LiftWEC

DEVELOPMENT OF A NEW CLASS OF WAVE ENERGY CONVERTER BASED ON HYDRODYNAMIC LIFT FORCES

Deliverable 8.5

Optimised device parameters

Deliverable Lead	Kim Nielsen, Aalborg University & Julia F. Chozas, Consulting Engineer
Delivery Date	27th January 2023
Dissemination Level	Public
Status	Final
Version	3.2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

Document Information

Project Acronym	LiftWEC
Project Title	Development of a new class of wave energy converter based on hydrodynamic lift forces
Grant Agreement Number	851885
Work Package	WP8
Related Task(s)	T8.5 & T8.6
Deliverable Number	D8.5
Deliverable Name	Optimised device parameters
Due Date	31st December 2022
Date Delivered	27th January 2023
Primary Author(s)	Kim Nielsen (AAU) & Julia Fernandez Chozas (JCC)*
Co-Author(s)	Rémy Pascal (InnoSea) Francesco Ferri (AAU)
Document Number	LW-D08-05

Version Control

Revision	Date	Description	Prepared By	Checked By
0.1-3.1	9.12.2022	Internal drafts for review	KIN, JFC, RP	PLK, FDM
3.2	27.01.2023	Draft final	KIN	JFC, PLK, RP

- Contact at: info@juliafchozas.com

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

EXECUTIVE SUMMARY

In this 3-year funded LiftWEC Project, partners collaborate to determine the economic potential of a new type of wave energy converter using lift forces to convert wave energy into electricity. The LiftWEC consist of two hydrofoils rotating around a horizontal axis interacting with the incident waves. Different configurations of support structures for attaching the rotor and generators have been analysed and evaluated in Deliverable 8.4 using the LiftWEC Levelised Cost of Energy (LCoE) Calculation Tool. Based on these results, and with consensus from the consortium, the Spar Buoy LiftWEC concept shown below on Figure 1 was selected for final optimisation.

The assumptions used for each cost centre are detailed in Deliverable 8.4 and the assumed effect on costs from changing the dimension on Capital Expenditures, Operational Expenditures and Annual Energy Production will be described in this deliverable.

This deliverable describes a methodology and assumptions in which the effect of changing a design parameter effects the system weight, cost and performance and resulting LCoE. If the specified range of parameter change leads to a minimum LCOE value this can be identified as an optimal solution in terms of cost effectiveness. The parameter chosen for demonstrating this methodology is the span of the rotor foils varied from 20 meter to 50 meter.

The general form of the hydrofoil rotor, power take-off system and its pitch control are essentially the same for all dimensions of the span, the difference being increased power rating due to increased foil span, and the structural loads experienced by the foils, support structure and moorings.

By quantifying this relationship and calculating the LCoE for four different spans at three different installation sites, an indication of how much the LCoE is affected not only by span, but also by the given site is obtained and presented. The study shows that the longer the span the lower the LCOE. The optimal dimension of the LiftWEC concept for the chosen location is the LiftWEC with the longest span. The trend shows that the LCOE is lowest at a deployment location with most incident wave power.

The resulting LCoE calculated for 4 different spans and three deployment sites will allow to quantify the project to further detail the relationship between economic cost and structural span.

Results from the LCoE assessment will be fed back into the concept evaluation (WP2) to help identifying the design elements of the configuration that offer the greatest potential for reduction in LCoE with further investigation.

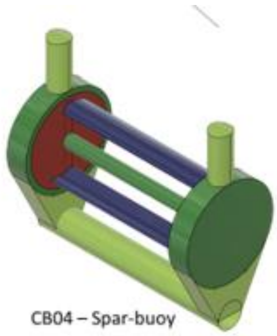


Figure 1: The Spar-buoy LiftWEC Baseline Configuration

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

1 Introduction

The spar buoy LiftWEC configuration consists of two-hydrofoils with a span “s” attached at both ends to a rotor of diameter 12 meter, driving a direct drive generator included at both sides (i.e. nacelles) of the spar buoy support structure.

The mooring of the Spar buoy allows the structure to weathervane to keep the rotor perpendicular to the direction of the incoming waves.

The mooring is a single-point connection type that allows connecting and disconnecting the device in a relatively short time.

In this optimisation study the span “s” of the hydrofoils is varied to evaluate its influence on the LCoE and to provide some general trends towards optimisation of the Spar buoy LiftWEC (indicated on Figure 1.1).

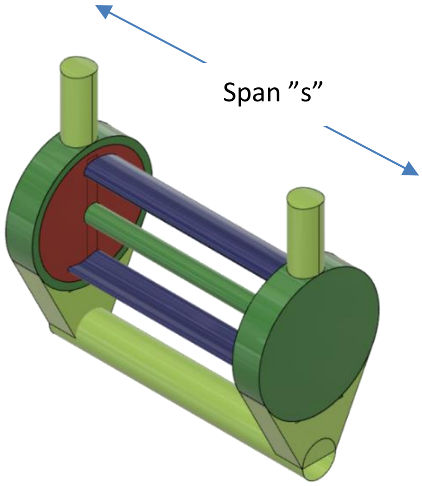


Figure 1.1: Spar buoy LiftWEC

1.1 Optimisation Methodology

Optimisation of the Spar-buoy concept will be carried out using the LiftWEC LCoE Calculation Tool to evaluate the effect of parametrical design changes. The first parameter to evaluate will be the span of the hydrofoil. Four rotor spans are considered: 20m, 30m (baseline), 40m and 50m. The effect on cost is evaluated in terms of capital expenditure (CAPEX), operating expenditure (OPEX), and the annual energy production throughout its lifetime (AEP), leading to the Levelized Cost of Electricity (LCoE) in EUR per MWh. The effect of rated power will be discussed along with the effect of deployment location on the LCoE. Tracing the trends of the LCoE can help pointing to an optimal solution.

1.2 Assumptions

Unless specifically stated, cost estimates have been calculated based on the costs gathered under Deliverable 8.1 (Têtu and Fernandez-Chozas, 2020) and included as default values in the LiftWEC LCoE Calculation Tool (Fernandez-Chozas *et al.*, 2022a). It could be discussed whether these default costs, gathered in 2020, are no longer representative of current (end of 2022) prices. For example, steel prices are currently higher (about 20%) than a year ago. In the present exercise, prices before Covid and supply chain issues are considered, to ensure relative comparison and trends within the project remain valid. Also, the current volatility of the price of raw materials might not be representative of future long-term trends, and therefore caution should be used before using the latest data for R&D projects with potential realisation in the medium to long term future. To assess this, Deliverable 8.6 will relate the variations in unit price of raw materials and the uncertainties they pose to the LCoE estimates.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

2 Deployment Sites

2.1 France, off Quimper LiftWEC test Site

In this section we look at three possible deployment locations and their wave resource, which are also included in the LiftWEC LCoE tool, as described in Del. 8.3 (Fernandez-Chozas *et al.*, 2022). The first deployment location is the *LiftWEC Test site*: off the North Atlantic coast of France (coordinates 47:84° N, 4:83° W), in the Bay of Audierne close to Quimper. Water depth at the selected location should be at least 80 m, distance to shore about 10 km and the wave resource is estimated at 36 kW/m.

