LiftWEC

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

Deliverable 8.6
LCoE of the Final Configuration

Deliverable Lead Kim Nielsen, Aalborg University & Julia F. Chozas, Consulting Engineer
Delivery Date 29th March 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)	T8.4 & T8.5
Deliverable Number	D 8.6
Deliverable Name	LCoE of the final configuration
Due Date	31st March 2023
Date Delivered	28-03-2023
Primary Author(s)	Kim Nielsen (AAU) & Julia Fernandez Chozas (JCC)*
Co-Author(s)	Rémy Pascal (InnoSea) Francesco Ferri (AAU)
Document Number	LW-D08-06

Version Control

Revision	Date	Description	Prepared By	Checked By
1.0	9.03.2023	Internal drafts for review	KIN	JFC, PL
2.0	24.03.2023	Draft final for review	Kin	JFC, PL, RP
3.2	28.03.2023	Final	KIN	JFC, PL, 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

Deliverable D8.6 presents the final LCoE estimate of the Spar Buoy LiftWEC configuration with a span of 30 meter, a rated power of 1.25 MW, installed in deep water (>80 m), at the Atlantic coast west of France with wave power average 36kW/m.

Assuming a 25 year lifetime; and a discount rate of 5% we have estimated:

A first, full-scale single LiftWEC (no grid connection):

- Total CAPEX: 6.3 MEUR
- annual OPEX 110.000EUR/y
- LCOE (5%, 25years) = 153 EUR/MWh

A first, 100 MW wave farm of 80 LiftWECs (grid connection has been included):

- Total CAPEX: 453 MEUR
- annual OPEX 8,74 MEUR/y
- LCOE (5%, 25years) = 143 EUR/MWh

This deliverable also describes a series of sensitivity studies carried out investigating the significance of varying the key assumptions in an interval of ±10% . Based on the many possible combinations of cost and energy production input, the resulting LCoE vary between -20% combining the min energy production with the max costs and +20% combining the max energy production with the minimum costs.

The LiftWEC LCOE Calculation Tool now includes a Monte Carlo simulation subroutine, to investigate the significance of key assumptions and produce an estimate of the confidence in the obtained LCoE figures. The sensitivity study has been led by AAU, with contributions from JFC, INN, WavEC, UCC and Maynooth University.

This deliverable shows that the target LCoE set for the project, which has been calculated based on the numerically modelled performance and preliminary structural design should be able to produce energy at a cost comparable to state-of-the-art wave energy technologies as well as other competing marine renewable technologies such as offshore wind.

In addition, further cost reductions can be obtained by optimization as described in D8.5 by increasing the span and work ongoing in WP3 indicate that the weight of steel can be reduced further by 30 %. This would directly reduce CAPEX by 25%, having a direct impact on the LCOE.

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 LCoE of the final configuration of the Spar buoy LiftWEC is presented and the uncertainty related to the underlaying assumptions are described and evaluated in this deliverable D8.6.

The final Spar buoy LiftWEC configuration consists of two-hydrofoils with a span 30 m attached at both ends to a rotor driving a direct drive generator included in nacelles at both sides of the spar buoy support structure (indicated on Figure 1). The circular path of the foils has a diameter of 12 meter and the diameter of the nacelle is 18 meters.

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.

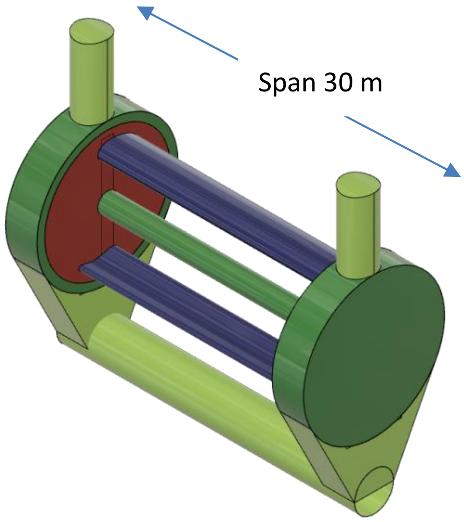


Figure1.1 Spar buoy LiftWEC

1.1 Methodology and Assumptions

The LiftWEC LCoE Calculation Tool has been used to evaluate the LCOE of the Final LiftWEC Configuration. The cost is evaluated in terms of capital expenditure (CAPEX), operating cost (OPEX), and the annual energy production throughout its lifetime (AEP), leading to the Levelized Cost of Electricity (LCOE) in EUR per MWh.

1.1.1 Assumptions

The LCOE is calculated for a single WEC , installed at Western European Ocean conditions with a rated power of 1.25 MW, 25 year lifetime and a discount rate of 5%. There are no grid connection costs included as a single WEC as it is expected to be demonstrated at a site with grid connection. The LCOE calculations for the 100 MW array consisting of 80 LiftWECs (Section 7) includes the cost of grid connection and assumptions derive from the farm modelling in WP7 are indicated. These are the assumptions behind Sections 2, 3, 4, 5 and 6.

The underlaying cost assumptions 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). In this deliverable we will assess what uncertainty exists using default costs, gathered in 2020. Material prices fluctuate as well as the price of energy and labour costs, thus, the future long-term trends are difficult to predict so even if the calculation is accurate based on the assumptions – the resulting cost can be affected by changes to the assumptions over time. Therefore, we present the variation in LCOE based on an uncertainty of a prescribed variation of 10% on the associated input unit cost data as a reasonable estimate for the medium future.

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 Annual Energy Production

The average annually generated energy is affected by

1. The resource at the site and its variations
2. The power matrix specified for the WEC
3. The PTO efficiency
4. The WEC availability

Each of these input components are discussed in this section.

2.1 Wave Resource of Specific Locations

In general, the cost of energy is affected by the resource of the location in such a way that the cost of energy decreases with increasing wave resources - expressed in kW/m of average incoming wave power. The trend of the LCoE was investigated in D8.5 (Nielsen et al, 2023) for three different sites and for different spans as shown on figure below.

1. Pilot Zone in Portugal, with an annual average wave power of about 20 kW/m.
2. The LiftWEC test site representative of Western Europe conditions, off France where the wave resource is estimated at 36 kW/m.
3. Atlantic Ocean west of Ireland and off Scotland (UK), higher than 74 kW/m.

and the trends are illustrated on the graph below.

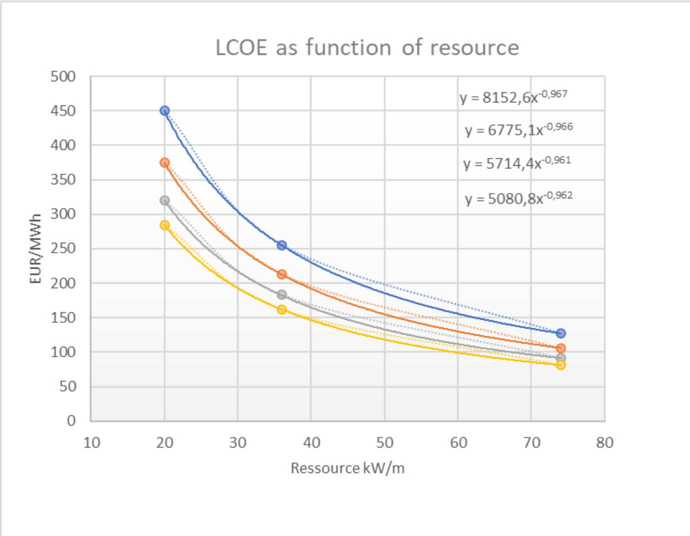


Figure 2.1 LCOE was investigated in D8.5 for three different sites

The LCoE as a function of the resource "*Pw*" can be expressed as:

$$LCOE\ (Pw) = C * Pw^{-\alpha} \quad (1)$$

Where C is a constant depending on the WEC input data and the exponent α=0.96.

The absolute LCoE is therefore very site specific and the uncertainty of the LCoE is also related to the uncertainty of the Resource with a similar trend.

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.

2.1.1 Selection of central sea states

For the final configuration we have simplified the calculation of the power matrix to the calculation of six sea states. The selected sea states are found from the scatter diagram off the Quimper LiftWEC test site in France, presented below.

