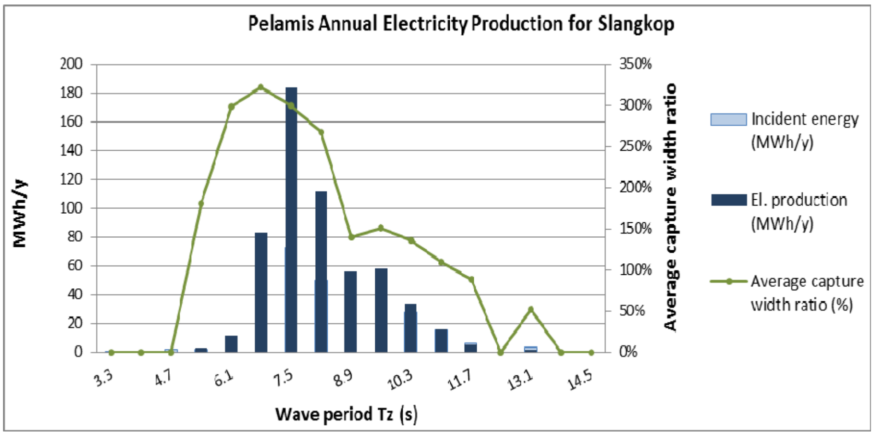

Fig. 3 Pelamis power production at specific wave periods simulated for Slangkop site

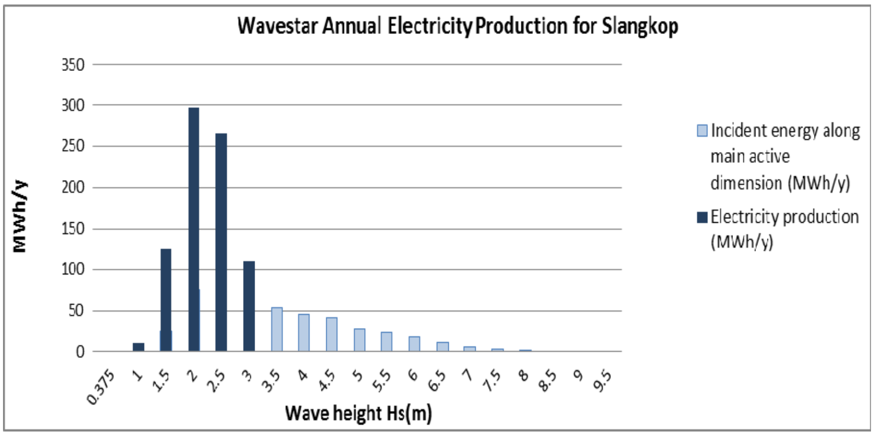

Fig. 4 Wavestar power production at specific wave heights simulated for Slangkop site

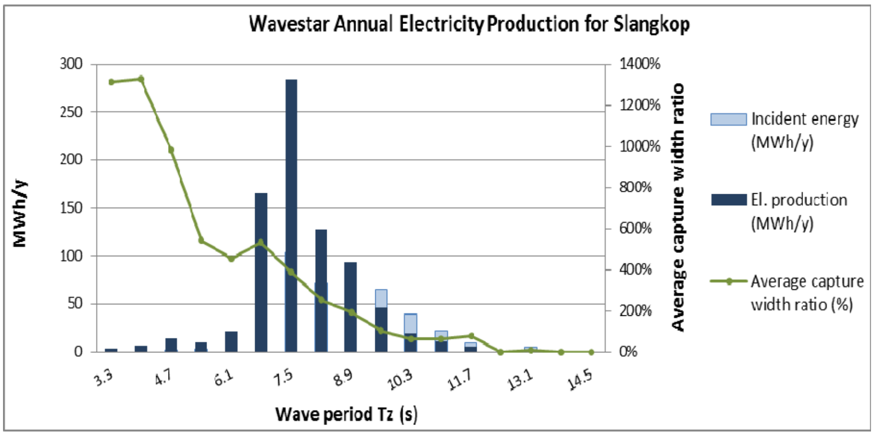

Fig. 5 Wavestar power production at specific wave periods simulated for Slangkop site