Table 2.1 Site for a Wave Power Plant. Characteristics of France, off Quimper LiftWEC test Site

Distance to grid conn. point:	10 km
Distance to maintenance port:	20 km
Distance to fabrication assembly	50 km
Water depth	80 m
Seabed for mooring:	Sand / Clay
Wave Power level	36 kW/m
Hs max	12 m
Tz max	12 sec
Tidal range	+1 m -1 m

Table 2.2 Scatter table for the LiftWEC Test Site, Off Quimper, France

Hm0 / T02	2,92	3,75	4,58	5,42	6,25	7,08	7,92	8,75	9,58	10,42	11,25	12,08	12,92	13,75	14,58	15,63	16,50	T02 ave	dP (kW/m)
0,25	0	1	3	4	2	1	0	0	0	0	0	0	0	0	0	0	0	5,4	2,4
0,75	7	47	129	213	204	97	40	8	3	1	0	0	0	0	0	0	0	5,8	1406,1
1,25	0	41	239	396	451	367	196	79	29	7	3	1	0	0	0	0	0	6,3	10332,3
1,75	0	5	114	309	381	384	306	175	78	29	13	1	0	0	0	0	0	7,0	22068,1
2,25	0	0	16	183	294	270	232	177	90	33	12	3	1	0	0	0	0	7,3	28043,3
2,75	0	0	1	53	194	199	181	137	91	31	11	3	0	0	0	0	0	7,7	30093,3
3,25	0	0	0	7	101	153	128	111	63	36	11	5	0	0	0	0	0	8,0	29992,6
3,75	0	0	0	0	33	119	120	89	55	30	12	2	1	1	0	0	0	8,2	30905,7
4,25	0	0	0	0	5	73	105	87	41	20	14	4	0	0	0	0	0	8,5	30889,1
4,75	0	0	0	0	0	30	82	77	46	14	8	3	1	0	0	0	0	8,7	29699,0
5,25	0	0	0	0	0	7	50	55	35	13	7	2	1	0	0	0	0	8,9	24440,2
5,75	0	0	0	0	0	0	23	45	29	12	5	2	1	0	0	0	0	9,2	20368,3
6,25	0	0	0	0	0	0	6	31	24	9	3	1	0	0	0	0	0	9,4	16019,7
6,75	0	0	0	0	0	0	1	15	18	7	3	1	1	0	0	0	0	9,6	11321,8
7,25	0	0	0	0	0	0	0	5	15	6	3	1	0	0	0	0	0	9,9	9649,4
7,75	0	0	0	0	0	0	0	1	8	7	3	1	0	0	0	0	0	10,2	7241,8
8,25	0	0	0	0	0	0	0	0	3	4	2	2	0	0	0	0	0	10,7	4788,2
8,75	0	0	0	0	0	0	0	1	1	2	1	2	0	0	0	0	0	10,8	3010,3
9,25	0	0	0	0	0	0	0	0	1	1	3	2	1	0	0	0	0	11,5	4114,8
	7	94	502	1167	1666	1703	1469	1095	631	265	114	36	9	2	1	0	0	8761,4	35,9

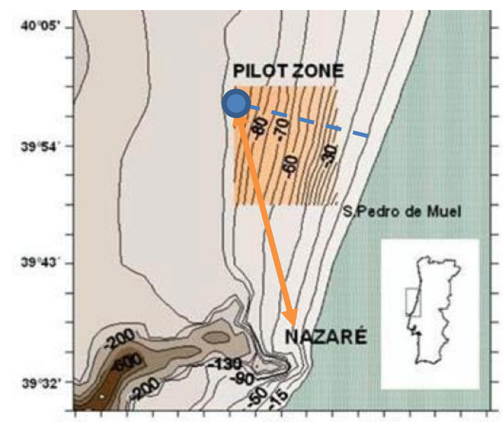
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

2.2 Pilot Zone Portugal

To evaluate a location with a lower power resource of 20 kW/m at 80m the Pilot Zone in Portugal is considered. Portugal has been able to attract many wave energy companies due to its favorable wave resource, mild climate, and attractive testing conditions such as permit availability and favorable feed-in tariffs for produced energy. As such, many of the first large scale tests have taken place in Portugal such as the 2 MW Archimedes Wave Swing, tested near Porto in the period 2000 – 2006, Pelamis prototype tests of three 750 kW devices in 2008, as well as the Finish Wave Roller. As a result of the continued interest in wave energy prototype testing in the region, Portugal provides in 2007 a dedicated area for testing wave energy systems known as the Pilot Zone.

The pilot zone water depth varies between 30 and 90 m with a sandy seabed. The distance from the 80 m bathymetric depth to shore is about 10 km. Table 3.4 shows a scatter table from the site as included in the LCoE tool. The scatter diagram was obtained from buoy data 2004 – 2005 and indicates an annual wave power average of about 20 kW/m.

Table 2.3 Pilot Zone Portugal 39º54' N 9º06' W



Distance to grid	10 km
Distance to main port:	20 km
Distance to fab port:	50 km
Water depth	80 m
Seabed for mooring:	Sand
Wave Power level	20 kW/m
Hs max	12 m
Tz max	12 sec
Tidal range	+1 m -1 m

Table 2.4 Scatter table for Pilot Zone in Portugal

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17		
Hm0 / T02	3,70	4,58	5,42	6,25	7,08	7,92	8,75	9,58	10,42	11,25	12,08	12,92	14,00	15,00	16,00	17,00	18,00	T02 ave	dP (kW/m)
0,25	9	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4,4	5,5
0,75	88	228	368	377	123	70	9	9	0	0	0	0	0	0	0	0	0	5,7	2369,1
1,25	26	184	359	473	412	359	149	44	0	0	0	0	0	0	0	0	0	6,6	12013,2
1,75	0	70	315	420	412	298	307	149	53	35	0	0	0	0	0	0	0	7,3	26476,3
2,25	0	0	131	263	324	315	263	158	61	18	0	0	0	0	0	0	0	7,7	34448,5
2,75	0	0	26	158	149	166	166	140	53	9	0	0	0	0	0	0	0	8,0	30309,1
3,25	0	0	0	53	79	70	79	123	53	18	0	9	0	0	0	0	0	8,6	25381,7
3,75	0	0	0	9	9	26	53	53	61	26	0	0	0	0	0	0	0	9,4	18036,3
4,25	0	0	0	0	9	0	53	26	35	18	0	0	0	0	0	0	0	9,5	13922,8
4,75	0	0	0	0	9	0	9	26	9	9	0	0	0	0	0	0	0	9,5	7555,3
5,25	0	0	0	0	0	9	0	0	9	9	0	0	0	0	0	0	0	9,9	4121,4
5,75	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	7,9	1323,0
6,25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,0	0,0
6,75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,0	0,0
7,25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,0	0,0
7,75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,0	0,0
8,25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,0	0,0
8,75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,0	0,0
9,25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,0	0,0
	122,64	508,08	1200,12	1752	1524,24	1322,76	1086,24	727,08	332,88	140,16	0	8,76	0	0	0	0	0	8725,0	20,2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

2.3 Belmullet in the North Atlantic Ocean (Ireland)

High wave power levels are found in the Atlantic Ocean west of Ireland and off Scotland (UK). To evaluate the effect of high wave energy resources, a site is chosen off Ireland with an annual average higher than 70 kW/m. At this site the longer wave periods are dominating similar to the Pilot Zone location in Portugal, but combined with much higher waves.

In this study we have only considered the increased power available at the site and not considered the effect on cost imposed by the more severe extreme wave conditions in terms of increased design loads or more costly maintenance driven by longer waiting times.