Hs/Te	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5	sum	Te ave	dP	
0,25	0	1	3	4	2	1	0	0	0	0	0	0	0	0	13	6,5	0,00	
0,75	7	47	129	213	204	97	40	8	3	1	0	0	0	0	749	6,9	0,16	
1,25	0	41	239	396	451	367	196	79	29	7	3	1	0	0	1810	7,6	1,18	
1,75	0	5	114	309	381	384	306	175	78	29	13	1	0	0	1796	8,3	2,52	
2,25	0	0	16	183	294	270	232	177	90	33	12	3	1	0	1313	8,8	3,20	
2,75	0	0	1	53	194	199	181	137	91	31	11	3	0	0	900	9,2	3,44	
3,25	0	0	0	7	101	153	128	111	63	36	11	5	0	0	617	9,6	3,42	
3,75	0	0	0	0	33	119	120	89	55	30	12	2	1	1	463	9,9	3,53	
4,25	0	0	0	0	5	73	105	87	41	20	14	4	0	0	351	10,1	3,53	
4,75	0	0	0	0	0	30	82	77	46	14	8	3	1	0	263	10,4	3,39	
5,25	0	0	0	0	0	7	50	55	35	13	7	2	1	0	172	10,7	2,79	
5,75	0	0	0	0	0	0	23	45	29	12	5	2	1	0	117	11	2,33	
6,25	0	0	0	0	0	0	6	31	24	9	3	1	0	0	76	11	1,83	
6,75	0	0	0	0	0	0	1	15	18	7	3	1	1	0	45	12	1,29	
7,25	0	0	0	0	0	0	0	5	15	6	3	1	0	0	32	12	1,10	
7,75	0	0	0	0	0	0	0	1	8	7	3	1	0	0	20	12	0,83	
8,25	0	0	0	0	0	0	0	0	3	4	2	2	0	0	11	13	0,55	
8,75	0	0	0	0	0	0	0	1	1	2	1	2	0	0	6	13	0,34	
9,25	0	0	0	0	0	0	0	0	0	1	1	0	0	0	3	13	0,21	
9,75	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	14	0,09	
															8759	Pave:	**36**	kW/m

Figure 2.2 Scatter diagram for the Quimper LiftWEC test Site showing hours/year for each bin with interval Hs of 0,5 meter and Te of 1 second.

For each interval of Hs the average energy period T_{e_ave} for each row is calculated by weighing the value of Te with the number of hours and averaging with the total sum of hours. The value of $T_{e\ ave}$ is shown in the second last column

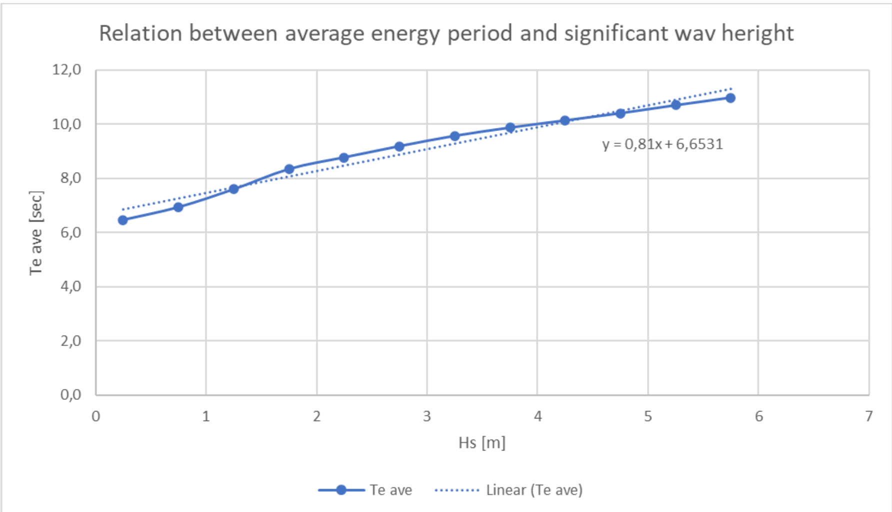


Figure 2.3 Average Wave energy period T_{e_ave} as a function of H_s

In the range Hs 0,5 meter to 5,75 meter a linear relation between Hs and $T_{e\ ave}$ is shown on the figure above, which can be described by:

$$T_{e\_ave} = 6.65\,\text{sec} + 0.81\frac{sec}{m} * H_s \tag{2}$$

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.

The site resource data can be presented as a set of central sea-states as shown in the table below. The first column is the centre value of the significant wave height Hs, the second column is the related average energy period $T_{e\ ave}$ using (2), the third column is the average zero crossing period ($T_{02} = T_e/1{,}2$). The wave power per unit wave crest is the fourth column ($0{,}48*H_s\text{^}2*_{Te\ ave}$). The fifth column indicate the hours per year this sea state would occur (from sum of the row in the scatter diagram). The last column shows the contribution to the average power summing up to 36kW/m for the site.

The central sea states show that sea states with Hs in the interval 2 – 5 meters all contribute relatively equally to the annual average power (last column).

Table 2.1 Average wave energy periods for central bin intervals of Sea-states Hs for the LiftWEC site in France

Hs [m]	Te ave [s]	To2 [s]	Pw [kW/m]	[hours/year]	dPw [kW/m]
< 0,75				387	
1,25	7,7	6,39	5,76	3082	2,0
2,25	8,5	7,06	20,63	2661	6,3
3,25	9,3	7,74	47,16	1299	7,0
4,25	10,1	8,41	87,68	714	7,1
5,25	10,9	9,09	144,53	362	6,0
6,25	11,7	9,76	220,05	157	3,9
7,25	12,5	10,4	316,57	97	3,5
			Sum:	8759	36

The LiftWEC LCoE Calculation tool includes the functionality of giving the Annual Energy Production of the wave energy device through the *user defined sea states* – in this case they should be inserted in the following format:

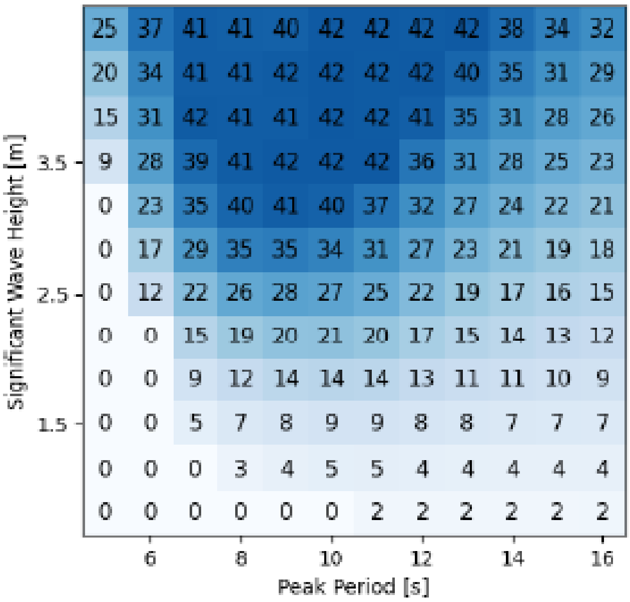
Table 2.2 User defined sea-states for the LiftWEC site in France as input to the LiftWEC LCOE Calculation Tool

Sea State	1	2	3	4	5	6
Wave Power Pw [kW/m]	5,8	20,6	47,2	87,7	144,5	220,0
Hours per year	3082	2661	1299	714	362	222
Significant Wave Height Hs [m]	1,25	2,25	3,25	4,25	5,25	6,25
Average Wave Period To2 [s]	6,39	7,06	7,74	8,41	9,09	9,76

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 Power Performance of the LiftWEC

LiftWEC power performance was initially based on data from a similar wave energy converter "CycWEC" driven by lift-forces having similar dimensions (12-meter diameter, 5-meter chord length). The original power matrix from (Siegel, 2019), is shown on figure below expressed in power per unit length kW/m. This performance is obtained theoretically using full control of both rotational speed and pitch angel relative to the incoming waves with a defined maximum of 42 kW/m.



Absorbed Power per meter															
Hs/Te	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5	P abs	
0,75	0	0	0	0	0	0	2	2	2	2	2	2	2	2	0,14	
1,25	0	0	1	3	4	5	5	5	4	4	4	4	4	4	3,65	
1,75	0	0	2	8	10	11	11	11	8	8	8	8	7	7	9,44	
2,25	0	0	2	15	19	20	21	18	16	14	13	13	11	10	18,25	
2,75	0	0	0	25	28	30	28	26	23	19	18	16	14	13	26,96	
3,25	0	0	0	35	38	38	37	34	29	24	22	20	18	17	34,83	
3,75	0	0	0	40	41	41	42	39	35	29	28	25	24	24	38,90	
4,25	0	0	0		41	42	42	42	42	38	34	30	28	27	41,29	
4,75	0	0	0	0	41	42	42	42	42	38	35	33	31	30	41,40	
5,25	0	0	0	0	0	41	42	42	42	39	36	35	31	30	41,29	
5,75	0	0	0	0	0	0	42	42	42	42	38	36	34	31	41,54	
6,25	0	0	0	0	0	0	42	42	42	42	42	38	36	34	41,87	
6,75	0	0	0	0	0	0	42	42	42	42	42	42	38	36	41,94	
7,25	0	0	0	0	0	0	0	42	42	42	42	42	42	38	41,72	
7,75	0	0	0	0	0	0	0	42	42	42	42	42	42	42	42,00	
8,25	0	0	0	0	0	0	0	42	42	42	42	42	42	42	42,00	
8,75	0	0	0	0	0	0	0	42	42	42	42	42	42	42	42,00	
9,25	0	0	0	0	0	0	0	42	42	42	42	42	42	42	42,00	
9,75	0	0	0	0	0	0	0	42	42	42	42	42	42	42	42,00	
														Pabs av	18	kW/m

Figure 2.4 On top and in blue original Power Matrix per kW/m of CycWEC based on (Siegel, 2019) and below transferred to bin intervals of 0,5 meter Hs and intervals of 1 sec of energy period Te.