Currency	USD	Development stage: Phase 3 / TRL 6		[-20 to 20%] uncertainty
FIT-User ($/MWh)	798.0	336.0		
Total CapEx	13.21 M$	Annual OpEx	1056.83 k$/y	
Payback period	Greater than project lifetime			
Discount rate		0%	4%	12.0%
LCOE (20 years, in $/MWh)		3049	3464	4479
NPV (20 years, in k$)		-30562.2	-25001.2	-19690.8

Fig. 6 Pelamis economic results from a COE_Tool

Currency	USD	Development stage: Phase 3 / TRL 6		[-20 to 20%] uncertainty
FIT-User ($/MWh)	798.0	336.0		
Total CapEx	31.92 M$	Annual OpEx	2553.60 k$/y	
Payback period	Greater than project lifetime			
Discount rate		0%	4%	12.0%
LCOE (20 years, in $/MWh)		5136	5834	7544
NPV (20 years, in k$)		-77562.5	-62934.8	-48966.2

Fig. 7 Wavestar economic results from a COE_Tool

B. Economic Results

Both WEC devices' economic analysis yielded a relatively high LCOE for an assumed FIT and predetermined discount rates as seen on Figs. 6 and 7 for the Pelamis and Wavestar respectively. One may note that even with lower discount rates the LCOE is still relatively high but reduces with decreasing rate.

The results show that both WEC are not economically viable at this stage given that the assumptions made are correct. The positive cash flow represented by a NPV is never achieved within the expected lifetime of the project for each case, thus resulting in a payback period to drag longer than project lifetime. A negative NPV was also obtained for Belmullet test site in Ireland for both WECs at different power ratings [6]. A LCOE at a discounted rate of 12% and assumed 51% capacity factor for a Stellenbosch Wave Energy Converter (SWEC) at different sites on the Western Cape coast was predicted in [4], to be $2056 /MWh. The two WEC analysed in this paper are the most expensive to deploy as compared to SWEC and other form of renewable technologies deployed in SA. The highest LCOE estimated for SA renewable is $548.1 /MWh, estimated for concentrating solar technologies without storage [13].

It is stated in [7], that the unit cost of WEC devices reduces with multiple device purchase, and this is due to the discounts provided by manufactures to encourage multiple purchases. The discount is based on a cumulative factorial reduction price. Percentage reduction is given by (3):

$$P = N \exp(\ln(tf) / \ln(2)) \tag{3}$$

where P is the percentage reduction, N is the number of devices and 'tf' is the technology factor (usually ranges from 0.85 to 0.95) [6].

It can be deduced that the LCOE estimates on the paper may reduce significantly with higher rated wave energy farm.

VII. Future Work

More WEC technologies will be analysed for the same site including a concept design of the WEC at University of the Witwatersrand. The WEC system dynamics will be modeled and simulated using multi-body dynamics methods to obtained technical data of dynamic operation. The mathematical modeling will be done on Wave Energy Converter Simulator (WEC-Sim), WEC-Sim is an open-source tool developed on Matlab with reference models for marine energy conversion. It is developed by National Renewable Energy Laboratory, Pacific Northwest National Laboratory and Oak Ridge National Laboratory with two consulting firms, Re-Vision Consulting and LLC & Cardinal Engineering, also with the University of Washington and Pennsylvania State University [17]. WEC-Sim simulates interactions between waves, the WEC device motion, and the PTO mechanism to predict hydrodynamic forces and electrical output parameters. The WECs power matrices will be predicted from this tool for those WECs with unpublished or untested power matrices. A techno-economic analysis framework for WEC will be developed from the study findings as outlined in [20].

VIII. Conclusion

The renewable industry is optimistic that the cost of WEC devices will significantly reduce over the years having gone through thorough optimisation by design, testing, gaining operational experience and technology improvement (i.e. reaching a maturity stage) to competitive cost levels. The west coast of SA has a potential to attract WEC technology developers. More exploration of different WEC using longer timeframe scatter diagrams may help to influence WEC to be designed to accommodate sea states there are more apparent on this coast.

REIPPPP to date has proven to be successful renewable energy program to attract private sponsors to invest in renewable energies. With this framework and other studies on WEC technologies there is hope that wave energy may be included in the next Integrated Resource Plan (IRP). In that IRP appropriate REFIT should be stipulated to attract investors and for WEC technology to make sense.