Table 2.5 Location of Belmullet in the North Atlantic Ocean (Ireland) 54º N 12º W

Distance to grid	100 km
Distance to maintenance port:	150 km
Distance to fab port:	400 km
Water depth	80 m
Seabed for mooring:	Sand
Wave Power level	74 kW/m
Hs max	18 m
Tz max	17 sec
Tidal range	+1 m -1 m

Table 3.61 Scatter table for Off Ireland, Belmullet

Hm0 / T02	3,96	4,37	4,79	5,21	5,63	6,04	6,46	6,88	7,29	7,71	8,12	8,54	8,96	9,37	9,79	10,21	10,63	T02 ave	dP
0,5	0	0	0	0	4	0	0	12	0	12	8	0	0	4	8	0	0	7,9	55,7
1	12	8	4	12	4	20	16	28	56	16	64	53	36	8	8	0	8	7,5	1537,9
1,5	8	40	12	25	53	81	104	96	101	96	64	56	20	12	20	0	4	7,0	7179,0
2	0	4	12	32	32	84	104	137	141	145	137	73	20	25	25	4	8	7,3	16631,1
2,5	0	0	0	16	40	68	109	137	169	181	160	81	60	56	25	0	0	7,5	29887,5
3	0	0	0	4	12	68	93	104	145	181	152	117	48	40	28	16	4	7,7	40473,2
3,5	0	0	0	0	0	12	56	89	149	173	209	149	68	81	8	8	0	7,9	56274,3
4	0	0	0	0	0	0	4	28	76	93	181	145	109	53	44	8	4	8,4	57394,1
4,5	0	0	0	0	0	0	4	20	60	93	177	177	93	117	36	20	0	8,5	78935,1
5	0	0	0	0	0	0	0	0	20	48	104	132	141	48	36	28	12	8,7	71834,4
5,5	0	0	0	0	0	0	0	0	0	20	48	93	141	81	25	16	4	8,9	66457,7
6	0	0	0	0	0	0	0	0	0	0	4	48	73	81	44	20	12	9,3	54415,7
6,5	0	0	0	0	0	0	0	0	0	0	0	25	40	56	44	25	4	9,4	44428,0
7	0	0	0	0	0	0	0	0	0	0	0	12	28	32	53	32	12	9,6	46259,3
7,5	0	0	0	0	0	0	0	0	0	0	0	0	8	20	40	20	16	9,9	33355,1
8	0	0	0	0	0	0	0	0	0	0	0	0	4	12	16	12	8	9,8	19120,0
8,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	8	10,2	6714,6
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	10,0	4095,8
9,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	9,8	2234,5
	20,15641	52,58067	28,92026	89,38792	146,3507	333,8892	490,7589	651,1229	917,5469	1056,871	1309,266	1159,411	890,3617	725,6167	474,1038	213,8291	106,0393	8666,2	73,5

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

3 Power Performance of the LiftWEC

An early estimate of the potential LiftWEC power performance was previously replicated from the Atargis CycWEC studied in by (Siegel, 2019), a similar lift driven WEC with 60m hydrofoil span. To resemble the 30-meter baseline configuration of the LiftWEC, which was analysed in the assessment (Fernandez-Chozas *et al*, 2022 b), the power capture in each sea state of the scatter table presented by (Siegel, 2019) was divided by two.

Now, an early estimate of LiftWEC's potential performance has been generated within the LiftWEC project [Andrei Ermakov] as shown in Table 3.1, and will now be used for the estimation of LCoE. However, it is noted that this early estimate of LiftWEC performance is in the absence of real-time control and thus further increases to performance are expected as research continues. The average mechanical power absorbed per meter span of the device is provided in a range of combinations of significant wave height (H_s) and energy period (T_e).

Table 3.1 LiftWEC Performance in kW for a 1-meter section of the rotor with a diameter of 12 meter [Andrei Ermakov].

$H_s(m) \setminus T_e(s)$	4	5	6	7	8	9	10	11	12	13	14	15	16
5	18.3	34.39	48.15	58.24	68.49	73.24	79.6	83.43	88.4	86.29	95.22	96.65	105.0
4	9.73	19.16	26.41	31.28	36.46	38.59	41.41	43.06	45.17	44.18	49.22	53.46	62.94
3	4.38	7.46	10.31	12.5	14.78	15.79	16.92	17.5	18.44	17.81	20.52	21.79	25.63
2	1.81	2.64	3.23	3.45	3.79	3.59	3.81	4.07	4.12	4.05	4.26	4.29	4.56
1	0.33	0.51	0.6	0.65	0.69	0.68	0.7	0.69	0.76	0.73	0.77	0.83	0.93

The power capture from the incoming waves over the span for different significant wave heights are shown in the figure below. The Atargis CycWEC performance is very high and even above 100% for sea states with Hs between 1 - 2 meter. The new LiftWEC performance matrix without control shown to the right has much lower efficiencies for wave heights in the 1-2m region – and then increasing with growing wave heights. It is expected that the difference between the performance of the Atargis CycWEC and LiftWEC is primarily associated with the lack of real-time control currently applied to the LiftWEC system. Indeed, preliminary tests with the application of real-time control show further and significant increase in the LiftWEC performance.

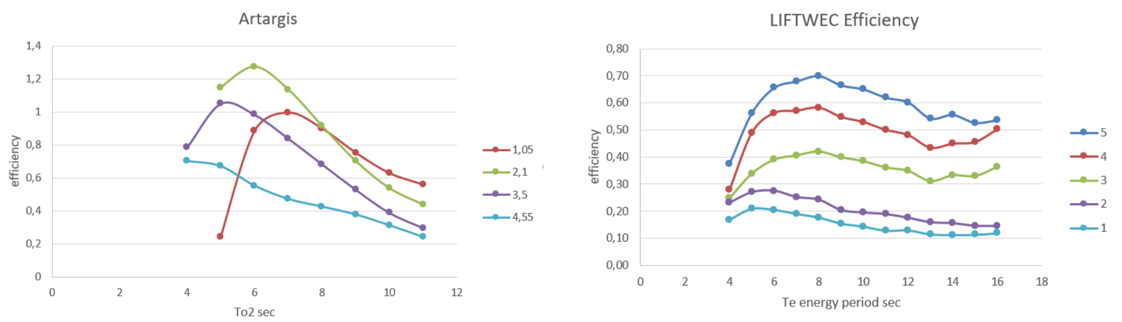


Figure 3.1 Comparison of the capture width ratio (CWR) for the previous used Atargis CycWEC Power Matrix and the newly generated results for the LiftWEC Power Matrix

Using this data, and assuming the power absorbed is proportional to the span, the resulting power matrices for the four different spans (see section 1.1) are shown in Table 4.2. To comply with the input format for the LiftWEC LCoE Tool the T_{02} wave period has been calculated from the energy period T_e as $T_{02}=T_e/1,2$.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

Table 3.2 Power Matrices for four different spans of the spar buoy LiftWEC configuration