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 performance of the CycWEC as presented in the scatter diagram above can also be simplified into several selected sea states. For each interval of Hs the average absorbed power (P_{abs}) is inserted in column four and in column five the efficiency of capture is calculated. In the last column the contribution to the average annual absorbed power is calculated and summed to 18 kW/m - indicating an average wave apsorbtion efficiency over the simplified sea states of 50%.

Table 2.3 CycWEC performance in seven selected sea states.

Hs [m]	Te ave [s]	Pw [kW/m]	Pabs [kW/m]	Efficiency of capture	hours/year	dPw [kW/m]	dpabs [kW/m]
<0,75					387		
1,25	7,7	5,76	3,65	0,63	3082	2,0	1,3
2,25	8,5	20,63	18,25	0,88	2661	6,3	5,5
3,25	9,3	47,16	34,83	0,74	1299	7,0	5,2
4,25	10,1	87,68	41,29	0,47	714	7,1	3,4
5,25	10,9	144,53	41,29	0,29	362	6,0	1,7
6,25	11,7	220,05	41,87	0,19	157	3,9	0,7
7,25	12,5	316,57	41,72	0,13	97	3,5	0,5
				sum	**8759**	**36**	**18**
Annual absorbed energy (span 30m, PTOeff=100%; availability=100%):						**4057**	**MWh/y**

In previous deliverable D8.5, the LiftWEC performance matrix was representative of a control strategy only applying pitch control. Also, performance was limited to provide the rated power of 42 kW/m per meter span and the annual absorbed power calculated to 2900 MWh/y. If represented in terms of the simplified seven sea states the performance looks like:

Table 2.4. D8.5 LiftWEC performance in the seven selected sea states.

Hs [m]	Te ave [s]	Pw kW/m	Pabs kW/m	Efficiency of capture	hours/year	dPw kW/m	dpabs kW/m
<0,75	6,9	0,2	0,0	0,00	387	0,0	0,0
1,25	7,7	5,8	1,2	0,21	3082	2,0	0,4
2,25	8,5	20,6	6,3	0,30	2661	6,3	1,9
3,25	9,3	47,2	20,5	0,43	1299	7,0	3,0
4,25	10,1	87,7	42,0	0,48	714	7,1	3,4
5,25	10,9	144,5	42,0	0,29	362	6,0	1,7
6,25	11,7	220,0	42,0	0,19	157	3,9	0,8
7,25	12,5	316,6	42,0	0,13	97	3,5	0,5
					8759	**36**	**12**
Annual absorbed energy (span 30m, PTOeff=100%, availability=100%):						**3084**	**MWh/y**

In this deliverable D8.6 the performance has been calculated numerically using approximate analytical model in WP5 completing calculations corresponding to 15 minutes presented by the separate 1min simulation of irregular wave exposure for 2 types of control strategies, and four

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.

wave conditions. The results are shown in the table below for four selected sea states, which confirm the CycWEC performance and high efficiency when both rotational and pitch Control is implemented. This is called **Joint Control (JC)** meaning variable pitch and variable rotational velocity.

The variable rotational velocity is kept within the limit of 0.5*optimal_constant to 2*optimal_constant, and the velocity of pitch is limited with 5rad/s. These limitations are introduced to avoid uncertainties in hydrodynamics and mechanics for the fast changes of the rotational velocity and pitching. This however also result in slightly smaller absorption values compared to CycWEC as seen on Figure , however is a more realistic representation.

Simulations of implementing **Pitch Control (PC)** with a constant rotational velocity optimised for a particular sea state (Hs,Te) has also been carried out by keeping the velocity of pitch regulation below 5rad/s to avoid unsteady effects.

Table 2.5. D8.6 LiftWEC performance in four selected sea states.

Hs [m]	Te ave [s]	Pw kW/m	Pitch Control (PC) Pabs [kW/m]	Joint Control(JC) Pabs [kW/m]	CycWEC Pabs [kW/m]
1,25	7,7	5,76	**1,7**	**3,6**	5,0
2,25	8,5	20,63	**6,1**	**17,3**	21,0
3,25	9,3	47,16	**15,6**	**27,7**	38,0
4,25	10,1	87,68	**22,1**	**36,4**	42,0

The results for constant rotational velocity and pitch, - and variable rotational velocity and constant pitch have been extracted from (Chitale et al, 2022) where CycWEC performance assessment was published in 2022.

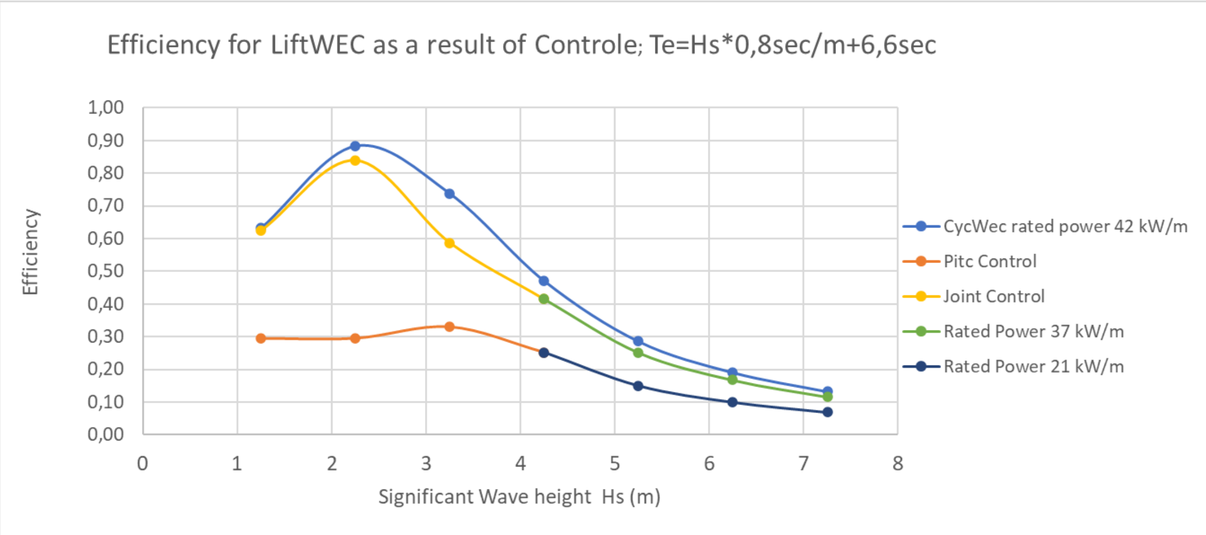


Figure 2.5 Comparison between the efficiency of the CycWEC performance and the results from LiftWEC using Joint control (combined rotational velocity and pitch control) and pitch control only.

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.

To compare the calculated energy production of the final LiftWEC configuration at the location in France, the results of the Joint Control simulations are inserted (bold) for the relevant sea states and the performance is calculated in the 7 central sea states (Hs from 1,25 meter increasing to 7.25 meter using the relation (2) to calculate the relevant energy period Te).

Table 2.6 D8.6 LiftWEC performance using Joint Control

Hs [m]	Te ave [s]	Pw kW/m	Pabs [kW/m]	efficiency of capture	hours/year	dPw [kW/m]	dpabs [kW/m]
<0,75	6,9	0,2	0,0	0,00	387	0,0	0,0
1,25	7,7	5,8	**3,6**	0,63	3082	2,0	1,3
2,25	8,5	20,6	**17,3**	0,84	2661	6,3	5,3
3,25	9,3	47,2	**27,7**	0,59	1299	7,0	4,1
4,25	10,1	87,7	**36,4**	0,42	714	7,1	3,0
5,25	10,9	144,5	36,3	0,25	362	6,0	1,5
6,25	11,7	220,0	36,8	0,17	157	3,9	0,7
7,25	12,5	316,6	36,7	0,12	97	3,5	0,4
				Sum:	**8759**	**36**	**16**
Annual absorbed energy (span 30m, PTOeff=100%, availability=100%):						**4247**	**MWh/y**

From the table the average wave power at the site is 36 kW/m and the average absorbed mechanical power per meter span is 16 kW/m. For a 30-meter span that is 4247 MWh/y.

Using Pitch control only, the resulting annual energy production would become approximately half of that for joint control, as shown in the table below.

Table 2.7 D8.6 LiftWEC performance using only Pitch Control.

