



## Open Sea Operating Experience to Reduce Wave Energy Costs

### **Deliverable D7.3**

Tracking metrics for wave energy technology performance  
(Global LCOE, LCA and SCOE analysis of OPERA wave energy technology)

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## EXECUTIVE SUMMARY

This OPERA project deliverable shows the results of the global economic model developed for the economic analysis of an array of point absorbers with Oscillating Water Columns (OWCs) Power Take-Off (PTO). The global economic model calculates Levelised Cost of Energy (LCOE), Socio-economic Cost of Energy (SCOE) and performs a Life-Cycle Assessment (LCA) as metrics.

Within the OPERA project, the global economic model is used to evaluate the economics of an array of “Bench Case” floating OWCs. These Bench Case devices comprise a spar buoy WEC, a Wells turbine, a conventional control methodology and mooring system. The economics of the Bench Case array are then compared to the economics of an array of devices comprising the Bench Case WEC hull refitted with cost reducing innovations: elastomeric mooring tethers, a bi-radial air turbine, innovative control strategies and a shared WEC mooring arrangement. Economic, life-cycle and social impact metrics and the 4 main project innovations are evaluated.

The global economic model showed a LCOE reduction of 56% when transitioning from the Bench Case WEC to the WEC with Innovations, showing that competitive LCOE values could be achieved in both deployment locations for the array scenarios. LCA results show that OPERA device saves between 374-981 g CO<sub>2</sub> compared to the same power from coal, heavy oil and gas, which means that OPERA WEC has potential to reduce emissions and assist with decarbonized targets. SCOE study showed insights of the potential benefits of an OPERA 18 MW array in terms the added benefits of investing in a marine renewable energy project to policy makers and potential funders. Results estimated a GVA £92M and around 1,309 job years supported.

Note, OPERA D7.3 was finalised whilst the Idom-Oceantec WEC was still operating, therefore OPERA D7.5 will update the global economic assessment in light of the final learnings of OPERA’s operational phase. D7.5 will also show the future cost reduction opportunities, an evaluation of the impact of reliability improvements of various components on OPEX.

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## ABBREVIATIONS AND ACRONYMS

AEP	Annual Energy Production
BiMEP	Biscay Marine Energy Platform
CAPEX	Capital Expenditure
EIA	Environmental Impact Assessment
CfD	Contract for Difference
COE	Cost of Energy
GVA	Gross Value Added
CW	Capture Width
CWR	Capture Width Ratio
EPBT	Energy Payback Time
ERA	Environmental Risk Assessment
EROI	Energy Return of Investment
GVA	Gross Value Added
GWP	Global Warming Potential
IxI	Industry by Industry
IC	Initial Costs
IO	Input-Output
IRR	Internal Rate of Return
LCA	Life-Cycle Analysis
LCOE	Levelised Cost of Energy
NPV	Net Present Value
O&M	Operation and Maintenance
OPEX	Operational Expenditure
OWC	Oscillating Water Column
PTO	Power Take-Off
RET	Renewable-energy and Energy-efficient Technologies
SCF	Ship Capacity Factor waiting at wave farm
SCOE	Socio-economic Cost of Energy/Social Cost of Energy
SD	Single Device
SEA	Strategic Environmental Assessment
STD	Standard Deviation
WEC	Wave Energy Converter
WWWT	Weather Window Waiting Time

## 1. INTRODUCTION

This document represents Deliverable 7.3 (D7.3) of OPERA's Work Package 7 (WP7).

OPERA is a European Commission funded project that ultimately aims to reduce the time to market of wave energy. Wave energy is an underutilised, clean and sustainable renewable energy source that has the potential to contribute to meeting Europe's electricity demand and create significant job opportunities [1].

OPERA is tackling the challenge of uncertainty in Wave Energy Converter (WEC) projects and achieving its aims through the following objectives:

- ▶ Gather, analyse and share data obtained during the development, operation and decommissioning of a real-world floating Oscillating Water Column (OWC) WEC deployed at the BiMEP test site in the north of Spain to better inform cost and energy yield estimates and,
- ▶ Undertake a technology de-risking case study; the floating OWC WEC on which four cost-reducing innovations are tested, namely elastomeric mooring tethers, a bi-radial air turbine, innovative control strategies and a shared WEC mooring arrangement.

### 1.1 WP7 OBJECTIVES

OPERA's WP7 "Risk management, cost of energy and final assessment" gathers information from all other OPERA WPs to analyse the influence of their respective innovations on project economics and risk. At its completion, WP7 will have gained knowledge from technology developers (Idom, University of Exeter and Kymaner) and sea-trial data, resulting in guidance and recommendations for future WEC project economic analysis and risk assessments.

### 1.2 DELIVERABLE OBJECTIVES

When assessing the potential benefits of marine energy systems, studies evaluate the performance of the energy trilemma perspective, which comprehends economics, security of supply and environmental impacts. To date, a multiplicity of studies has covered the economic side, by determining the viability of ocean energy projects. However, in the offshore renewable energy sector, the socio-economic side of the analysis is often left aside and remains as a separate area of research. Extensive work is also available on supply security, through the characterisation of resource, dispatchability and network operation. Nevertheless, whilst the environmental benefits of ocean energy are known qualitatively, there is scarcity in quantitative evidence such as carbon footprint, to support decision makers.

The *Global Economic Model* has been assembled within OPERA WP7. Three economic calculations are executed within the model: Levelised Cost of Energy (LCOE), Life-Cycle



Assessment (LCA) and Socio-economic Cost of Energy (SCOE). Since the model contains these three calculations, the deliverable refers to the model as the *Global Economic Model*. Each of the three calculations use common inputs and are interdependent. In addition to yield and Capital Expenditure (CAPEX) inputs, parametrically related to WEC rated power, the global economic model's calculations are informed by a new Operational Expenditure (OPEX) model.

The OPEX model was developed through work undertaken in the OPERA project's WP6 and is informed by data obtained during the operational phases of OPERA and logged in an Operation and Maintenance (O&M) framework spreadsheet. The OPEX model, and inclusion of operating data, satisfies one of the key objectives of the OPERA project - to reduce the uncertainty associated with WEC OPEX estimation. In addition to estimating OPEX values, the OPEX model also has the flexibility to produce outputs indicating the environmental impact of probable O&M activities and their influence on WEC/array availability.

This deliverable has the objective of:

- ▶ Calculating the LCOE reduction from the *Bench Case scenario* due to the *innovations tested at-sea* during OPERA.
- ▶ Identifying future cost reduction opportunities from the *open-sea experience* including component improvements that could be expected from subsequent R&D.
- ▶ Estimating the socio-economic and environmental impacts of wave energy in different scenarios of future energy mix through SCOE and LCA evaluations.

## 1.3 DESCRIPTION OF WORK AND ROLE OF EACH PARTNER

The work on this deliverable was led by the University of Edinburgh, assistance was provided by Tecnalia. Both of these OPERA partners prepared technical notes reviewing available techno-economic models and a technical note describing the global economic model. Additional OPERA partners (Kymaner, Idom-Oceantec and the University of Exeter) provided inputs for the latter technical note and the global economic model.