	Power Matrix														
spand	20	Hs/T02	3,3	4,2	5,0	5,8	6,7	7,5	8,3	9,2	10,0	10,8	11,7	12,5	13,3
Rated Pov	833	1	7	10	12	13	14	14	14	14	15	15	15	17	19
		2	36	53	65	69	76	72	76	81	82	81	85	86	91
		3	88	149	206	250	296	316	338	350	369	356	410	436	513
		4	175	383	528	626	729	772	828	833	833	833	833	833	833
		5	366	688	833	833	833	833	833	833	833	833	833	833	833
	Power Matrix														
spand	30	Hs/T02	3,3	4,2	5,0	5,8	6,7	7,5	8,3	9,2	10,0	10,8	11,7	12,5	13,3
Rated Pov	1250	1	10	15	18	20	21	20	21	21	23	22	23	25	28
		2	54	79	97	104	114	108	114	122	124	122	128	129	137
		3	131	224	309	375	443	474	508	525	553	534	616	654	769
		4	262	575	792	938	1094	1158	1242	1250	1250	1250	1250	1250	1250
		5	549	1032	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250
	Power Matrix														
spand	40	Hs/T02	3,3	4,2	5,0	5,8	6,7	7,5	8,3	9,2	10,0	10,8	11,7	12,5	13,3
Rated Pov	1666	1	13	20	24	26	28	27	28	28	30	29	31	33	37
		2	72	106	129	138	152	144	152	163	165	162	170	172	182
		3	175	298	412	500	591	632	677	700	738	712	821	872	1025
		4	349	766	1056	1251	1458	1544	1656	1666	1666	1666	1666	1666	1666
		5	732	1376	1666	1666	1666	1666	1666	1666	1666	1666	1666	1666	1666
	Power Matrix														
spand	50	Hs/T02	3,3	4,2	5,0	5,8	6,7	7,5	8,3	9,2	10,0	10,8	11,7	12,5	13,3
Rated Pov	2083	1	17	26	30	33	35	34	35	35	38	37	39	42	47
		2	91	132	162	173	190	180	191	204	206	203	213	215	228
		3	219	373	516	625	739	790	846	875	922	891	1026	1090	1282
		4	437	958	1321	1564	1823	1930	2071	2083	2083	2083	2083	2083	2083
		5	915	1720	2083	2083	2083	2083	2083	2083	2083	2083	2083	2083	2083

For $H_s > 5$ m it is assumed that the rated power can be generated. The rated power of the nominal configuration is fixed at 1250kW, similar to the Atargis CycWEC being rated at 2.5 MW for the 60 m span (see D8.4). The rated power of the alternative spans are estimated using a linear extrapolation based on the device span.

3.1 Annual Energy Production for Selected Sites

Combining the power matrix for the specific span with the scatter diagram of the specific deployment site allows the annual energy production to be estimated. The annual electricity production has been calculated assuming a constant generator/PTO efficiency of 90% and availability of 95%. These values are independent of the span as indicated in the table below. The reference case was calculated with a higher PTO efficiency (95%) and lower availability (90%).

Table 3.1.1. WEC Rated Power, PTO efficiency and availability

Span of the WEC [m]	20	Ref. 30m	30	40	50
Rated Power [kW]	835	1250	1250	1666	2100
PTO & Generator efficiency	90%	95%	90%	90%	90%
WEC Availability	95%	90%	95%	95%	95%

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

Table 4.1.2. Performance of a single LiftWEC at Test Site, Off Quimper, France

Pwave = 36 kW/m					
Span of the WEC [m]	**20**	**Ref. 30m**	**30**	**40**	**50**
Rated Power (P_r) [kW]	835	1250	1250	1666	2100
Annual Energy Production (AEP) MWh/y	**1660**	**3320**	**2490**	**3321**	**4151**
Capacity factor	23%	30%	23%	23%	23%
Average annual Capture width ratio	29.%	37%	29.3%	29.3%	29.3%

Table 4.1.3. Performance of a single LiftWEC at Test Location 2: Off Portugal, Pilot Zone

Pwave = 20 kW/m				
Span of the WEC [m]	20	30	40	50
Rated Power (P_r) [kW]	835	1250	1666	2100
Annual Energy Production (AEP) MWh/y	**940**	**1410**	**1880**	**2352**
Capacity factor	13%	13%	13%	13%
Average annual Capture width ratio	29.6%	29.6%	29.6%	29.6%

Table 4.1.4 Performance of a single LiftWEC at Test Location 3: Off Ireland, Belmullet

Pwave = 74 kW/m				
Span of the WEC [m]	20	30	40	50
Rated Power (P_r) [kW]	835	1250	1666	2100
Annual Energy Production (AEP) MWh/y	**3350**	**5020**	**6691**	**8365**
Capacity factor	46%	46%	46%	46%
Average annual Capture width ratio	28.9	28.8%	28.8%	28.8%

For the three different locations the annual energy production has been calculated and is shown in table 4.1.5 below. The new power performance gives a more conservative estimate of the annual energy production compared to those previously estimated in Deliverable 8.4.

Table 4.1.5. Energy production summary for a single LiftWEC of different spans and sites

Annual energy production - AEP [MWh/y]	20m	ref	30m	40m	50m
Rated Power (P_r) [kW]	833	1.250	1.250	1.666	2.083
20 kW/m offshore Portugal, Pilot Zone	**940**		**1410**	**1880**	**2352**
36 kW/m LiftWEC offshore Quimper, France	**1660**	**3320**	**2490**	**3321**	**4151**
74 kW/m offshore Ireland, Belmullet	**3350**		**5020**	**6691**	**8365**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

The annual energy production calculated using the LiftWEC performance on the 40 meter span compares well to the reference performance of 30 meter span previously calculated using the Atargis CycWEC power matrix. However, it is once again noted at the Atargis performance figures included the application of real-time control whereas those for LiftWEC do not.

As a result of our assumption, the annual energy production is proportional to the span as shown in previous tables 4.1.2 to 4.1.4 and the capacity factor CF is therefore independent of span. The Capacity Factor CF, which represents the ratio between average absorbed power and Rated Power, increases linearly with the site resource as shown in figure 4.1 from 13% at sites with 20 kW/m, to 45% at Belmullet with 74kW/m.

The average annual Capture Width Ratio (CWR) is close to 26% independent of the site resource. These results assume operation at rated power in all sea states above Hs>5m.

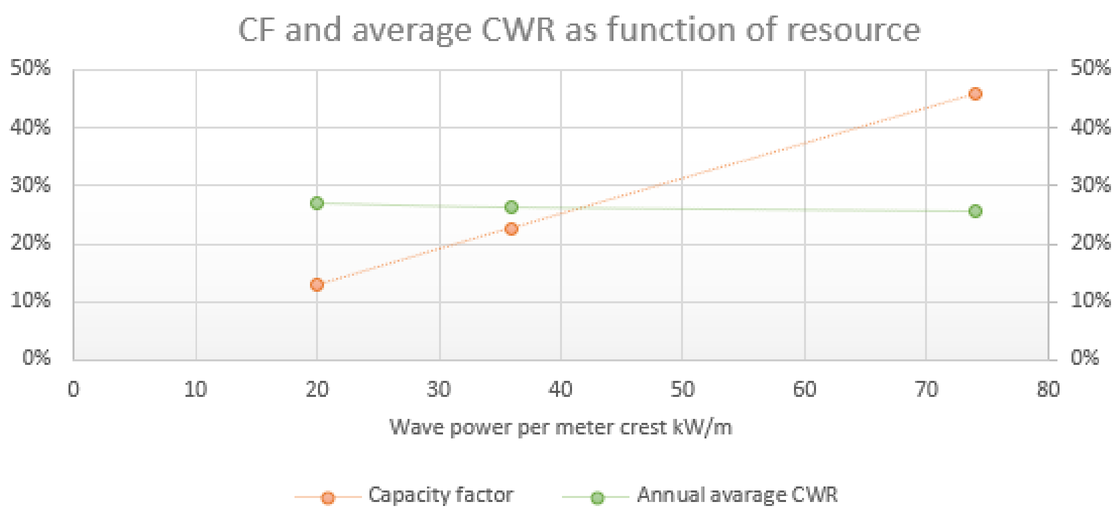


Figure 4.1 The Capacity factor increases linearly with the wave resource and the annual average capture width (CW) is constant.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

3.2 CAPEX

3.2.1 Development and Project management costs

Development and consenting costs are considered a fixed cost of 0.5 MEUR independent of the span, this is about 10% of CAPEX of the 20-meter span and 7% for the 50-meter span.