Hs [m]	Te ave [s]	Pw [kW/m]	Pabs [kW/m]	efficiency of capture	hours/year	dPw [kW/m]	dpabs [kW/m]
<0,75	6,9	0,21	0,00	0,00	387	0,0	0,0
1,25	7,7	5,76	1,70	0,30	3082	2,0	0,6
2,25	8,5	20,69	6,12	0,30	2661	6,3	1,9
3,25	9,3	47,16	15,60	0,33	1299	7,0	2,3
4,25	10,1	87,68	22,10	0,25	714	7,1	1,8
5,25	10,9	144,53	21,73	0,15	362	6,0	0,9
6,25	11,7	220,05	21,99	0,10	157	3,9	0,4
7,25	12,5	316,57	21,96	0,07	97	3,5	0,2
				sum	**8758**	**36**	**8**
Annual absorbed energy (span 30m, PTOeff=100%,; availability=100%):						**2130**	**MWh/y**

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 Uncertainty of the Annual Energy Production

The annually absorbed energy of the final WEC configuration using Joint Control is shown in table and is estimated to be 4247 MWh/y. This absorbed energy represents mechanical power, i.e. before taking PTO efficiency and availability into consideration. The accuracy of the absorbed energy will to a large extent dependent on how well the control will work in real wave conditions. However, if the system works as predicted, the annual absorbed energy is estimated to vary between plus and minus 10% for the final configuration, assuming Joint Control as shown in the table 8 below.

Table 2.8 Comparison of LiftWEC Absorbed energy estimates under different assumptions, as detailed in each deliverable (i.e. Del8.5 and Del8.6)) at the site of 36 kW/m average wave power, offshore Quimper, France

WEC reference	D8.4 –	D8.5. –	D8.6 Ave	D8.6 Min	D8.6 Max
Control method ref	CycWEC	Slow control	Joint Control		
Rated Power (P_r) [kW]	1.250	1.250	1250	1250	1250
Absorbed Energy [MWh/y]	3880	2900	4250	3820	4670
Electrical Energy [MWh/y]	3320	2490	3600	3200	4260

2.3.1 PTO efficiency

Being a direct drive mechanical to electrical conversion, the generator/PTO efficiency of the final configuration is estimated to 92% and the uncertainty of the PTO efficiency evaluated to range between 90% and 95%.

2.3.2 Availability

The availability of the final configuration has been calculated to 94% and with a variation between a minimum value of 93% and maximum value of 96%. The availability is an input from WP7 looking into Operation and Maintenance [McAuliffe (2023)]. The availability for the single WEC is assuming all is running as expected when deployed in array, this does not include unexpected learnings due to failures that typically can occur during first of the kind demonstrations.

Table 2.9 PTO efficiency and availability for a single LiftWEC

WEC reference	D8.4 –	D8.5. –	D8.6 ave	D8.6 min	D8.6 max
PTO & Generator efficiency	95%	90%	92%	90%	95%
WEC Availability	90%	95%	94%	93%	96%

The range of values for the Final configuration (for a single unit) placed in the uncertainty section of the LCOE Tool are shown below, where *brutto annual energy production* refers to absorbed power. This value multiplied by the PTO efficiency and the availability provides the annual energy production 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.

3 CAPEX

The total Capex is a sum of the several elements that are included in the WEC. The new sensitivity? routines in the LCoE tool allows to place limits on each of cost centre with a maximum and minimum value indicating the uncertainty of the estimate. Based on these inputs the likely variation of the total LCoE is calculated.

3.1 Development and Project management costs

Development and consenting costs are considered approx. 500 kEUR, this is approximately 8% of CAPEX with a variation estimated between 450 and 550 k€.

3.2 Main variation of structural costs

In the assessment of uncertainties related to the structural costs these are expressed in terms of uncertainties related to the unit costs of the materials – assuming the volume and weight of the structure are accurate and not changed. The unit costs included are for steel, glass fibre and ballast concrete shown in the table below. The values are inserted in the LCOE tool and ticked to be included in the simulation.

Table 3.1 Material costs

Unit	Average	min	max
Steel	3400	3060	3740
Ballast	70	63	77
Glass	9500	8550	10450

The volumes of the structural mass of steel and concrete have been calculated as part of a deliverable of WP3 [Louis Papillon (2023)] It roughly corresponds to using a plate thickness of 25 – 30 mm, which provides values ranging around 1000 ton of steel including the centrally rotating shaft, the PTO and two lateral supports at both ends. Weight estimates for ballast concrete are about 1600 ton, and 30 ton on glass fibre for the two hydrofoils. Further ooptimization in WP3 not included in this deliverable indicate that the weight of steel probably can be reduced by 30 % - a reduction of CAPEX by as much as 25%.

Table 3.2 Structural mases and costs for the single WEC

WEC reference	D8.4 –	D8.5. –	D8.6 ave	D8.6 min	D8.6 max
Steel [ton]	120	790	1000	1000	1000
Ballast concrete [ton]		2367	1600	1600	1600
Glass fiber [ton]	36	30	30	30	30
Total weight [ton]	235	3193	2630	2630	2630
Structural cost steel [k€]	*690*	2.686	3400	3060	3740
Structural cost ballast [k€]		166	112	100	123
Structural cost Hydrofoils [k€]	*340*	285	285	256	313
Structural cost total [k€]	1030	3137	3797	3416	4176

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.

3.3 DIRECT DRIVE PTO INCLUDING GENERATOR

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 3.4 Generator cost

WEC reference	D8.4 –	D8.5. –	D8.6 ave	D8.6 min	D8.6 max
Generator [k€]	*750*	750	750	675	825

3.4 ELECTRICAL CONNECTOR, UMBILICAL

The umbilical connection for the 1250 MW unit is estimated to 60k€ and varied plus minus 10%. The single WEC is expected to be connected at a site with grid connection and therefore no grid connection costs are included. Grid connection has been included in the 100 MW array calculations (Section 7).

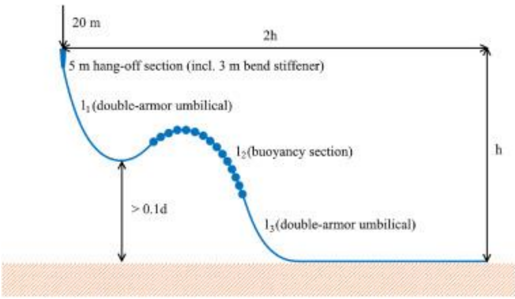


Figure 3.1. Illustration of a generic flexible electrical cable from the WEC to the seabed.

Table 3.5 Cost of grid connection for a single WEC

WEC reference	D8.4 –	D8.5. –	D8.6 ave	D8.6 min	D8.6 max
Umbilical/Dynamic Cable [k€]	60	60	60	54	66
Electrical from WEC to Grid	-	-	-	-	-

3.5 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). For the sensitivity analysis, a 10% variation over the average in the minimum and maximum has been used.

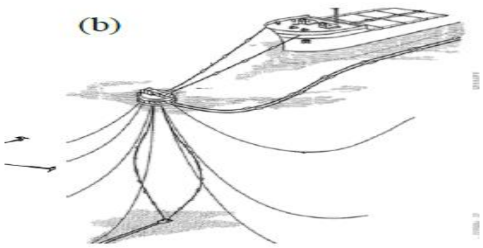


Figure 3.2 Illustration of a single point mooring from the WEC to the seabed.

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 3.6 Cost of single point mooring for a single WEC

WEC reference	D8.4 –	D8.5.	D8.6	D8.6 - Min	D8.6 - Max
Mooring [k€]	300	300	300	270	330

3.6 Control Cost Estimates

The control estimate is 110 k€. The control ensures optimal performance of the spar LiftWEC and include pitch control, rotational speed control and control of submergence.

- Pitch control of the hydrofoils is enabled by two actuators per hydrofoil, one at each end.
- Phase control is implemented by the direct drive generators.
- Submergence is enabled by water 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 1 Cost of control systems for a single WEC

WEC reference	D8.4 –	D8.5. –	D8.6 ave	D8.6 min	D8.6
SCADA [k€]					
Pitch control [k€]	75	75	75	67	82
Submergence control [k€]	35	35	35	31	38
Rotational velocity control [k€]					
Control cost total [k€]	**110**	**110**	**110**	**99**	**121**

3.7 Installation Cost Estimates

The installation strategy assumes the pre-installation of anchors and moorings and floating the device to site with small, cheap vessels (i.e. tug boats). The mooring connection type also allows for a simple connection procedure, that requires minimal time offshore. WP7 has modelled the installation procedures using a set of 1000 iterations. Installation cost estimates derive from the modelling of a 100 MW array with 80 WECs [McAuliffe (2023)]. WP8 has inferred Installation costs for the single WEC by dividing total array installation costs by 80 and adding a 10% on top – the amount expected to get discounted in a farm thanks to economies of scale.

Table 3.8 Installation and decommissioning cost of a single WEC

WEC reference	D8.4 –	D8.5. –	D8.6 ave	D8.6 min	D8.6
Total installation [k€]	275	330	170	153	187
Decommissioning	-	-	39	35	43

Decommisioning costs are also included in the LCoE Tool. They are calculated as 77% of instllation Costs, and discounted to present value. Miminum and maximum values in the analysis are shown in the table above.

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.

3.8 TOTAL CAPEX

Total CAPEX for the Single LiftWEc Amount to 5.7 MEUR. By adding 10% contingencies, total CAPEX amount to 6.3 MEUR. CAPEX breakdown of costs is shown in below, where it is clearly seen how structural costs of LiftWEC are the highest contributor to CAPEX with a relative value of 60% of total CAPEX; or 3.8 MEUR in absolute value.