The University of Edinburgh combined the contributions of all the partners and drafted deliverable D7.3. The OPEX model development was undertaken by Tecnalia, while the integration of the OPEX model within the techno-economic model was led by the University of Edinburgh.

## 1.4 CONTENT

The contents of the present report are as follows:

**Section 2** describes the Global Economic Model main inputs and the three scenario groups considered.



**Section 3** describes the LCOE modelling and **section 4** describes the LCOE model results and discussion. The study evaluates LCOE for two different locations, different array sizes and different technology stages. Furthermore, comparisons with global sector figures are also provided, in terms of CAPEX, OPEX, and LCOE. A sensitivity analysis identifies the most influential variables in LCOE.

**Section 5** focuses on the LCA of the representative Idom-Oceantec device. The LCA study identifies and quantifies the materials, components and life cycle stages that contribute to energy input and carbon emissions of the array over its full lifetime and provides comparisons with alternative electricity generation technologies (both renewables and non-renewables).

**Section 6** completes the holistic study by presenting the SCOE evaluation, which complements LCOE and provides insights of the potential benefits in terms of job years support and gross value added.

Finally, global conclusions on the overall study are outlined in **section 7**.

## 2. GLOBAL ECONOMIC MODEL

This report analyses the performance of the Idom-Oceantec OWC from three perspectives: economic, social and environmental. It is important to highlight the connections among the aforementioned three different visions as shown in Figure 1.

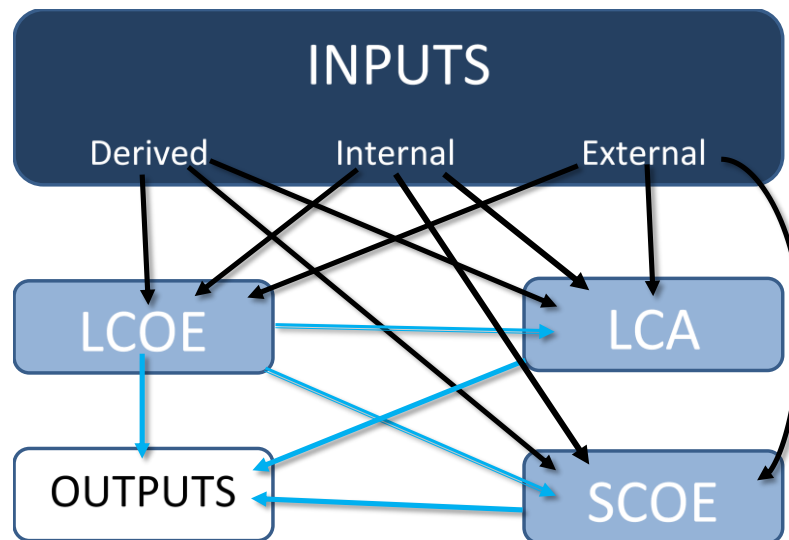


FIGURE 1: CONNECTIVITY BETWEEN INPUTS/OUTPUTS, LCOE, SCOE AND LCA CALCULATIONS.

### 2.1 SCENARIOS

This section details the scenarios investigated in this study. There are three elements to each of the scenario: technology stage, location and the number of devices deployed.

To evaluate the improvements on LCOE from the four innovations developed through the OPERA project over the Bench Case, two cases were analysed.

- Bench Case
- With Innovation

The two deployment locations selected for analysis are:

- BiMEP
- EMEC

The demonstration and validation activities in OPERA will generate valuable information to assess the economic, life-cycle and social impact of the innovations and associated activities. However, basing an assessment of these impacts on the single prototype device tested during the OPERA project alone doesn't present a true picture of the impacts of a developed industry. Instead, a number of realistic deployment scenarios need to be defined. Three different array scenarios were analysed.

- Single device of 250 kW
- Array 1 of 10 MW (40 devices - 250 kW each)
- Array 2 of 18 MW (72 devices - 250 kW each)

The case studies evaluated in the LCOE, SCOE and LCA analyses are summarised in Figure 2.

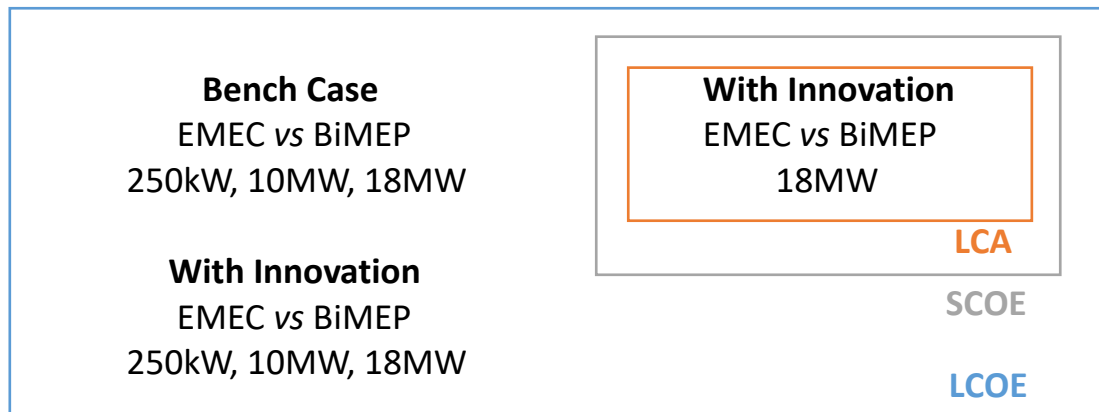


FIGURE 2: CASE STUDIES CONSIDERED IN THE LCOE, SCOE AND LCA ANALYSIS.

The following sections show the differences between each scenario group.

### 2.1.1 TECHNOLOGY STAGE

As discussed, the OPERA project covers the development of four cost-reducing innovations. The innovations are outlined in the Table 1 along with their expected impacts on cost.

TABLE 1: TECHNOLOGY INNOVATION AND PREDICTION ON ECONOMIC RESULTS

Innovation	Target	Impact on cost component
Biradial air turbine	50% higher annual mean efficiency compared to Wells turbine	To be assessed in project
Predictive & latching Control	30% increase in energy production	Minor
Elastomeric tether	Reduce extreme loads by 70%	70% reduction of mooring cost based on linear cost to breaking assumption - structural survivability enhanced.
Shared mooring	50% reduction in overall mooring costs in arrays	50% reduction

When considering different technologies, the following parameters are modified on the model: turbine cost, mooring cost (due to configuration and material) and AEP (due to turbine

efficiency and control system). Therefore, different economic results are produced when comparing the scenarios with and without the innovations.

The Bench Case scenario did not contain the innovations; the following was considered for this case:

- **Wells turbine:** the cost of wells turbine was provided by IST/Kymaner and its efficiency was considered in the AEP calculation.
- **Standard moorings:** mooring line costs were provided by University of Exeter. Further to this, the model considers WECS to be clustered with shared moorings. This is detailed further in Table 8. For the Bench Case scenario, the cost of a standard mooring was considered as the cost of the cluster arrangement 1 configuration, which considers one device per cluster. The cost provided was for an elastomeric material, which was assumed to be similar as the cost of non-elastomeric one.
- **Control algorithms:** for this scenario no control algorithm was considered, which resulted in lower AEP values.