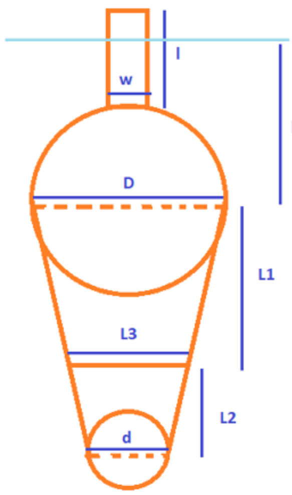
3.2.2 Main dimensions

The two hydrofoils on the rotor have a NACA 0012 profile (curved along hydrofoil path), with a 6m chord length independent of the span. The volume of material used for the 3 meter foils is about 9 m^3. This corresponds to the surface of the upper and lower side of the 30 meters long and 6 meters wide hydrofoils with an assumed thickness of 2.5 cm. Built of composite, and assuming an average density of fiberglass of 2000 kg/m^3, total mass of the two hydrofoils is 36 tonnes. In this study we assume this can be produced at a unit cost of 9.500 €/ton

The dimensions of the support structure are shown in table 3.1 below.

Table 2.1 Dimensions of the Lift-WEC spar buoy support structure

Dimensions	Parameter		
immersion	h	15	m
diameter nacelle	D	18	m
length of legs	l	9	m
base thickness nacelle	w	3	m
length trapeze nacelle	L1	10	m
length trapeze ballast	L2	5	m
length connection	L3	11,6	m
extra thickness nacelle	t2	0	m
side trapeze nacelle	S1	11,87	m
side trapeze ballast	S2	7,51	m
ballast pipe diameter	d	6	m
rotor span	s	30	m
rotor axis diameter	rd	3	m
trapeze ballast volume	V_tb	131,6	m3
Portion concrete trapeze	p_tb	0%	
relative immersion correction	v	3	m
water density	rho	1025	kg/m3
plate thickness	th	0,025	m
steel density	rho_s	7800	kg/m3
ballast concrete density	rho_c	3500	kg/m3



The volumes of the structural mass of steel have been calculated using a plate thickness of 25mm. Results for the four spans are shown in table below, ranging from 657 ton to 856 ton including the centrally rotating shaft, the PTO and two lateral supports at both ends. This is about six times more

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

compared to the reference structure of the nacelle with a mass of 120 tonnes of steel (Arredondo-Galeana *et al.*, 2021). This increase of mass is principally the results of the larger 18m diameter nacelle base case, and the need to equalise the hydrostatics of the device for different depth using water ballast (9 to 15m submergence dependent on sea state).

Table 3.2 Material weight and cost of the WEC

Span in meter:	20	30 ref	30 new	40	50
Steel (ton)	657	120	790	852	856
Ballast concrete (ton)	2058		2367	2731	2770
Glass fiber (ton)	20*	36	30	40	50
Total weight (ton)	3076	235	3193	3584	3697
Structural cost steel [k€]	2.234	*690*	2.686	2.897	2.910
Structural cost Hydrofoils [k€]	190	*340*	285	380	475
Structural cost ballast [k€]	144		166	191	194

3.2.3 Generator Cost Estimates

The direct drive PTO including the generator is expected to cost 700€/kW, thus being proportional with the rated power (which is also proportional to the span). It is assumed that this includes the cost of phase control.

Table 3.3 Generator rating as a function of span

Span in meter:	20	30 ref	30	40	50
Rated power [kW]:	833	1.250	1.250	1.666	2.083
Generator [k€]	500	*750*	750	1.000	1.250

3.2.4 Control Cost Estimates

The control estimate is 110 k€ and is assumed independent of the span. The spar LiftWEC has two controls, pitch and phase control:

- Pitch control of the hydrofoils is enabled by two actuators per hydrofoil, one at each end.
- Phase control is implemented by direct drive generators, one in each stator.

Submergence is enabled by ballasting, at an approximate cost of 35.000 EUR. There is no yaw control as such, but the system can weather-vane thanks to the moorings.

Total control costs are estimated at 75.000 EUR for the pitch control and 35.000 EUR for the ballasting, **in total 110.000 EUR**.

Table 3.4 Estimated cost for the control system

Span in meter:	20	30 ref	30	40	50
SCADA [k€]					
Pitch control [k€]	75	75	75	75	75
Submergence control [k€]	35	35	35	35	35
Radius control [k€]					
Control cost total [k€]	**110**	**110**	**110**	**110**	**110**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

3.2.5 Electrical connector,

The flexible electrical connection between the WEC and the sea bed, the umbilical connection, is estimated for the 30-meter span as 60k€. It is expected to vary linearly with the span proportional to the rated power of the WEC.

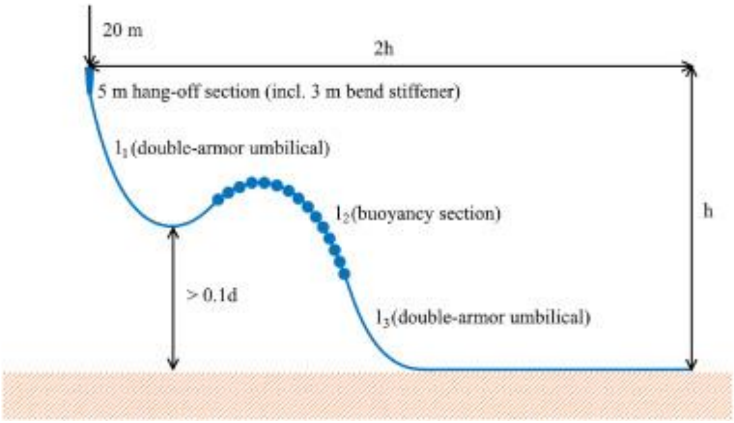


Figure 3.5. Illustration of a generic flexible electrical cable from the WEC to the seabed.

Span in meter:	20	30 ref	30new	40	50
Rated power [kW]	833	1.250	1.250	1.666	2.083
Umbilical/Dynamic Cable [k€]	40	60	60	80	100
Electrical from WEC to Grid					

3.2.6 The Moorings

The same mooring system used for the Pelamis P2 deployed at EMEC at 50-meter water depth is assumed, amounting to 300.000 EUR (WES, 2016). The mooring cost is expected to vary linearly with the span. The assumptions for each span are shown in the Table below.