Table 3.9 Total CAPEX for the Single LiftWEC

WEC reference	D8.4 –	D8.5. –	D8.6 ave	D8.6 min	D8.6 max
Contingencies (10% of CAPEX)	420	*325*	**572**	514	572
Total CAPEX incl. contingencies [kEUR]	*3.600*	5.788	6.299	5.659	6.928

3.9 OPEX COST AND MAINTENANCE STRATEGY

The operation and maintenance modelling or O&M assumes a return to base strategy and preventive maintenance veery 2 years. As explained above, the floating the device to site can be a relatively simple procedure as it implies small, cheap vessels (i.e. tug boats). The mooring connection type also allows for a simple connection procedure, making it easier to attach and detach the device; and requires minimal time offshore.

WP7 has extensively modelled O&M also considering failure rates of the critical components and different scenarios. O&M cost estimates derive from the modelling of a 100 MW array with 80 WECs [McAuliffe (2023)]. WP8 has inferred OPEX for the single WEC by dividing total array OPEX by 80 and adding a 10% on top – the amount expected to get discounted in a farm thanks to economies of scale.

Table 3.10 Operation and maintenance cost for single WEC

WEC reference	D8.4	D8.5	D8.6 ave	D8.6 min	D8.6 max
Minor repair & inspections [k€]			10	9	11
Major maintenance tow back[k€]			100	90	110
Fixed annual costs [k€]					
Annual OPEX [kEUR]	*125*	120	110	99	121

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 LCOE OF THE FINAL (SINGLE WEC) CONFIGURATION

The annual electricity production presented in section 2 and cost data from section 3 are combined to provide the LCOE estimates for the selected site. In the table 4.1 below is the LCoE presented as it has developed through the project. In this last delivery D8.6 the LCoE associated with the average input parameter is 155 €/MWh and the maximum LCoE which combines lower energy production with the higher costs 184 €/MWh, and the minimum LCoE 118 €/MWh which combines the higher energy production with the lower costs. This gives a resulting variation between ±20%.

Table 4.1 LCOE results for a first, full-commercial LiftWEC at, Off Quimper, France.

Pwave = 36 kW/m					
WEC reference	D8.4	D8.5	D8.6 ave	D8.6 min	D8.6 max
Rated Power (P_r) [kW]	1250	1250	*1250*		
LCOE (25 years, r=5%) [EUR/MWh]	**115**	**213**	***155***	***118***	***184***
Uncertainty estimate	***±80%***	***±30%***	***±20%***	***-20%***	***+20%***

Below is shown a summery plot of the Single WEC results using the LiftWEC LCOE tool

LiftWEC LCOE Calculation Tool

JULIA F. CHOZAS CONSULTING ENGINEER — DEPARTMENT OF CIVIL ENGINEERING AALBORG UNIVERSITY

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885 - The LiftWEC Project. The development of the COE Calculation Tool has been previously funded by the Danish funded projects "The COE tool for WECs – Improvement and Dissemination" (grant agreement 2013-1-12135, 2013-2014) and "Beton til Bølgeenergi" (64018-

Output Summary. Economic and Performance Assessment. Single WEC - Spar LiftWEC

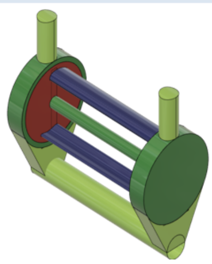
Project summary

Project name	Spar LiftWEC
Deployment location	France off Quimper, LiftWEC Test Site
Power density at the location	36 kW/m
Project lifetime	25 years

Main dimensions and characteristics

Main active dimension	30,0 m
Secondary dimension (length/width)	12,0 m
Total dry weight	863 ton
Station keeping type	Floating
PTO type	Direct drive
PTO average efficiency	92%
Generator rated power	1250 kW

Concept picture



Economic Assessment for Spar LiftWEC

Development stage: Phase 2 / TRL 4 — [-30 to 30%] Uncertainty

Total CAPEX	6,30 MEUR	[CAPEX / MW]	5,0 MEUR/MW
Annual OPEX	110 kEUR/year	[annual OPEX / CAPEX]	2%

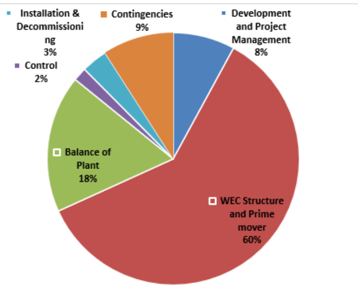
Discount rate	0%	3,5%	5,0%
LCOE (25 years, in EUR/MWh)	101	137	155

Performance Assessment for Spar LiftWEC

WEC rated power	1250 kW	Average annual electricity production	411 kW
Annual Energy Production	3600 MWh/y	Average annual Capture width	12,4 m
Capacity factor (C_f)	33%	Average annual Capture width ratio	41%

Breakdown of costs

Total CapEx	**6,30 MEUR**
Development and Project Manag	500 kEUR
WEC Structure and Prime mover	3797 kEUR
Balance of Plant	1110 kEUR
Control	110 kEUR
Installation & Decommissioning	209 kEUR
Contingencies	573 kEUR
Annual OpEx	**110 kEUR/year**



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.

4.1 Sensitivity and Uncertainties

There are uncertainties associated both to the input as well as the output values. The economic assessment is subject of several assumptions that will be verified as the development process evolves.

The LCoE tool can now evaluate the sensitivity to variations of a selected input variables within a specified minimum and maximum range. In the example below we investigate the how the LCoE will be affected by a plus and minus 10% variation of input variables as ticked in the boxes below, such as the AEP, some CAPEX subcomponents and total OPEX.

Table 4.2 Selected input values for the Monte Carlo simulation are shown below with a "tick"

AEP	Name	Value	Range (default +-10%) Min	Max	
	Brutto Annual Energy Produ	4163	3800,00	4400,00	☑
	WEC availability	94%	0,93	0,96	☑
	PTO average efficiency	92%	0,90	0,95	☑

CAPEX	Name	Value	Range (default +-10%) Min	Max	
	Total CAPEX	6299,1	5669,18	6928,99	☐
	Development and Project Management	500,0	450,00	550,00	☐
WEC Structure and Prime move	*Steel unit cost*	3400,0	3060,00	3740,00	☑
	Glass fibre unit cost	9500,0	8550,00	10450,00	☑
	Ballast concrete unit cost	70,0	63,00	77,00	☑
Balance of Plant	*Direct drive PTO including Generator*	750,0	675,00	825,00	☑
	Umbilical / Dynamic cable (from PTO to connector)	60,0	54,00	66,00	☐
	Electrical connection (from WEC to grid)	0,0	0,00	0,00	☐
	Single point connection	300,0	270,00	330,00	☐
Control	*Control*	110,0	99,00	121,00	☐
	SCADA	0,0	0,00	0,00	☐
	Hydrofoil Pitch control	75,0	67,50	82,50	☐
	Rotor Submergence control	35,0	31,50	38,50	☐
	Rotational velocity control	0,0	0,00	0,00	☐
Installation and Commissioning	*Installation and Commissioning*	170,6	153,58	187,70	☑
	Pre-assembly and transport	0,0	0,00	0,00	☐
	Installation: moorings, spar, prime-mover	0,0	0,00	0,00	☐
Decommissioning	*Decommissioning discounted to present value*	38,8	0,00	38,80	☑
Contingencies	*Contingencies*	572,6	343,59	572,64	☑

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.

OPEX	Name	Value	Range (default +-10%) Min	Max	
	Total OPEX	110	99,0	121,0	☑
	Minor repair & Inspection. Annual costs	10	9,0	11,0	☐
	Major maintenance/repair: tow back or lift. Annual costs	100	90,0	110,0	☐
	Fixed OPEX: Annual Site lease, Insurance & Management	0	0,0	0,0	☐

The sensitivity is calculated by randomly using any combination of cost and energy production numbers from the list to calculate the LCOE. This process is called a Monte Carlo simulation. The calculation is in this case repeated 10.000 times, giving a distribution of results as indicated in the plot below.

With a discount rate of 5% the LCOE will most likely fall between the P30 148 €/MWh and P70 value of 157 €/MWh. Further it can be seen from the plot below that the minimum value simulated is about 130 €/MWh and the maximum value about 180 €/MWh which is in the range - 15% to 20% for the selected values.