The following was considered in the With Innovation scenario:

- **Bi-radial Turbine:** the cost and efficiency of the bi-radial turbine was included in this scenario. Costs were provided by Kymaner and the improved efficiency was considered in the AEP calculation.
- **Elastomeric mooring tethers:** the shared moorings cost was provided by the University of Exeter and included in the model. It is worth noting that University of Exeter indicated that the CAPEX of the elastomeric mooring line would be similar to that of the standard mooring line but that cost reduction due to the innovation would instead be observed in OPEX.
- **Control algorithms:** advanced control laws were considered in this scenario and considered in the calculation of AEP.

### 2.1.2 DEPLOYMENT LOCATION

When considering different sites, the following parameters are modified within the global economic model: distance to connection point; distance to port; distance to shore; and environmental data (occurrence matrix).

These modifications influence directly: electrical infrastructure costs; Annual Energy Production (AEP) values; Weather Window Waiting Time (WWWT, used to feed the OPEX model); O&M costs, availability and fuel consumption; installation costs and fuel consumption; decommissioning costs and fuel consumption. Therefore, different economic outputs are produced when deploying in different sites.



## BiMEP (BASQUE COUNTRY)

The first site selected is located at the BiMEP test site in the Basque Country. The average wave energy flux of this location is 24.2 kW/m. Table 2 shows its occurrence matrix.

**TABLE 2: BIMEP OCCURRENCE MATRIX**

		T <sub>g</sub> (s)																							
		0.5	1.5	2.5	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	17.5	18.5	19.5	20.5	21.5	22.5	23.5
H <sub>max</sub> (m)	0.25	0	0	0	17	93	212	220	107	18	5	2	1	2	0	0	0	0	0	11	11	13	10	6	5
	0.75	0	0	0	18	434	1055	1031	1131	717	536	430	98	29	21	4	0	0	0	0	0	0	0	0	0
	1.25	0	0	0	0	68	469	815	1015	857	636	476	353	156	40	17	0	0	0	0	0	0	0	0	0
	1.75	0	0	0	0	0	111	342	245	554	648	547	342	254	66	12	0	0	0	0	0	0	0	0	0
	2.25	0	0	0	0	0	32	171	130	296	331	479	373	215	138	13	2	0	0	0	0	0	0	0	0
	2.75	0	0	0	0	0	0	32	123	180	150	177	123	149	83	15	0	0	0	0	0	0	0	0	0
	3.25	0	0	0	0	0	0	9	77	166	118	166	103	121	135	45	2	0	0	0	0	0	0	0	0
	3.75	0	0	0	0	0	0	0	6	75	53	87	97	57	50	25	0	0	0	0	0	0	0	0	0
	4.25	0	0	0	0	0	0	0	1	14	36	39	74	48	2	1	2	0	0	0	0	0	0	0	0
	4.75	0	0	0	0	0	0	0	0	11	26	12	20	27	1	0	0	0	0	0	0	0	0	0	0
	5.25	0	0	0	0	0	0	0	0	2	15	22	20	4	0	0	0	0	0	0	0	0	0	0	0
	5.75	0	0	0	0	0	0	0	0	0	6	16	11	0	0	0	0	0	0	0	0	0	0	0	0
	6.25	0	0	0	0	0	0	0	0	0	0	8	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	2	3	0	0	0	0	0	0	0	0	0	0	0

The occurrence matrix refers to field-measured data for a 10 months period (from December 2016 until September 2017).

Table 3 presents the general parameters of the testing area.

**TABLE 3: GENERAL DATA OF BIMEP**

Parameter	Data	Unit
Distance to p <sub>cc</sub>	5.5	km
Distance to harbour	15	km
Distance to shore	4.5	km
Water depth	85	m
Type of seabed	sand	-

The data presented on Table 3 is input to the electrical infrastructure cost calculation and also impact the overall OPEX model outputs. In addition to Table 3, the WWWT information is integrated into the OPEX model to account with BiMEP environmental data. Figure 3 shows the location of the BiMEP test area relative to Bilbao harbour, the location of a proposed array of WECs and the site's bathymetric profile.