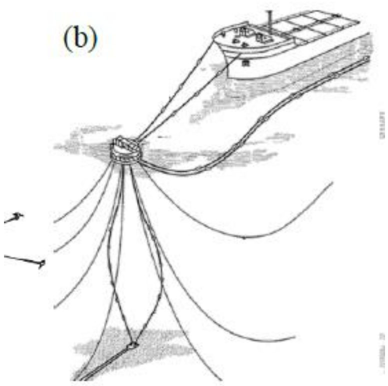


Figure 1 illustration of a Calm mooring system

Span in meter:	20	30 ref	30new	40	50
Rated power [kW]	833	1.250	1.500	1.666	2.083
Mooring [k€]	200	300	300	400	500

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

3.2.7 Installation Cost Estimates

Many types of installation vessels exist, which vary greatly on capabilities and daily rates. Generally, as components get larger, vessels become more expensive. Vessels maximum operational limits (wave height, current) are also a key factor.

A **towing-to-site cost for the prime mover of 25.000 EUR** is assumed for the reference dimensions L=30 m and assumed proportional to the drag area of the WEC. As a generic estimate, a 3-day weather standby is assumed in the installation. This waiting time considers that daily rates of vessels at port or offshore in operation are the same.

Table 3 Cost of installation

Span in meter:	20	30 ref	30	40	50
Preassembly and transport [k€]					
Installation: moorings, spar, [k€]					
Total installation	220	275	330	440	550

3.3 OPEX COST AND MAINTENANCE STRATEGY

A set of marine activities are involved during maintenance. These are:

- Small repairs
- Visual inspections
- Subsea inspections (with divers or ROVs)
- Large component replacement

Due to the limited data available on OPEX, it is estimated as indicative 2% of CAPEX (before contingencies and divided as shown below).

Table 4 Annual OPEX is fixed at 2% of CAPEX

Span in meter:	20	30 ref	30	40	50
Total CAPEX [kEUR]	4.690	*3.600*	5.788	6.680	7.386
Minor repair & inspections [k€]					
Major maintenance tow back[k€]					
Fixed annual costs [k€]					
Annual OPEX [kEUR]	95.2	*125*	120	132	153

3.4 UNCERTAINTIES

There are uncertainties associated both to the input as well as the output values of this LCoE analysis. The economic assessment is subject to several assumptions that will be verified as the development process evolves. It is estimated that at the current stage of development of LiftWEC, results have an uncertainty that varies between [-25% to 30%]. Compared to the previous economic estimates presented at Deliverable 8.4 (Fernandez-Chozas et al, 2022b), we believe we have increased the certainty in the economic assessment as this Deliverable includes the results of the modelling of the power performance computed by work package 5; as well as the results of the preliminary structural design [INNOSEA (2022)].

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

4 CAPEX & OPEX SUMMARY TABLE OF COMPARISON

In the table 4.1 below the cost centres of the Spar buoy LiftWEC are summarised with spans from 20m to 50m, including ref. 30m span from previous report Del. 8.4 for comparison.

Table 4.1. Optimisation of WEC Structure and Prime mover.

	Spar Buoy				
Main dimension (width of the WEC) [m]	20	Ref. 30m	30	40	50
Secondary dimension (Rotor diameter) [m]	12	12	12	12	12
Water depth [m]	50	50	50	50	50
Prime mover: Rotor in steel [ton]		120			
Prime mover: Hydrofoils (glassfiber) [ton]	20	36	30	40	50
Support structure weight (in steel) [ton]	657	85	750	852	856
Ballast concrete [ton]	2058		2367	2731	2770
Foundation / mooring [ton]	NA	140	NA	NA	NA

CAPEX [kEUR]					
Development costs	500	*500*	500	500	500
Structural cost: nacelle and rotor	2.234	*690*	2.686	2.897	2.910
Hydrofoils	190	*340*	285	380	475
Ballast concrete	144		166	191	194
Single point connection	200	*330*	300	400	500
PTO and housing	500	*750*	750	1.000	1.250
Umbilical	40	*60*	60	80	100
Control cost	110	*110*	110	110	110
Installation and Commissioning	220	*275*	330	440	550
Decommissioning		*212*			
Decommissioning discounted to PV	50		75	100	125
Contingencies (10% of CAPEX)	420	*325*	526	600	670
Total CAPEX [kEUR]	**4.608**	***3.600***	**5.788**	**6.698**	**7.386**
Annual OPEX [kEUR/y]	95	*125*	120	133	153
Rated Power (P_r) [kW]	**835**	**1250**	**1.250**	**1.666**	**2.100**
CAPEX per MW [MEUR/MW]	5,5	*2,9*	4,6	4,0	3,5

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

5 LCoE of the four spans at different locations

The annual electricity production presented in section 3 and cost data from section 4 combines to the LCOE estimates for the three selected sited presented in the tables 5.1 to 5.3 below.

Table 5.1 LCoE results from LiftWEC Test Site, Off Quimper, France

Pwave = 36 kW/m					
Span of the WEC [m]	**20**	**Ref. 30m**	**30**	**40**	**50**
Rated Power (P_r) [kW]	835	1250	1.250	1.666	2.100
LCoE (25 years, r=5%) [EUR/MWh]	**254**	**115**	**213**	**183**	**163**

Table 5.2 Performance at Test Location 2: Off Portugal, Pilot Zone

Pwave = 20 kW/m				
Span of the WEC [m]	20	30	40	50
Rated Power (P_r) [kW]	835	1.250	1.666	2.100
LCoE (25 years, r=5%) [EUR/MWh]	**449**	**376**	**323**	**288**

Table 5.3 Performance at Test Location 3: Off Ireland, Belmullet

Pwave = 74 kW/m				
Span of the WEC [m]	20	30	40	50
Rated Power (P_r) [kW]	835	1.250	1.666	2.100
LCoE (25 years, r=5%) [EUR/MWh]	**126**	**106**	**91**	**81**

The uncertainty for the LCoE assessment is estimated to be in the range - 25% to 30%.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

6 Discussion and Conclusions

This optimisation study has considered the effect on cost and performance if the span of the LiftWEC rotor is increased from 20 to 50 meters with intervals of 10 meter. Some generic assumptions have been made to compare the different spans which are described in this deliverable. Based on these assumptions the study shows (Figure 6.1) that the CAPEX and the annual energy production AEP both increase approximately linearly with increased span – and the LCoE reduces as the span increases. There is a large initial cost associated with building the nacelle and support structure for the generator housing and attachment of the rotors.