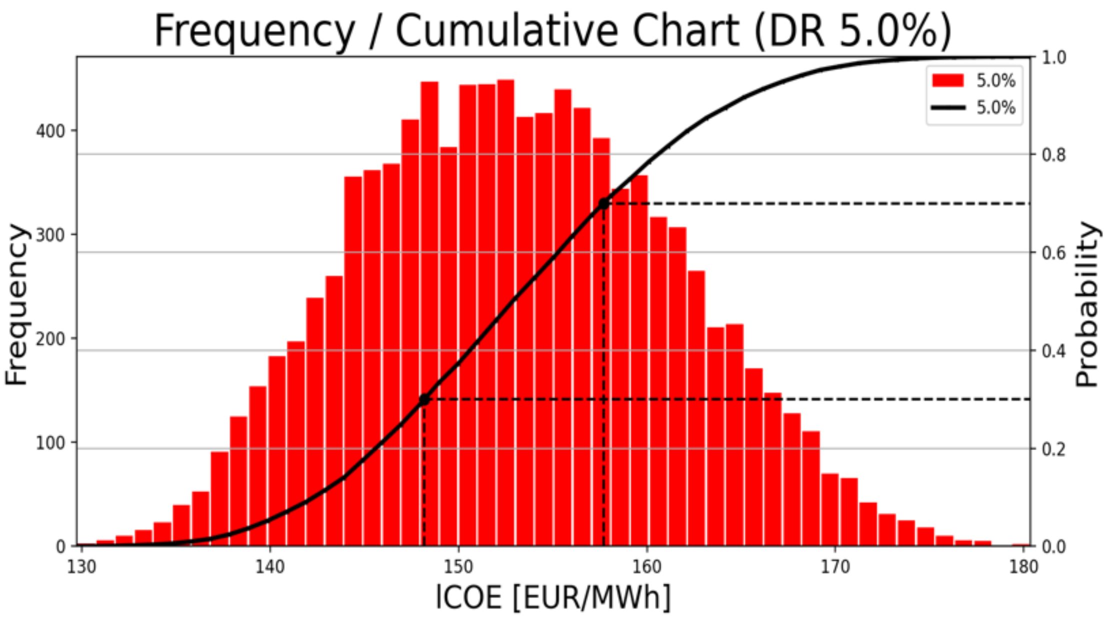


Figure 4.1 Result of Mote Carlo simulation of the LCoE because of variation of input values

It is estimated that at the LCOE is estimated with an uncertainty between -20% to 20%. 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 WP5 (A. Ermakov, F. Thiebaut, G.S. Payne et al., (2023); as well as the results of the detailed analysis on the structural design and mass [Louis Papillon (2023)].

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 Comparative Table of the Final Configuration

Table 5.1. Comparative table of the LiftWEC Spar including main dimensions for the different designs as the work has evolved in the project.

	Spar Buoy				
WEC reference	*D8.4*	D8.5	**D8.6 ave**	D8.6min	D8.6max
Rotor diameter [m]	*12*	12	**12**	12	12
Water depth [m]	*50*	50	**50**	50	50
Prime mover & structure in steel [ton]	*120*	790	**1000**	1000	1000
Hydrofoils (glassfiber) [ton]	*36*	30	**30**	30	30
Ballast concrete [ton]		2367	**1600**	1600	1600
Total weight	*235*	3193	**2630**	2630	2630
Foundation / mooring [ton]	*140*	NA	NA	NA	NA
CAPEX [kEUR]					
Development costs	*500*	**500**	**500**	450	550
Structural cost: nacelle and rotor	*690*	**2686**	**3400**	3060	3740
Hydrofoils	*340*	**285**	**285**	256	313
Ballast concrete		**166**	**112**	100	123
Single point connection	*330*	**300**	**300**	270	330
PTO and housing	*750*	**750**	**750**	675	825
Umbilical	*60*	**60**	**60**	54	66
Control cost	*110*	**110**	**110**	99	121
Installation and Commissioning	*275*	**330**	**170**	153	187
Decommissioning	*212*	**75**	**38**	0	38
Contingencies (10% of CAPEX)	*325*	***526***	**572**	343	572
Total CAPEX [kEUR]	***3600***	**5788**	**6299**	**5659**	**6928**
Annual OPEX [kEUR/y]	*125*	**120**	**110**		
Rated Power (P_r) [kW]	***1250***	**1250**	**1250**	**1250**	**1250**
CAPEX per MW [MEUR/MW]	*2,9*	**4,6**	5,0	4,5	5,5
LCoE EUR/MWh	*115*	**213**	153	118	184

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 Deployment in a 100 MW LiftWEC Array

When developing a 100 MW wave farm there will be a benefit of scales to be considered. This includes rational fabrication, installation, and maintenance which have not yet been included for the calculation of the single WEC.

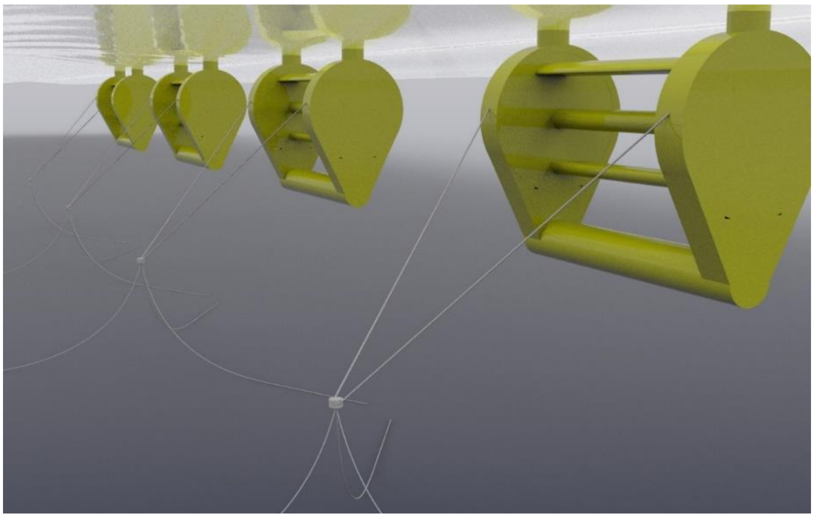


Figure 6.1 Artist illustration of an array of four LiftWECs ("Olbert, G., TU Hamburg").

The wave farm in addition includes new costs associated with the gird connection and its installations: a floating substation for transformers, export power cable to the shore, and the inter array cables connecting the WECs to the substation. Figure 6.3 shows a sketch of how the WEC farm array layout could be defined in terms of number of WECS, number of rows, number of WECs per row.

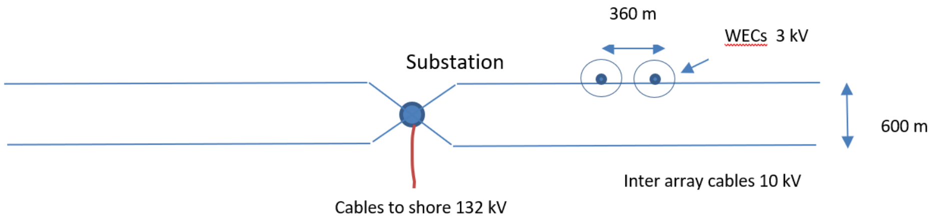


Figure 6.2 System definition of the array layout

The proposed farm layout considers 4 inter-array cable strings of 20 devices in a zig zag pattern There are 300m between devices and 600m between rows. Each string is 7.2km in length including an additional 60m (20%) for each cable to span the 30m length of a device and consider additional length required for connections or dynamic cabling. They are connected in the centre to an offshore floating substation. The inter-array cables are 10kV and there is one export cable of 132 kV from the offshore substation to shore. The distance to shore is 10km and an additional 20% of export cable length is included to consider connections etc. Therefore, rounding up, the total inter-array cable length is 29km and the export cable is 12km.

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 6.1 Main parameters of the Array

Main characteristics of the Array	Default	Enter	Used	
Total number of WECs	20	80	80	WECs
Number of rows in the array	4	2	2	rows
Number of WECs per row	40		40	WECs/row
Distance between WECs in the same row	210	360	360	m
Distance between rows	210	600	600	m
Distance from off. substation to onshore conn. point	10	12	12	km
Distance to maintenance port	20		20	km
Distance to fabrication / assembly port	50		50	km

The Annual energy production is calculated from the single WEC by multiplying with the number of WECs in the farm and including a percentual energy loss and disturbance due to the placements of one row in front of the other. This loss is estimated to be small with the chosen layout to about 2%.

Table 6.2 Summary of the Energy production

Array performance - Annual Energy Production	Default	Enter	Used
Single WEC Annual Energy Production	3600		3600 MWh/y
approx. Percentual Energy Loss row after row	2%		2%
Total Array Annual Energy Production	285		285 GWh/y
Single WEC rated power	1250		1250 kW
Total Array Capacity	100,0		100,0 MW

6.1 CAPEX RELATED TO FARM

The cost of building a Wave Farm can be calculated in the LiftWEC LCoE tool. 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. To account for the benefit of scales all costs from the single WEC are transferred and reduced by 10%.