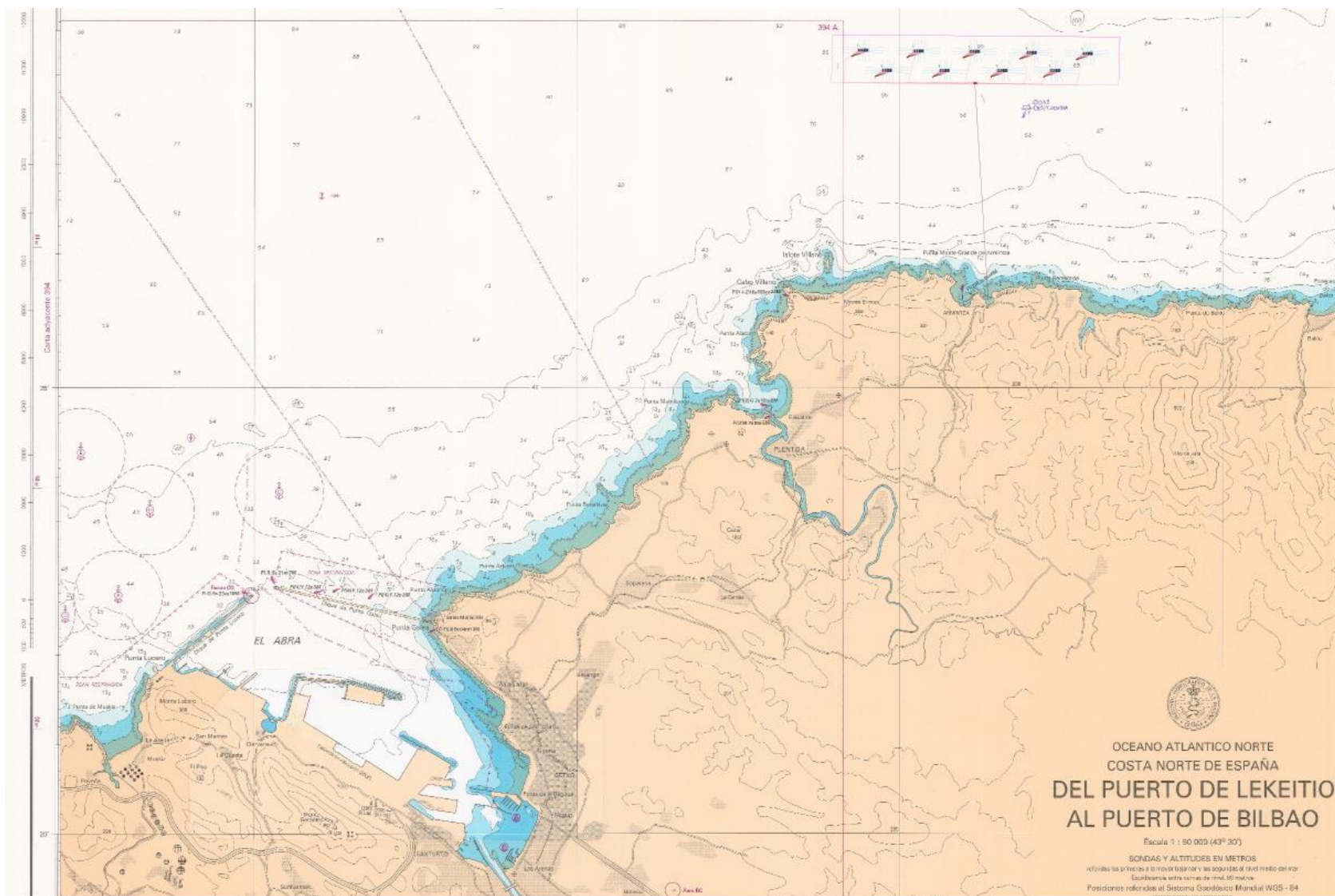
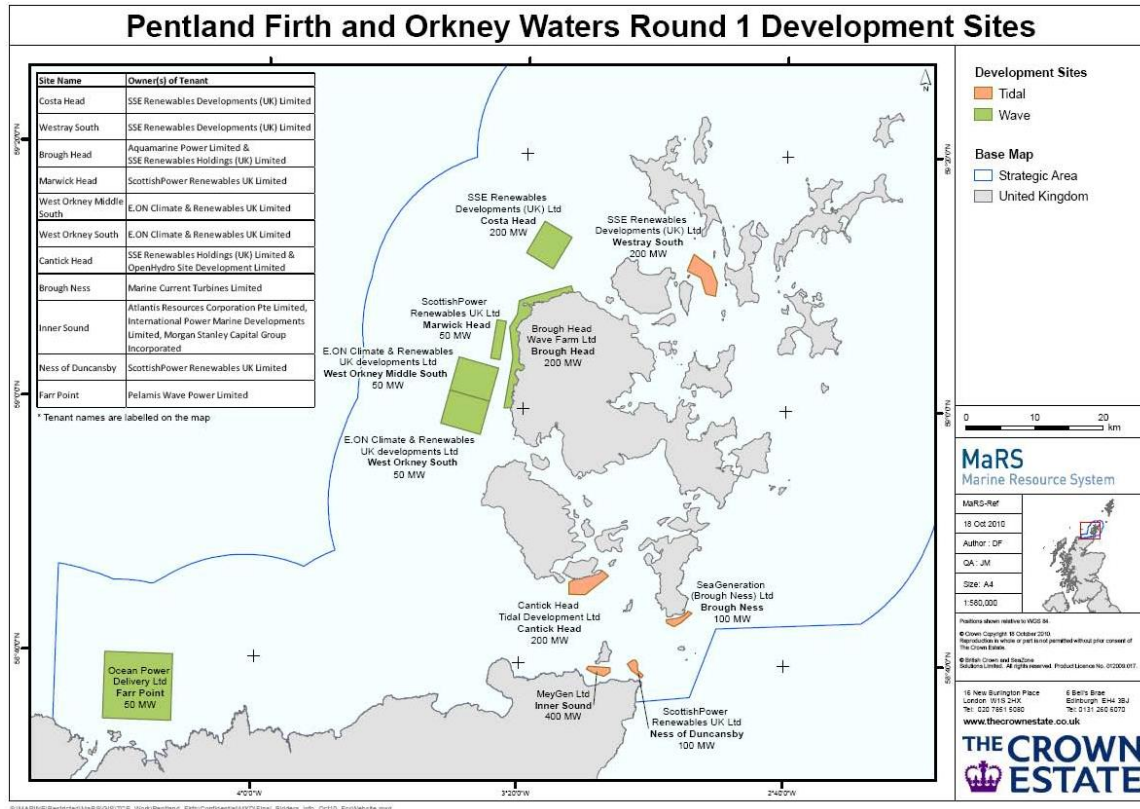


FIGURE 3: BATHYMETRY OF BIMEP, ARRAY LOCATION AND BILBAO HARBOUR

## EMEC (WEST ORKNEY)

The second site selected is EMEC. Figure 4 is a map of EMEC's consented test areas. Figure 5 presents a proposed array deployment location along with a heat map of the wave energy resource.



**FIGURE 4: PENTLAND FIRTH AND ORKNEY WATERS ROUND 1 DEVELOPMENT SITES [2]**

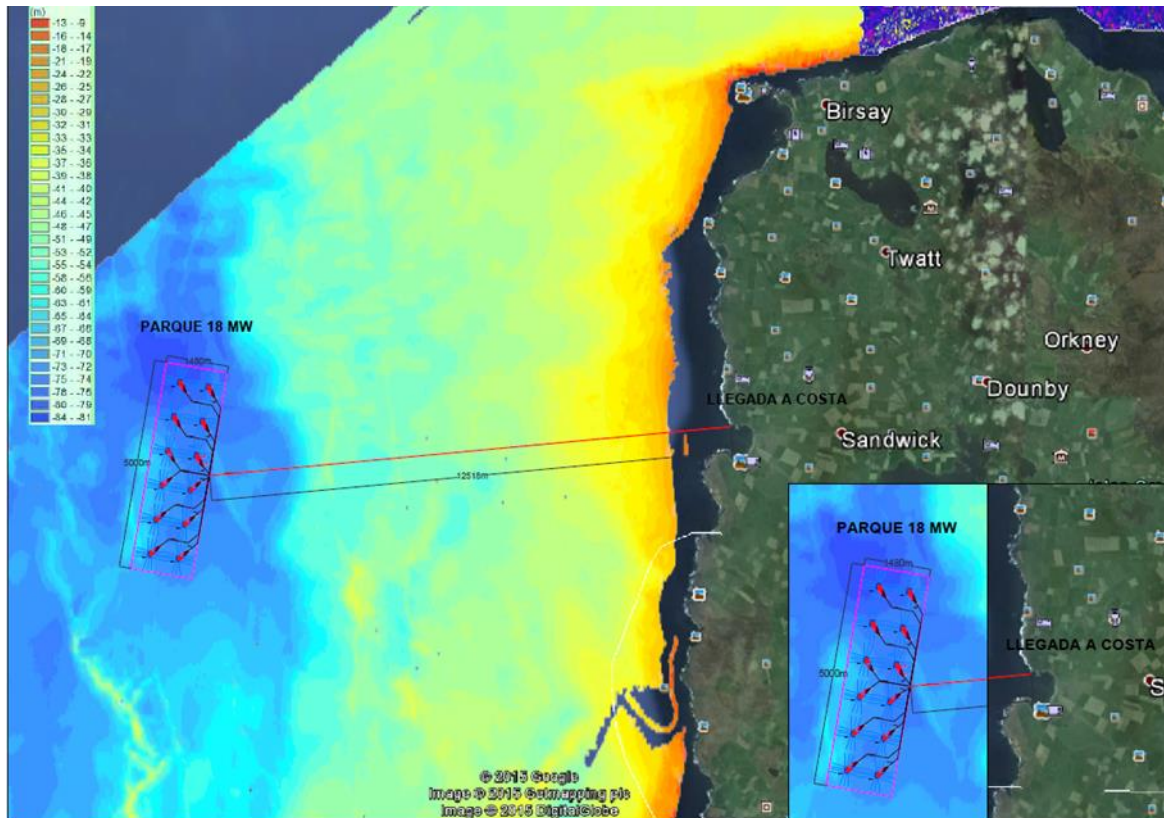


FIGURE 5: WAVE ARRAY AREA FOR 18MW IDOM-OCEANTEC WEC

The EMEC location selected for the study has 39.3 kW/m and the occurrence matrix is represented in Table 4.