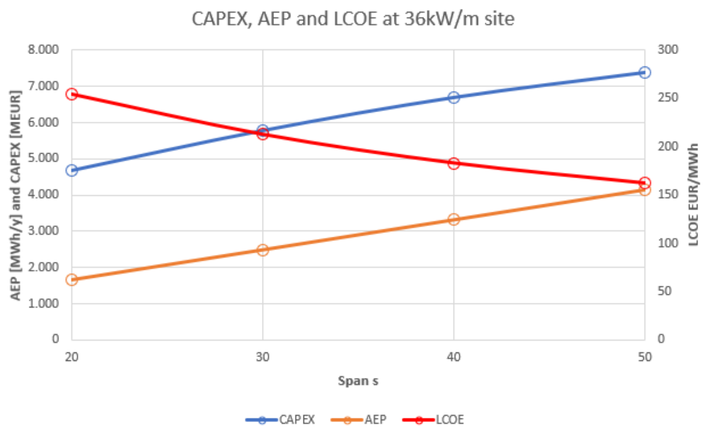


Figure 6.1 LCoE variation for four different span s with resource of 36 kW/m

The effect of deploying the rotor at different deployment sites with wave power levels ranging from 20 kW/m, 36kW/m and 74 kW/m has also been analysed as shown on Figure 6.2

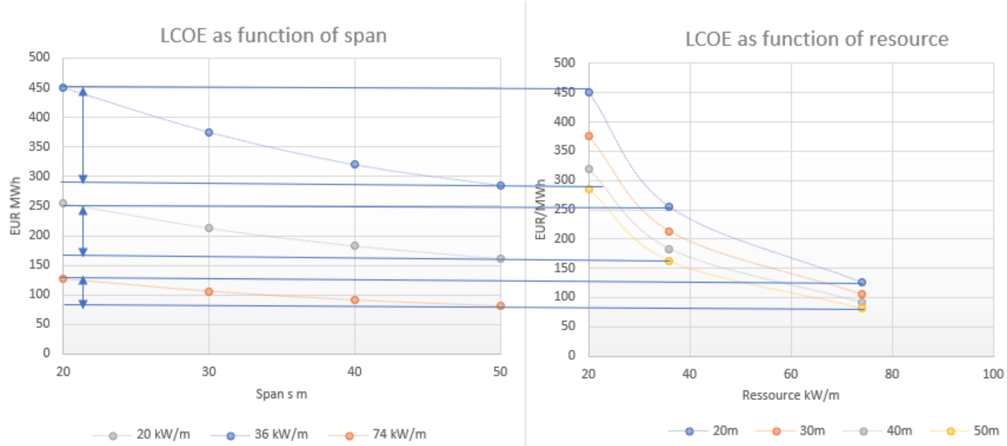


Figure 6.2 LCoE variation with Span s for three different sites with resource from 20 kW/m to 74kW/m

Figure 6.2 on the left shows how the LCoE decreases with increased span from 20 – 50 meter and to the right how the cost reduces as a function of the resource from 20 kW/m to 74kW/m.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

At the site in France with 36kW/m the LCoE decreases from about 250 €/MWh at span 20 meter to about 155€/MWh at span 50 meter.

In Portugal with 20 kW/m the LCoE reduces from 450 €/MWh for a span of 20 meter to about 300€/MWh for a 50-meter span (almost twice as high as at the 36kW/m LiftWEC site in France).

At the Belmullet site with 74 kW/m the LCoE is as low as 125 €/MWh for a span of 20 meter reducing to about 80€/MWh for a span of 50 meter (almost half as expensive as at the 36kW/m LiftWEC site in France).

6.1 Summary of assumptions

The assumptions behind the study are summarised in the table 6.1 below.

Table 6.1: Summary of assumptions

Item	Scaling up strategy with respect to span
Power	linear
Power rated	linear
Foils	Composite volume for foils is linearly adjusted with span.
Structure material mass	Nacelles are identical for all span, as well as diameter of ballast and rotor axis. Ratio of concrete ballast is adjusted for hydrostatic stability.
Devex and PM cost	Constant with span
Generator cost	Proportional to power rated, therefore linear to span
Controller cost	Constant with Span
Electrical connector	Linear
Moorings	Linear
Installation cost	Fixed 3 days contingency for all span at rated tug cost + cost of towing increasing linearly with span.
OPEX	Proportional to overall CAPEX, with rate constant as a function of span.

With these assumptions the power produced increases more than the cost by increasing rotor span, which results in lower LCoE.

However, there is no doubt than an optimal span in terms of LCoE for the given concept and chosen site of deployment exists. It means that costs will have to increase faster than production as a function of span past a certain value. Some of the simplified assumptions in Table 6.1 can be evolved further to allow the identification of an optima:

- Power: the power produced by the rotor will increase less than linearly; as the span gets larger, the rotor will exceed the length of the crest of short-crested seas, and this suggests

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

that a reduction in the overall efficiency of the rotor could be considered for larger spans and deviate from the point absorber theory (Lamont-Kane & Folley, 2021).

- Foil costs: as it stands, the section of the foils and associated quantity of materials is considered constant for all the span considered, whereas the structural requirement on the foils should be expected to raise with the span. This would result in a more than linear increase in foil costs, and even an upper limit of feasibility could therefore be considered.
- Nacelle costs: at this stage, the nacelle is nearly identical for all the cases considered. The shorter span devices, with lower rated power, could be optimised further toward smaller nacelles reducing their costs, providing slighter less expensive nacelle for short span devices and more costly larger span devices.
- In the context of large farms, small span devices would have to be installed in higher number. This tends to favour larger devices in general, as less installation and maintenance operations would be required. However, the higher number of devices also implies larger redundancies, and therefore one could potentially expect a better overall availability for a farm of smaller devices. Threshold effect regarding the type of support vessel necessary to manage even longer span could also be identified and might have an important impact on the identification of the optimal span of the device.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

6.2 Further optimisation

Based on the results above it was decided to investigate the effect on LCoE of reducing the nacelle diameter from 18 m to 13 m and the nacelle thickness from 3 m to 2.5 m, which should still give enough space for generators and equipment. Doing so, buoyancy is reduced, and the diameter of the ballast cylinder also reduces from 6 m to 4 m.

Result are shown in Table 6.2, the LCoE reduces from 213 €/MWh to 178 €/MWh for the 30-meter span and provides a 15% to 20% reduction in the LCoE calculations: 190€/MWh for the 20.meter span, and 139€/MWh for the 50-meter span at the 36 kW/m LiftWEC Test Site in France.

Table 6.2 LCoE for four Spans of the LiftWEC Spar Buoy at the 36 kW/m LiftWEC Test Site in France.

Span [m]	20	30	40	50
Initial CAPEX [MEUR/MW]	**4.690**	**5.980**	**6.680**	**7.340**
LCoE (25 years, r=5%) [EUR/MWh]	**255**	**213**	**183**	**162**
Further optimisation CAPEX [MEUR/MW]	**3.260**	**4.550**	**5.250**	**5.910**
LCoE (25 years, r=5%) [EUR/MWh]	**190**	**178**	**150**	**139**
	25%	16%	18%	14%

The performance matrix used in this study was provided by [Andrei Ermakov] also needs further work. Work Package 5 is investigating if implementation of control strategies can increase the energy absorption. Further optimized control strategy is expected to increase the Annual Energy Absorption AEP and thereby reduce the LCoE.

6.3 Deployment in a 100 MW Array

When developing a 100 MW wave farm there will normally be a benefit of scale to be considered. This includes rational fabrication, installation, and maintenance which have not yet been included. Figure 6.3 shows a sketch of how the array layout will be defined and what it will look like.