Table 6.3 Summary of the CAPEX values for the array

	Default	Enter	Used		Unit costs	
Array CAPEX						
Development and Project Management	23,7		**24**	**MEUR**	6% Total CAPEX	
WECs Structure and Prime mover	273,4		**273,4**	**MEUR**	10% discount (i.e. economies of scale)	
PTOs	54,0		**54,0**	**MEUR**	10% discount (i.e. economies of scale)	
Umbilical / Dynamic cables (from PTO to connector	4,3		**4,3**	**MEUR**	10% discount (i.e. economies of scale)	
Station keeping (Mooring)	21,6		**21,6**	**MEUR**	10% discount (i.e. economies of scale)	
Control	7,9		**7,9**	**MEUR**	10% discount (i.e. economies of scale)	
Others			0,0	MEUR		
Array - Electrical connection (not including Installation)			**11,3**	**MEUR**		
Inter-array electrical cables	4,3		4,3	MEUR	150 EUR/m (6 kV / 11 kV)	
Offshore collection hub (junction box / offshore connect	1,25	1,0	1,0	MEUR	1,25 MEUR	Offshore substa
Export cable (from substation to onshore connec. point)	6,0		6,0	MEUR	500 EUR/m (150 kV)	Export cable witl

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 cost of the installation of the different elements of the array is shown below. Compared to the installation of the single WEC specific costs are now included for installation of the inter array, export cable and substation, as well as WEC installation and moorings. These costs have been specified at ((McAuliffe (2023)).

Table 6.4 Array installation costs

Array - Installation	12,3		**12,5**	**MEUR**	10% discount (i.e. economies of scale)
Inter-array, export cable and Substation	0,0	5,132	5,1	MEUR	0 EUR/m
WECs Installation (structure and prime mover)	0,0	1,592	1,6	MEUR	0 MEUR
Moorings Installation	0,0	5,789	5,8	MEUR	0 EUR/m

Total array CAPEX account for 412 MEUR. Adding 10% contingencies on top (about 41 MEUR), Total CAPEX after contingencies is of 453 MEUR.

Table 6.5 Total Array Capex and contingencies

Array - Total CAPEX before contingencies			**412 MEUR**	
Contingencies	41,2		**41,2 MEUR**	10%
Array Total CAPEX with contingencies	453		**453 MEUR**	

6.2 OPEX RELATED TO FARM

The operation and maintenance of the Wave Farm offer some potential cost savings compare to the single WEC, as operation and maintenance can be planned to include several WECs during the same weather window using the same vessel. The maintenance has been evaluated by ((McAuliffe (2023)) as is estimated at 9 MEUR/year.

Table 6.6 OPEX costs associated with the array

OPEX				
Minor repair & Inspection. Annual costs	0,7		0,72 MEUR/year	10% discount (
Major maintenance/repair: tow back or lift. Annual costs	7,2		7,20 MEUR/year	10% discount (
Fixed OPEX: Annual Site lease, Insurance & Manageme	0,0	0,82	0,82 MEUR/year	10% discount (
Others			0,0 MEUR/year	
Annual Operational Expenditures (OPEX)			**8,736 MEUR/year**	

6.3 LCOE OF THE 100 MW FARM

Overall results indicate a competitive LCOE for being the first, full-scale LiftWEC farm in representative average European wave conditions. The LCOE estimates vary from around 90 EUR/MWh to around 145 EUR/MWh for three different discount rates (0% to 5%), showing that LIftWEC has great potential to being able to produce renewable energy electricity at a commercial competitive price.

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 6.7 Summery of the LCOE calculation as presented in the LiftWEC LCOE Tool

Economic Assessment	Development stage: Phase 2 / TRL 4	[-30 to 30%] Uncertainty	
Single WEC: Spar LiftWEC		**Array: 100 MW Array Spar LiftWEC**	
CAPEX	6,30 MEUR	**Array Total CAPEX with contingencies**	453 MEUR
Annual OPEX	110 kEUR/year	**Annual Operational Expenditures (OPE**	9 MEUR/year
[annual OPEX / CAPEX]	2%	[annual OPEX / CAPEX]	2%
[CAPEX per MW]	5,0 MEUR/MW	[CAPEX per MW]	4,5 MEUR/MW
Single WEC LCOE (r=5%)	**155 EUR/MWh**	**Array LCOE (r=5%)**	**143 EUR/MWh**

Table 6.8 Summary sheet from the LiftWEC LCOE tool

LiftWEC LCOE Calculation Tool

JULIA F. CHOZAS CONSULTING ENGINEER
DEPARTMENT OF CIVIL ENGINEERING AALBORG UNIVERSITY

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885 - The LiftWEC Project.

Summary, Array. Economic and Performance Assessment - 100 MW Array Spar LiftWEC

Project summary	
Project name	100 MW Array Spar LiftWEC
Deployment location	France off Quimper, LiftWEC Test Site
Power density at the location	36 kW/m
Project lifetime	25 years

Main characteristics of the Array	
Total number of WECs	80 WECs
Number of rows in the array	2 rows
Number of WECs per row	40 WECs/row
Station keeping type	Floating
Distance between WECs in the same row	360 m
Distance between rows	600 m
Distance off. substation to onshore conn. point	12 km

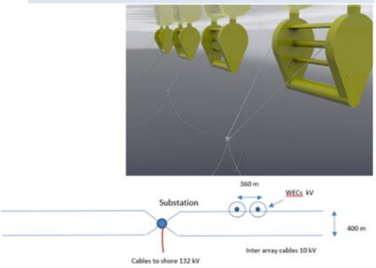
Economic Assessment for 100 MW Array Spar LiftWEC

Development stage: Phase 2 / TRL 4	[-30 to 30%] Uncertainty
Total CAPEX	452,74 MEUR
Annual OPEX	9 MEUR/year
[CAPEX / MW]	4,5 MEUR/MW
[annual OPEX / CAPEX]	2%
Array LCOE (r=5%)	**142 EUR/MWh**

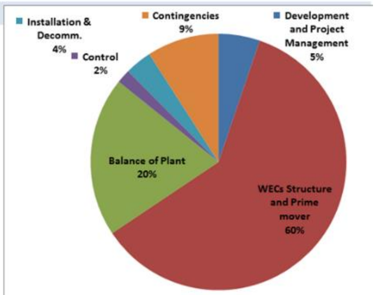
Performance Assessment for 100 MW Array Spar LiftWEC

Total array capacity	100 MW	**Average annual electricity production**	32,9 MW
Annual Energy Production	289 GWh/y	**average annual Array Capture width**	994,0 m
Capacity factor (C_f)	33%	**average annual Capture width ratio**	41%

Array layout - Picture



Breakdown of costs, Array	
Total CAPEX	**452,7 MEUR**
Development and Project Manage	23,7 MEUR
WECs Structure and Prime mover	273,4 MEUR
Balance of Plant	91,2 MEUR
Control	7,9 MEUR
Installation & Decomm.	15,4 MEUR
Contingencies	41,2 MEUR
Annual OPEX	**8,7 MEUR/year**



6.4 Sensitivity of the Wave Energy Farm LCoE

The LCoE tool can now evaluate the sensitivity to variations of a selected number of input variables within a specified minimum and maximum range. In the example below we investigate the how the LCoE will be affected by a plus minus 10% variation of input variables as ticked in the boxes below, such as the AEP, CAPEX subcomponents and OPEX.

Table 6.9 Selected values with range ±10% for the sensitivity analyses

AEP	Name	Value	Range (default +-10%) Min	Max	
	Total Array Annual Energy Production	285	257	314	☐
	Single WEC Annual Energy Production	3600	3240	3960	☐
	approx. Percentual Energy Loss row after r	2,0%	1,8%	2,2%	☑

CAPEX	Name	Value	Range (default +-10%) Min	Max	
	Array Total CAPEX with contingencies	452,7	407,47	498,02	☐
	Development and Project Management	23,7	21,31	26,05	☑
	WECs Structure and Prime mover	273,4	246,05	300,72	☑
	PTOs	54,0	48,60	59,40	☑
	Umbilical / Dynamic cables (from PTO to connector)	4,3	3,89	4,75	☑
	Station keeping (Mooring)	21,6	19,44	23,76	☑
	Control	7,9	7,13	8,71	☑
	Others	0,0	0,00	0,00	☑
	Array - Electrical connection (not including Installation)	11,3	10,19	12,45	☑
	Inter-array electrical cables	4,3	3,89	4,75	☑
	Offshore collection hub (junction box / offshore connectors)	1,0	0,90	1,10	☑
	Export cable (from substation to onshore connec. point)	6,0	5,40	6,60	☑
	Array - Installation	12,5	11,26	13,76	☐
	Inter-array, export cable and Substation	5,1	4,62	5,65	☑
	WECs Installation (structure and prime mover)	1,6	1,43	1,75	☑
	Moorings Installation	5,8	5,21	6,37	☑
	Array - Decommissioning Discounted to present value	2,8	2,56	3,13	☑
	Contingencies	41,2	37,04	45,27	☑

OPEX	Name	Value	Range (default +-10%) Min	Max	
	Annual Operational Expenditures (OPEX)	**8,73584**	**7,9**	**9,6**	☐
	Minor repair & Inspection. Annual costs	***0,72***	0,6	0,8	☑
	Major maintenance/repair: tow back or lift. Annual costs	***7,20***	6,5	7,9	☑
	Fixed OPEX: Annual Site lease, Insurance & Management	***0,82***	0,7	0,9	☑
	Others	***0,00***	0,0	0,0	☑

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 sensitivity is calculated using a Monte Carlo by randomly using any combination of cost and energy production numbers from the list above to calculate the LCoE. The simulation has been repeated 10.000 times, giving a distribution of results as indicated in the plot below.