TABLE 4: OCCURENCE MATRIX EMEC

		Tp (s)																																	
		1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0		
Hs (m)	0	0	2	0	0	0	0	0	5	6	7	5	7	13	2	5	17	14	10	11	6	5	6	2	2	2	0	0	0	0	0	0	0	0	0
	0.5	0	2	13	46	13	19	10	22	28	60	113	309	430	478	706	632	706	834	367	742	247	318	208	100	191	41	77	52	13	43	70	0	0	
	1.0	0	0	0	0	4	17	39	85	141	142	167	251	386	566	1114	1302	1629	1991	1162	2221	900	1380	1013	491	1027	263	313	245	68	235	191	0	0	
	1.5	0	0	0	0	0	0	13	66	140	181	171	245	185	200	489	518	1045	1647	1301	2456	1035	1904	1119	832	1817	438	461	319	95	437	224	0	0	
	2.0	0	0	0	0	0	0	1	0	29	97	278	308	200	270	251	214	390	724	541	1641	958	1405	1080	750	2212	730	584	335	120	507	103	0	0	
	2.5	0	0	0	0	0	0	0	0	4	12	91	225	135	207	241	153	255	273	259	784	535	908	783	611	2105	691	376	180	74	376	68	0	0	
	3.0	0	0	0	0	0	0	0	0	0	0	15	81	112	205	220	179	129	196	142	336	230	460	489	426	1764	796	339	145	78	473	26	0	0	
	3.5	0	0	0	0	0	0	0	0	0	0	0	7	35	116	212	169	161	126	89	181	128	214	238	240	1360	633	265	85	51	371	20	0	0	
	4.0	0	0	0	0	0	0	0	0	0	0	0	1	4	16	135	142	212	93	64	142	87	165	143	122	936	517	162	47	18	239	7	0	0	
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	27	56	126	93	67	144	50	92	92	79	810	454	95	27	18	178	4	0	0
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	11	80	62	50	84	54	73	62	55	532	316	86	26	7	107	1	0	0	
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	32	45	43	61	41	68	39	42	392	237	80	7	2	64	2	0	0	
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	12	19	47	44	28	18	28	379	204	55	5	9	57	2	0	0	
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	11	25	28	19	25	22	250	140	23	6	4	28	1	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	4	9	17	15	8	223	126	25	5	2	9	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	8	10	7	132	92	16	1	3	7	0	0	0
8.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1	3	4	90	74	11	1	2	4	0	0	0	
8.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	84	54	14	3	0	7	0	0	0		
9.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	35	46	5	0	0	7	1	0	0		
9.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	41	9	1	0	2	2	0	0	
10.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	22	19	0	0	0	3	0	0	0	
10.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	19	10	0	1	1	0	0	0		
11.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	16	3	0	0	0	0	0	0	0	
11.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	7	0	0	0	0	0	0	0	
12.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	4	0	0	0	0	0	0	0	
12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	3	0	0	0	0	0	0	0	0	
13.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	5	0	0	0	0	0	0	0	0	
13.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
14.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The occurrence matrix refers to modelled data for a 10 years period (from 2001 until 2010). Table 5 lists the parameters that feed into the global economic model's logistics calculations



**TABLE 5: GENERAL DATA OF EMEC**

Parameter	Data	Unit
Distance to p <sub>cc</sub>	1	km
Distance to harbour	10	km
Distance to shore	2.5	km
Water depth	85	m
Type of seabed	Sand and clay	-

The data presented on Table 5 is used for the electrical infrastructure cost calculation and is input to the OPEX model. In addition, WWWT information is integrated in the OPEX model along with environmental data of the EMEC site.

### 2.1.3 ARRAY SIZE

As previously presented, the following array scenarios were analysed:

- Single device (SD): single device of 250kW, as of today
- Array 1 (A1): installed capacity of 10MW
- Array 2 (A2): installed capacity of 18MW

It has been assumed that the industry-wide installed capacity prior to the development of each of the array scenarios is 5MW (for SD), 100 MW (before A1) and 1000 MW/1 GW (before A2). The prior installed capacity impacts on the cost reductions due to learning. In terms of inter-array interaction, no interference between devices for the array scenarios was assumed for simplicity.

#### Economies of volume and learning

The LCOE of a single WEC is too great to be commercially competitive. However, when costs are considered for future and larger WEC arrays LCOE decreases. This reduction is accounted for in the model using learning rates. Figure 6 illustrates an example of learning trends for the ocean energy sector.

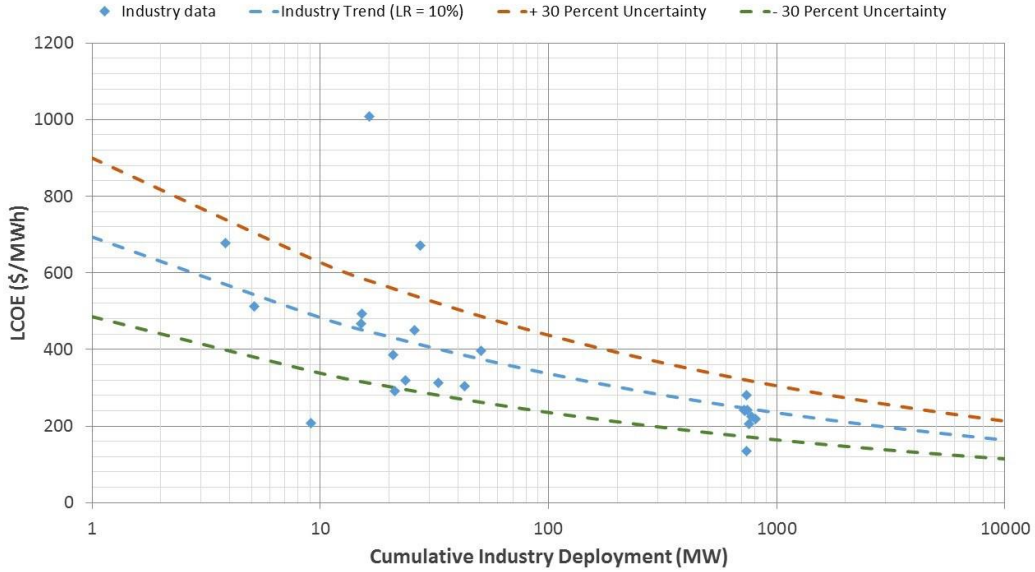


FIGURE 6: POSSIBLE LEARNING TRENDS FOR THE OCEAN ENERGY [3].