With a REFIT used for this study, assuming all the cost assumptions made were correct and the conditions stay the same, REFIT for a Pelamis to be economically viable would have to approximately 10 times more and 16 times more for a Wavestar. That reduces payback period to 16 years and 18 years respectively.

Appendix

Hs (m) \ Tz (s)	3.3	4.0	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.6	10.3	11.0	11.7	12.4	13.1	13.8	14.5
0.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.00	0.0	0.0	0.0	0.0	8.0	36.0	25.0	1.0	4.0	5.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
1.50	14.0	12.0	9.0	6.0	23.0	135.0	198.0	60.0	29.0	12.0	14.0	8.0	7.0	0.0	1.0	0.0	0.0
2.00	4.0	7.0	13.0	8.0	23.0	188.0	327.0	123.0	82.0	28.0	24.0	14.0	6.0	0.0	1.0	0.0	0.0
2.50	0.0	2.0	9.0	2.0	5.0	76.0	182.0	121.0	100.0	53.0	19.0	12.0	5.0	0.0	1.0	0.0	0.0
3.00	0.0	0.0	3.0	11.0	6.0	33.0	96.0	71.0	67.0	54.0	13.0	7.0	5.0	0.0	0.0	0.0	0.0
3.50	0.0	0.0	1.0	1.0	3.0	10.0	38.0	35.0	36.0	34.0	12.0	6.0	2.0	0.0	0.0	0.0	0.0
4.00	0.0	0.0	0.0	1.0	8.0	16.0	22.0	16.0	21.0	16.0	12.0	2.0	3.0	0.0	0.0	0.0	0.0
4.50	0.0	0.0	0.0	0.0	0.0	9.0	21.0	9.0	14.0	11.0	9.0	7.0	0.0	0.0	1.0	0.0	0.0
5.00	0.0	0.0	0.0	0.0	1.0	3.0	5.0	10.0	5.0	11.0	5.0	4.0	0.0	0.0	0.0	0.0	0.0
5.50	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.0	3.0	6.0	9.0	1.0	1.0	0.0	1.0	0.0	0.0
6.00	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	7.0	3.0	2.0	2.0	0.0	1.0	0.0	0.0
6.50	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.0	1.0	2.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0
7.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.0	1.0	0.0	0.0	0.0	0.0
7.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
8.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
8.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig. 8 Slangkop Scatter diagram reflecting ocean wave energy resource by a number of sea states

A. *Pelamis WEC*

The Pelamis is an attenuator wave device and extracts energy via both the heave and pitch motion of incoming wave trains. It is secured in position using a flexible mooring system. Each hinge joint features four hydraulic rams, a reservoir, high pressure accumulators and a generator set. High pressure fluid is transferred by a compression or extension of each hydraulic ram to an accumulator which drives a hydraulic motor, which in turn drives the electrical generator [19]. Ocean Power Delivery Ltd began demonstrating a full-scale 750 kW prototype of their Pelamis wave device.

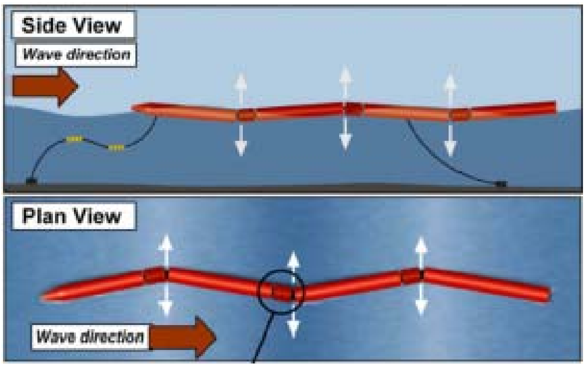

Fig. 9 Pelamis model [17]

B. Wavestar WEC

The Wavestar is a multiple point-absorber WEC that was developed by Wave Star Company from a concept realised in 2000. It is one of world leading wave energy technologies [18]. It consist of two rows of round floats attached to a bridge structure, secured to the sea bed by a use of steel piles that are cast into concrete foundations [12], shown in Fig.10. The floats move up and down with the passing wave, thereby pumping hydraulic fluid into a common hydraulic manifold system which produces high pressure oil into a Power take-Off (PTO). This device was installed at Hanstholm, Denmark in 2009 rated at 600 kW [12], [18].

Fig. 10 Wavestar prototype at Hanstholm [18]

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