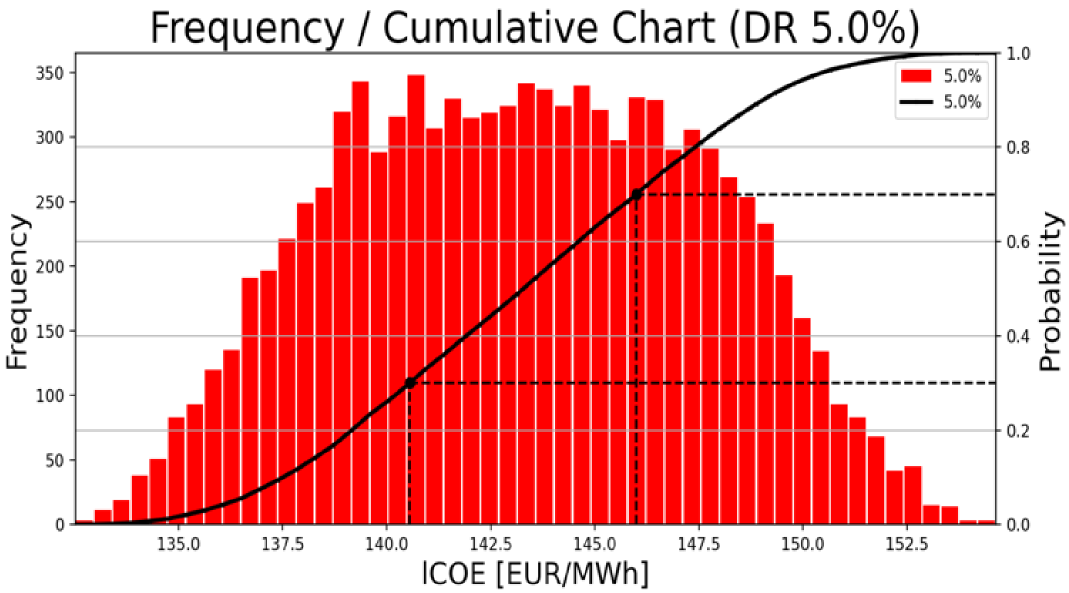


Figure 6.3 Plot of the Mote Carlo simulation LCOE for the array assumptions

The height of each red bar indicates how many simulations reached a certain cost interval. The LCoE value which is above the lowest 30% and below the 70% highest values of the simulations are indicated and summarized in the figure below.

Figure 1 Summery data from the sensitivity analyses

Actual key metrics values:
AEP [kWh]: 285.18
CAPEX [MEUR]: 452.74
OPEX [MEUR]: 8.74
Number of randomized realizations: 10000
P30 (5.0%): 140.56 EUR/MWh
P70 (5.0%): 145.99 EUR/MWh

7 Discussion and Conclusions

This study has calculated the LCOE of the Final LiftWEC configuration with a span of 30 meters and has also considered the uncertainty on cost and performance. The LCoE of the final LiftWEC configuration (the Spar Buoy) has been estimated to between 155 €/MWh for a first, full-scale LiftWEC and 142 €/MWh for a 100 MW first, 100 MW wave farm of 80 LiftWECs. The sensitivity to input costs uncertainty has been analysed and described in this deliverable. The impact of variation of different cost centres can be "ticked" and annual energy production AEP, can be included in the sensitivity analyses. In this way the variation of the LCoE can be estimated and the largest effect to the uncertainty on the LCoE, identified in so called “Tornado plot”.

The effect of deploying the rotor at different deployment sites with wave power levels has also been analysed. Figure 7.1 illustrates how the LCOE decrease as a function of the increasing wave power resource from 20 kW/m to 70 kW/m. The LCoE decreases from about 155 €/MWh at the 36 kW/m LiftWEC site in France to about 80 €/MWh at the Belmullet site with 74 kW/m. On the other hand, at location with smaller resource such as 20 kW/m in the North Sea or Portugal the LCoE will increase to 260 €/MWh.

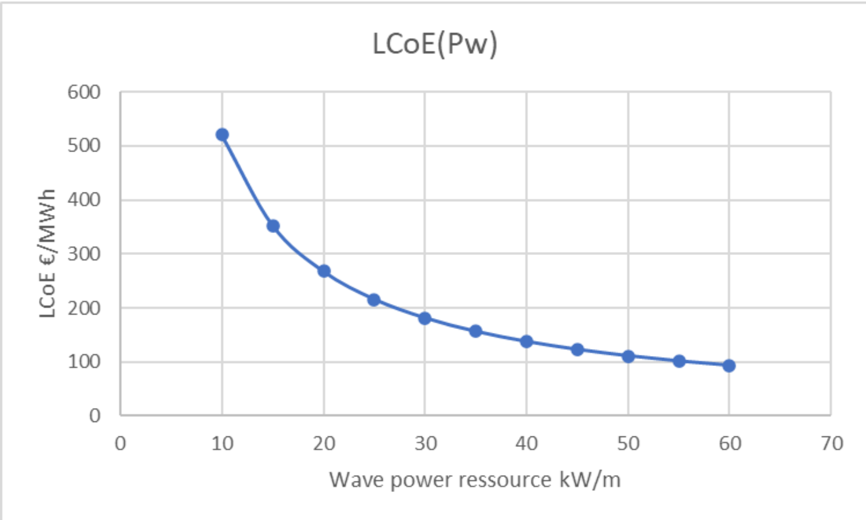


Figure 7.1 Estimated LCOE variation with resource from 20 kW/m to 74kW/m

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 well aligned to both 2030 JRC targets and the project targets of 120 EUR/MWh can be reached if deployed in larger volumes through learning rates. Using a learning rate of 6% the target should be reach when 1000 MW have been installed.

The authors acknowledge that there are some elements that could significantly change the economic results presented here. Further research as detailed below can help reduce the uncertainty of the LCOE calculations:

- As introduced in Del8.5, there is still a potential route to optimisation of the structure by reducing the volumes of steel and ballast concrete. The structural costs of the spar, mostly built-in steel present more than 60% of the CAPEX, (with a steel weight of 1000 ton, accounting for 3.4 MEUR). D3.4 initiated some additional optimisation modelling which indicate that a reduction from 1000ton of steel to 650 ton should be possible, compensated by increasing the expensive ballast [Louis Papillon (2023)].

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 hydrofoils of 30-meter span each are the main wave power absorption component of the WEC. Currently these are designed in glass fibre, and with a total weight of 30ton for the two, they amount to 280.00EUR. Their current design lifetime is estimated to 15 years – further research could investigate alternatives to glass fibre and alternative reinforcement materials.

- Annual Energy Production: Work Package 5 is still investigating how control strategies can increase and maintain the predicted energy absorption. These models still need to be fully validated and quantified and work is still ongoing to demonstrate the potential energy production with full control i.e. instantaneous pitch and rotational velocity control in a wider range of sea states. Future research can evaluate trade-off between improved power absorption capabilities, and increased maintenance expenditures due to more mechanical parts i.e if some control types induce structural failures?

- LCOE estimates have been drawn based on a discount rate of 5%. It has been recently recommended to use a 3.5% discount rate (Cochrane *et al.* (2021), which references (HM Treasury, 2018)), which would give a lower LCOE.

- The mooring design is at a preliminary design stage and as more information on the moorings become available, cost estimates will be updated.

- The market: The spar buoy needs deep water of 80-meter depth or more. It would be interesting to map the areas where deployment of the spar LiftWEC is possible and areas where potential benefits of sharing spaces with floating wind is possible, such as sharing the grid infrastructure, marine space and O&M infrastructure – as well as the very positive complementarity of wave power to wind power.

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.

8 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.
Chitale *et al*, (2022)	Chitale, K., Fagley, C., Mohtat, A., & Siegel, S. (2022). Numerical Evaluation of Climate Scatter Performance of a Cycloidal Wave Energy Conv(2023) erter. International Marine Energy Journal, 5(3), 315–326. https://doi.org/10.36688/imej.5.315-326
A. Ermakov, F. Thiebaut, G.S. Payne et al., (2023)	A. Ermakov, F. Thiebaut, G.S. Payne et al., "Validation of a control-oriented point vortex model for a cyclorotor-based wave energy device". Journal of Fluids and Structures (2023) 103875, https://doi.org/10.1016/j.jfluidstructs.2023.103875.
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/
McAuliffe (2023)	F. D. McAuliffe (2023), "Deliverable 7.5 - Assessment of Final Configurations". The LiftWEC Project. Development of a new class of wave energy converter based on hydrodynamic lift forces
Nielsen, Fernandez Chozas, Pascal and Ferri (2023)	K. Nielsen, J. Fernandez Chozas, R. Pascal and F. Ferri (2023), "Deliverable 8.5 - LCOE Optimised device parameters". The LiftWEC Project. Development of a new class of wave energy converter based on hydrodynamic lift forces.
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.

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.

	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/
Louis Papillon and Mateo Pimoult, (2023)	Louis Papillon and Mateo Pimoult, "D3.4 Implementation of Coupled Hydrodynamic Model"

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.