Cost data, such as WEC structure and turbine CAPEX, was supplied for the specific case of a single device. To enable the project scenarios of future large array deployments to be assessed, these costs must be rolled forward under the influence of learning rates and economies of volume. The methodology for learning rates and economies of volume is outlined below.

The unitary cost for cost centre  $i$  in scenario  $X$  is computed as:

$$Cost_{i,X} = Cost_{i,SD} * BDF_X * LCF_{i,X} \quad (1)$$

where  $BDF_X$  is the bulk discount factor for scenario  $X$  and  $LCF_{i,X}$  is the learning cost reduction factor for cost centre  $i$  in scenario  $X$ .  $Cost_{i,SD}$  is the cost of cost centre  $i$  for a single device.

The **Bulk Discount Factor** expresses the percentage in cost reduction owing to economies of volume and can be calculated as:

$$BDF_X = N_X^{\frac{\ln(EoV)}{\ln(2)}} \quad (2)$$

where  $N_X$  is the number of units in the purchase order (number of units in the array) and  $EoV$  is the saving rate thanks to economies of volume. The value of  $EoV$  represents the cost reduction that is obtained with every doubling of the number of units.

Considering that the wave energy sector has not reached the commercial stage yet, it must be stressed that there is significant uncertainty in establishing values for economies of volume. As a reference, in [4] a saving of 6.4 % was observed (*EoV* of 93.6 %) in purchase orders of Vestas and Gamesa wind turbines. Such a value would mean that, for instance, unitary prices of 10 and 100-unit orders would be equivalent to 84.53% and 67.83%, respectively, of the original single unit costs. In this present study, *EoV* has been set at a value of 95% (i.e. every doubling of *N*, a saving of 5 % is achieved). This is a more conservative value than that which is presented in [4], however it is deemed reasonable given the lower level of maturity and the consequent lack of experience in managing batch orders and spreading profit margins over the company's sales in the wave sector.

The **Learning Cost Reduction Factor** expresses the percentage in cost reduction owing to learning gained through research and through experience in device deployment and is obtained through equation (3).

$$LCF_{i,x} = \frac{C_X}{C_{SD}} \frac{\ln(PR)}{\ln(2)} \quad (3)$$

$C_X$  is the installed capacity prior to the deployment of that array scenario,  $C_{SD}$  is the installed capacity prior to the deployment of the single device scenario and *PR* is the progress rate; equal to 1 – learning rate (LR).

Learning rates were applied to CAPEX, OPEX, DECOMM and AEP (inverse learning, it is anticipated that AEP will increase in future generations). Learning rates were applied to each of the cost centres and are based on the values given in [5].

Table 6 shows the learning rate and *EoV* values adopted for each cost centre.

**TABLE 6: LEARNING RATES FOR DIFFERENT COST CENTRES.**

Learnings and discounts	Value	Source
LR structure	9%	[5]
LR Power Take-Off (PTO)	7%	
LR mooring	12%	
LR electrical infrastructure	1%	
LR installation	8%	
LR decommissioning	8%	
LR OPEX	12%	
LR AEP	102%	[4]
WEC Bulk discount factor (EoV)	95%	

### 3. LCOE MODELLING

A top-level description of the LCOE model and its operation was provided in OPERA deliverable (D7.2). Hence, this section will primarily focus instead on the LCOE calculation methodology, its assumptions and the corresponding results.

LCOE is calculated through equation (4) in which *CAPEX* represents the capital expenditures, *OPEX* the operational expenditures, *DECOMM* the decommissioning costs, *n* is the project lifetime, *t* is time in years and *r* is the discount rate.

$$LCOE = \frac{\sum_{t=0}^n \frac{CAPEX_t + OPEX_t + DECOMM_t}{(1+r)^t}}{\sum_{t=1}^n \frac{AEP_t}{(1+r)^t}} \quad (4)$$

The following sections describe the inputs of the internally developed LCOE model.

#### 3.1 GENERAL ANALYSIS PARAMETERS

This deliverable presents a detailed description of all the assumptions employed in the calculation of LCOE.

It is assumed that in each scenario the WEC array is designed for a 20-year life-cycle. The manufacturing, installation and decommissioning periods are designed for 2 years.

Within the economic model, the following financing inputs are set:

- Discount rate of 8%;
- Electricity sale price of £305/MWh;

These values are the centre points of a sensitivity study presented in this study to demonstrate their influence on LCOE. The electricity sale price defined above is a first guess based on the draft strike price.

Insurance is included as a function of the CAPEX (1%), every year during the design life [6].

#### 3.2 CAPEX

In this study, CAPEX considers the initial costs (WEC structure, PTO, moorings and electrical system) plus the installation costs. This section presents the initial costs whilst section 3.3 presents the installation, operational and decommissioning costs, all inputs defined on the OPEX Model.



### 3.2.1 WEC STRUCTURE

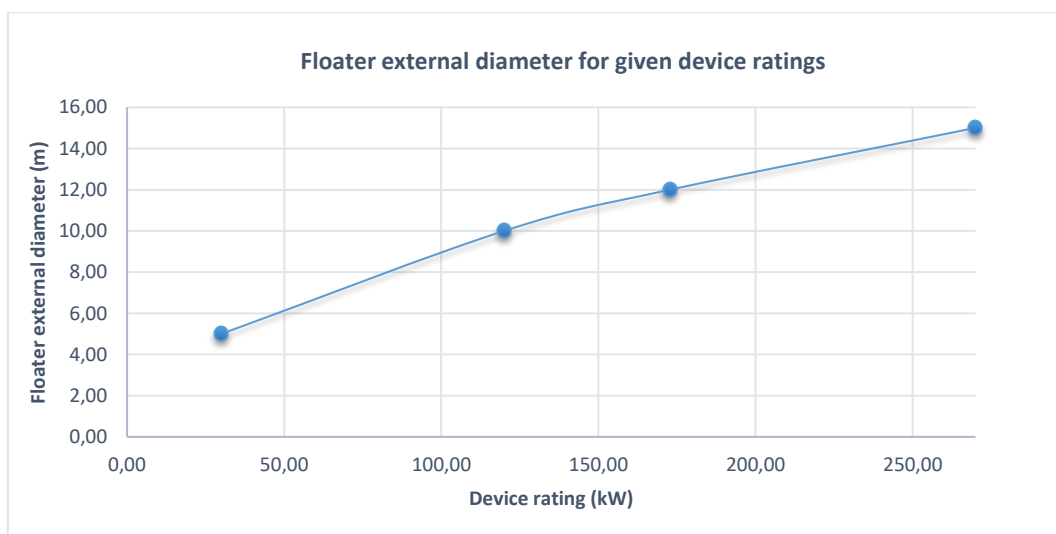
The characteristics of the WEC are set out in Table 7.