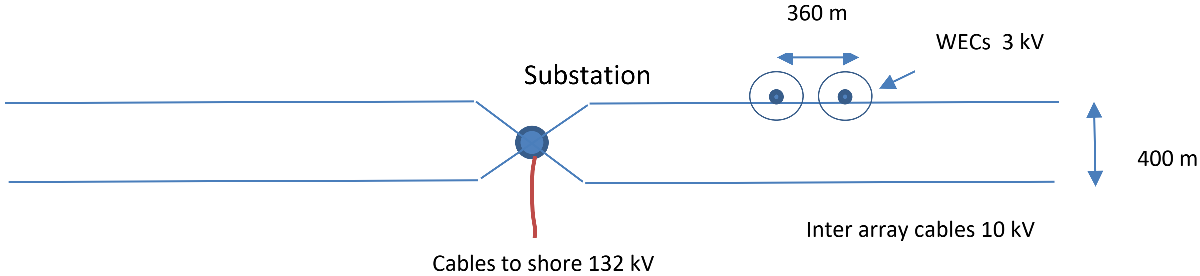


Figure 6.3 System definition of the array

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

The specification for an array of LiftWEC spars of span 30 m is shown below:

- Number of WEC's = 100MW/Rated Power pr Device
- Distance from shore to substation 10 km
- Distance from substation to maintenance port 20 km
- Distance deployment site to Fabrication / Assembly 50 km
- Distance between WEC's in a row 360 meter spacing
- Distance between rows of WEC's 400 meter
- Cabling installation and cable costs proportional to distance between WECs

The LiftWEC LCoE tool can calculate the cost of building a Wave Farm at a specified location and for a specified device rated power. The costs of the array are based on the costs calculated for a single device. WEC Rated farm capacity is proportional to the number of WECs.

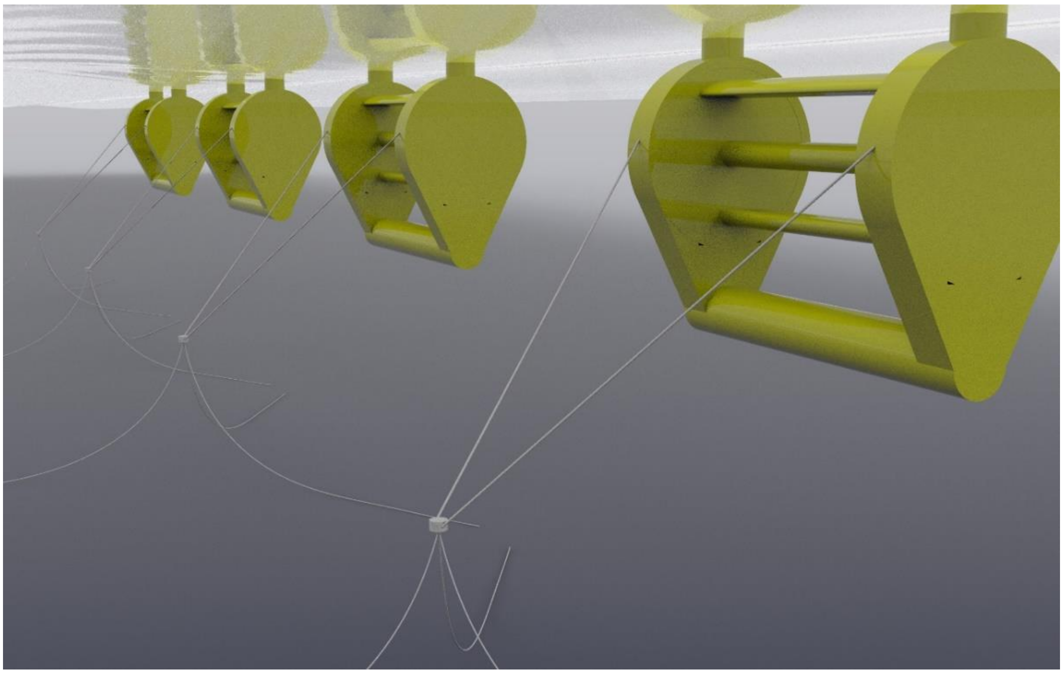


Figure 2 Figure 6.4 Artist illustration of an array of LiftWECs ("Olbert, G., TU Hamburg").

To finalise the conclusions, it is noted that the Joint Research Centre (JRC, 2019) estimated that wave energy technologies are expected to reach an LCoE of 150 EUR/MWh in 2030. Aligned to this target, the LiftWEC project set up an end-of-project LCoE target of 120 EUR/MWh. The analysis and results in this deliverable indicate that the LiftWEC is aligned to both 2030 JRC targets and the project targets if the Performance of the hydrofoil via optimised control can be further improved.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

7 REFERENCES

Arredondo-Galeana *et al* (2021)	A. Arredondo-Galeana, N. Clave, R. Pascal, W. Shi, F. Brennan, and P. Lamont-Kane, "Deliverable D6.2 – Transportation and Maintenance LiftWEC ULS Assessment," LiftWEC – Development of a new class of wave energy converter based on hydrodynamic lift forces, Tech. Rep., 2021.
Fernandez-Chozas *et al.* (2022a)	Fernandez-Chozas J, Nielsen K., Pascal R. "Deliverable 8.3 – The LiftWEC LCoE Calculation Tool". The LiftWEC Project. Development of a new class of wave energy converter based on hydrodynamic lift forces (2022a).
Fernandez-Chozas *et al.* (2022b)	Fernandez-Chozas, K. Nielsen and R. Pascal. "Deliverable 8.4 - LCoE Estimates of Baseline Configurations". The LiftWEC Project. Development of a new class of wave energy converter based on hydrodynamic lift forces (2022b).
Folley and Lamont-Kane (2022)	M. Folley and P. Lamont-Kane (2022), "Deliverable 2.8 - Specification of Baseline Configurations". The LiftWEC Project. Development of a new class of wave energy converter based on hydrodynamic lift forces. Available at: https://liftwec.com/d2-8-specification-of-baseline-configurations/
Lamont-Kane and Folley (2021)	P. Lamont-Kane and M.Folley (2021), "LW-WP02-PLK-N23-1x0 Harmonic Capture Width Ratio of any number of 3D hydrofoils". LiftWEC Technical Note. Released to Consortium Only.
WES (2016)	WES (2016) "Moorings and Connection Systems Cost Metrics". Prepared by Quoceant Ltd. to Wave Energy Scotland.
Siegel (2012)	Siegel S., 2012. "Final Scientific Report. Cycloidal Wave Energy Converter" Atargis Energy Corporation. DE-EE0003635. *Note: The values from this report, noted in USD and issued by the end of 2012, have been exchanged to EUR at an exchange rate of 1 USD = 0.77 EUR.*
Siegel (2019)	Siegel S., 2019. "Numerical benchmarking study of a Cycloidal Wave Energy Converter". Renewable Energy 134 (2019). 309-405.
Têtu and Fernandez - Chozas (2020)	A. Têtu and J. Fernandez-Chozas, "Deliverable D8.1 - Cost Database," The LiftWEC Project. Development of a new class of wave energy converter based on hydrodynamic lift forces, Tech. Rep., 2020. Available at: https://liftwec.com/wp-content/uploads/2020/06/LW-D08-01-1x3-Cost-database.pdf; [Accessed 19th January, 2022].
Têtu and Fernandez-Chozas (2021)	A. Têtu and J. Fernandez-Chozas, "Deliverable D8.2 - "Parametric Cost Model" The LiftWEC Project. Development of a new class of wave energy converter based on hydrodynamic lift forces, Tech. Rep., 2021. Available at: https://liftwec.com/d8-2-parametric-cost-model/ [Accessed 19th January, 2022].

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

Andrei Ermakov, (to be published)	Andrei Ermakov, John V. Ringwood, Florent Thiebaut and Gregory Payne "Validation of a control-oriented point vortex model for a cyclorotor-based wave energy device." Submitted to Computational Mechanics
INNOSEA (2022)	LW-WP02-INN-DT03-1x5 Analytical parametrisation of Spar configuration.xlsx, LiftWEC technical note. Released to consortium only.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.