**TABLE 7: IDOM-OCEANTEC WEC PARAMETERS**

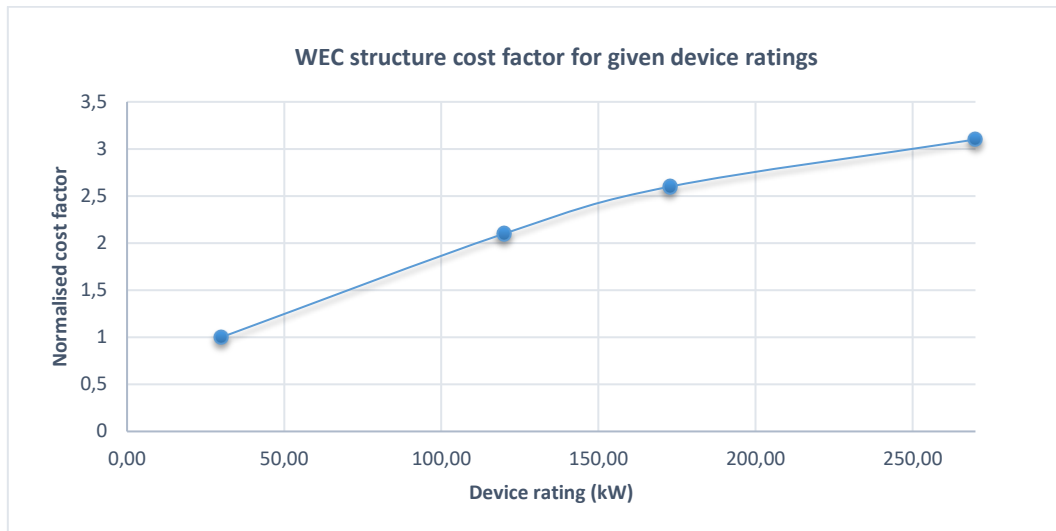
Parameter	Symbol	data	Unit
Free Surface area	A	153,93	m <sup>2</sup>
Turbine diameter	D	2	m
Nominal rated speed of electrical generator	$W_{nom}$	1500	r.p.m.
Nominal power output from the generator	$V_{nom\ gen}$	400	V
Internal nominal voltage output from back to back	$V_{red}$	670	V
Cos $\phi$ de output from WEC	Cos $\phi$	1	0-1
Nominal power	$P_{nom\ WEC}$	250	kW

The following information was provided: floater external diameter, WEC structure normalised cost, mass of steel, mass of concrete and coated area. Each of the parameters presented provided are a function of WEC rated power. The first two parameters were used for the LCOE and SCOE calculations, while the last three were used in LCA.

Figure 7 and Figure 8 show how the floater's external diameter and normalised cost factor varying with the device rating.



**FIGURE 7: FLOATER EXTERNAL DIAMETER VS DEVICE RATING**



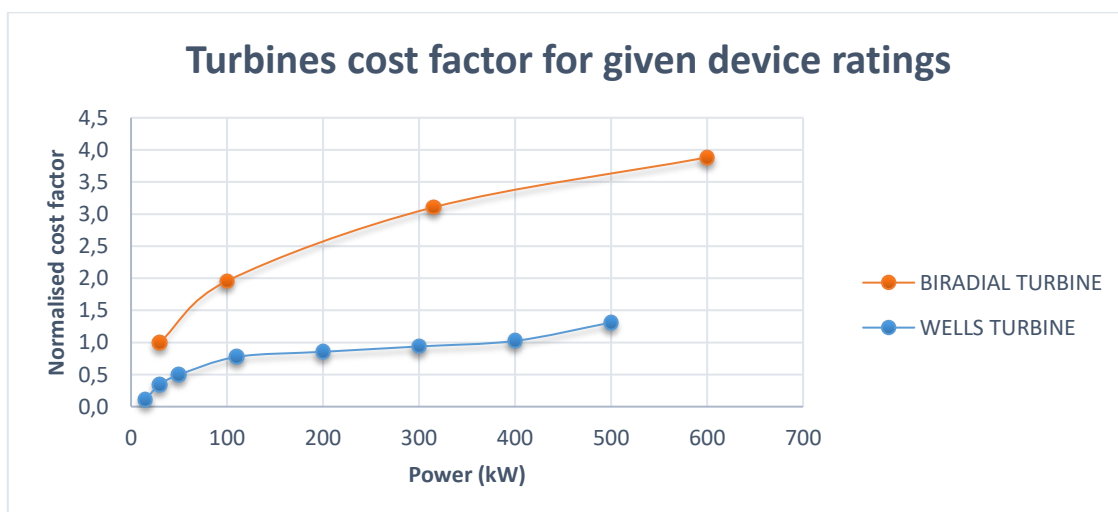
**FIGURE 8: STRUCTURE NORMALISED COST FACTOR VS DEVICE RATING**

### 3.2.2 PTO

The OWC turbines already introduced, Wells and bi-radial, are the WEC's PTOs. Both are considered in the economic assessment in different scenarios; without and with cost reducing innovations.

Information on the Wells and bi-radial turbines was also given as function of the WEC's rating. The IST/Kymaner provided the following data: diameter, cost, mass of each material, surface area and welding length.

Figure 9 show how both turbine's cost factors vary with device rating. The cost factor is normalised with 30kW bi-radial turbine cost.



**FIGURE 9: BI-RADIAL AND WELLS TURBINE NORMALISED COST FACTOR VS DEVICE RATING**

### 3.2.3 MOORING SYSTEM

A shared mooring configuration, forming clusters of devices, is utilised within an array, i.e. a cluster of multiple WECs sharing the same mooring infrastructure. Table 8 lists the various mooring system configuration options.

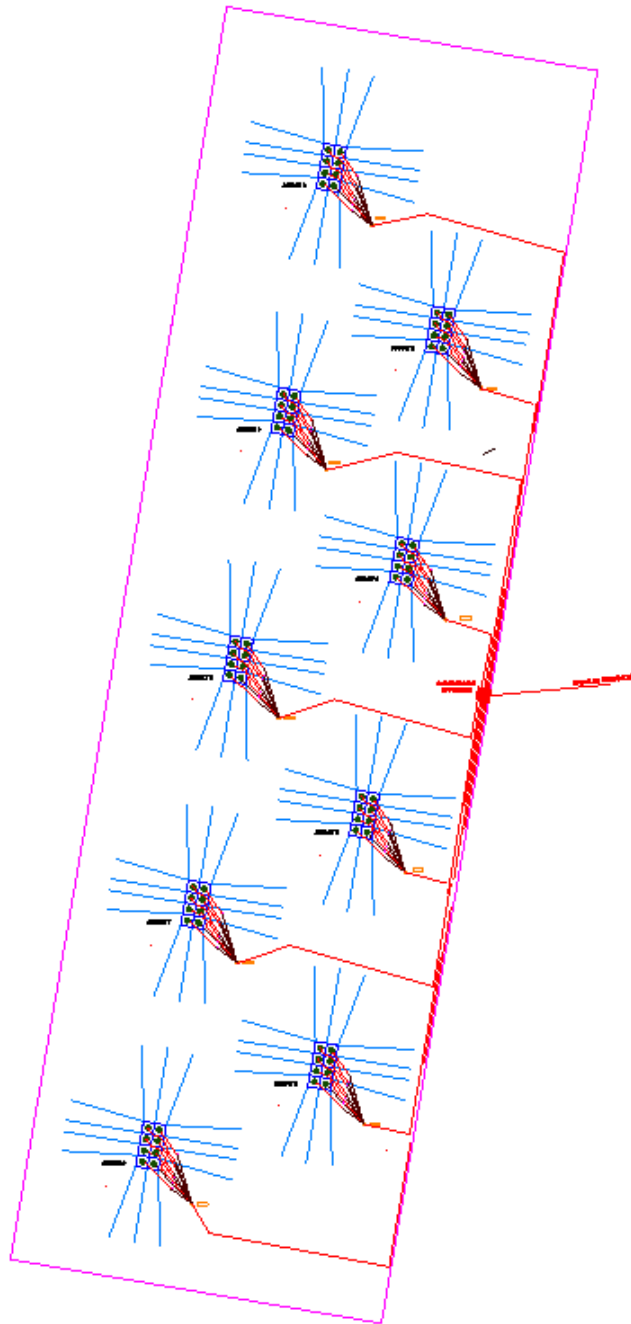
**TABLE 8: MOORING SYSTEM**

Cluster arrangement	10MW array	18MW array
1	No cluster, 40 devices with independent moorings	No cluster, 72 devices with independent moorings
1x2	20 clusters of 2 devices per cluster	36 clusters of 2 devices per cluster
2x2	10 clusters of 4 devices per cluster	18 clusters of 4 devices per cluster
4x2	5 clusters of 8 devices per cluster	9 clusters of 8 devices per cluster

Idom provided a bill of materials and cost of the mooring systems that could be calculated once the cluster arrangement was defined and a design load for the shared mooring configuration had been calculated. The latter input was dependent on the rated power of the device. Figure 10 shows the relationship between mooring cost and load factor for each of the cluster arrangements. Figure 11 shows a conceptual layout of 18MW array with a cluster arrangement of 4x2.



**FIGURE 10: MOORING NORMALISED COST PER CLUSTER VS LOAD FACTOR**



**FIGURE 11: ARRAY LAY-OUT 18MW, 9 CLUSTERS (4X2)**

### 3.2.4 ELECTRICAL SYSTEM

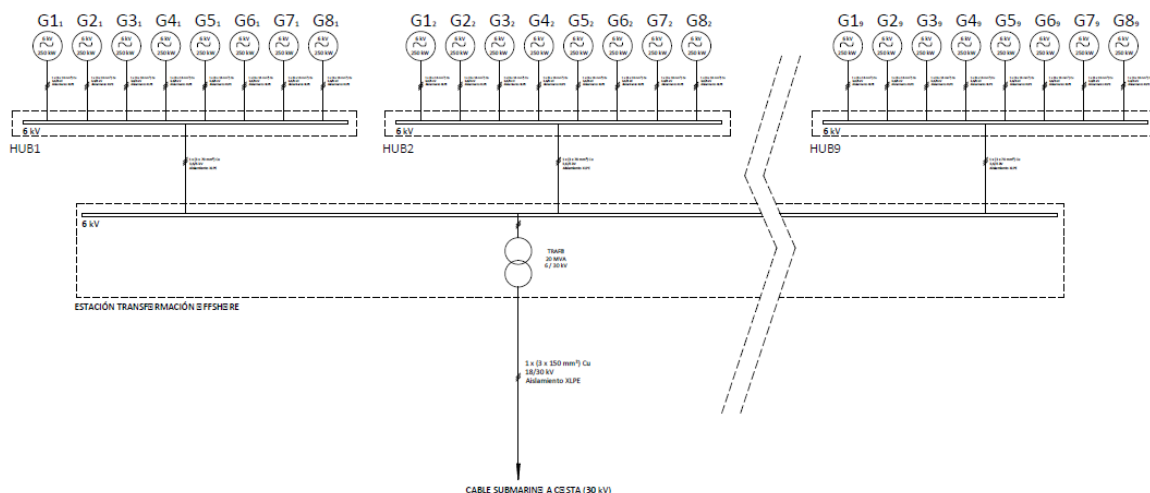
Electrical systems costs were not provided by the developers and they were already in the model. This section explains the assumptions adopted for the electrical cost calculation. The electrical system costs are incurred in the following cost centres: cables (onshore and offshore), rock coverage, offshore cable treatment and substations. Regarding electrical system, different layouts can be chosen; therefore, this study will assess different possibilities

of electrical layouts, evaluating their influence on the final cost of energy. The layouts evaluated are as follows:

- The **Case 1 (onshore substation)** electrical system comprises:
  - One offshore cable per cluster
  - One kilometer of rock coverage for each cluster
  - Offshore cable treatment
  - Onshore substation
  - One onshore cable
- The **Case 2 (offshore substation)** electrical system comprises:
  - One export cable
  - One kilometer of rock coverage for each cluster
  - Offshore cable treatment
  - Offshore substation
  - One onshore cable
- The **Case 3 (rock coverage)** considers one kilometer of rock coverage for every 8 devices.

Figure 12 shows a scheme of basic electrical lay-out consisting on two voltage transmission levels.

- Level 1: WEC/Hub to substation: 20 kV
- Level 2: Substation to connection point: 38kV



**FIGURE 12: ELECTRIC LAY-OUT, ARRAY 2**

On the economic model the electrical infrastructure costs is disregarded for a single device. The estimation of electrical infrastructure costs is dependent on the deployed location, number of clusters and array size.

### 3.3 OPEX, INSTALLATION AND DECOMMISSIONING COSTS

An operational model has been developed in WP6 (see D6.2 Operational model for offshore operation of wave energy converters), for site accessibility, analysis and optimisation of maritime methods and calculation of cost of offshore operations as an aid in decision making in the OPERA project. The operational model developed is focused on the cost of offshore operations, whereas other running costs such as insurance has been integrated in the overall cost model in WP7 of the project.

Along WP6, information from the rest of WPs has been collected on the probability of failure and the need for replacement of the equipment on board. Results have been used to feed into operational models for the OPEX calculation and O&M scheduling and will be validated against the effective failures and replacements occurring on site.

### 3.4 ENERGY GENERATION

#### 3.4.1 DEPLOYMENT LOCATIONS

AEP has been calculated through a numerical model which has been calibrated with the MARMOK-A-5 testing results at BiMEP. This model has been scaled up to the full-size device, and both EMEC and BiMEP occurrence matrixes have been reduced to a more manageable sea states number, 29 and 27 respectively. A simplified control strategy has been adopted for this study, considering an optimized constant turbine rotational speed per sea state.

#### 3.4.2 ANNUAL ENERGY PRODUCTION

Annual Energy Production (AEP) is the energy produced by a device, or array of devices, in an average year. The “ideal” annual energy production of a wave energy device deployed at a particular location can be obtained as explained above.

“Ideal” here means assuming an availability value of 100%. The “actual” AEP is then derived by multiplying the previous value by the corresponding availability figure for that site.

$$AEP = \alpha * AEP_{ideal} \quad (5)$$

The availability is calculated based on the total time out of the device(s) along the entire operational lifetime.

$$\alpha = 1 - TTO.\% \quad (6)$$

$$TTO.\% = \frac{\text{Total time out}}{\text{Operational lifetime}} \quad (7)$$

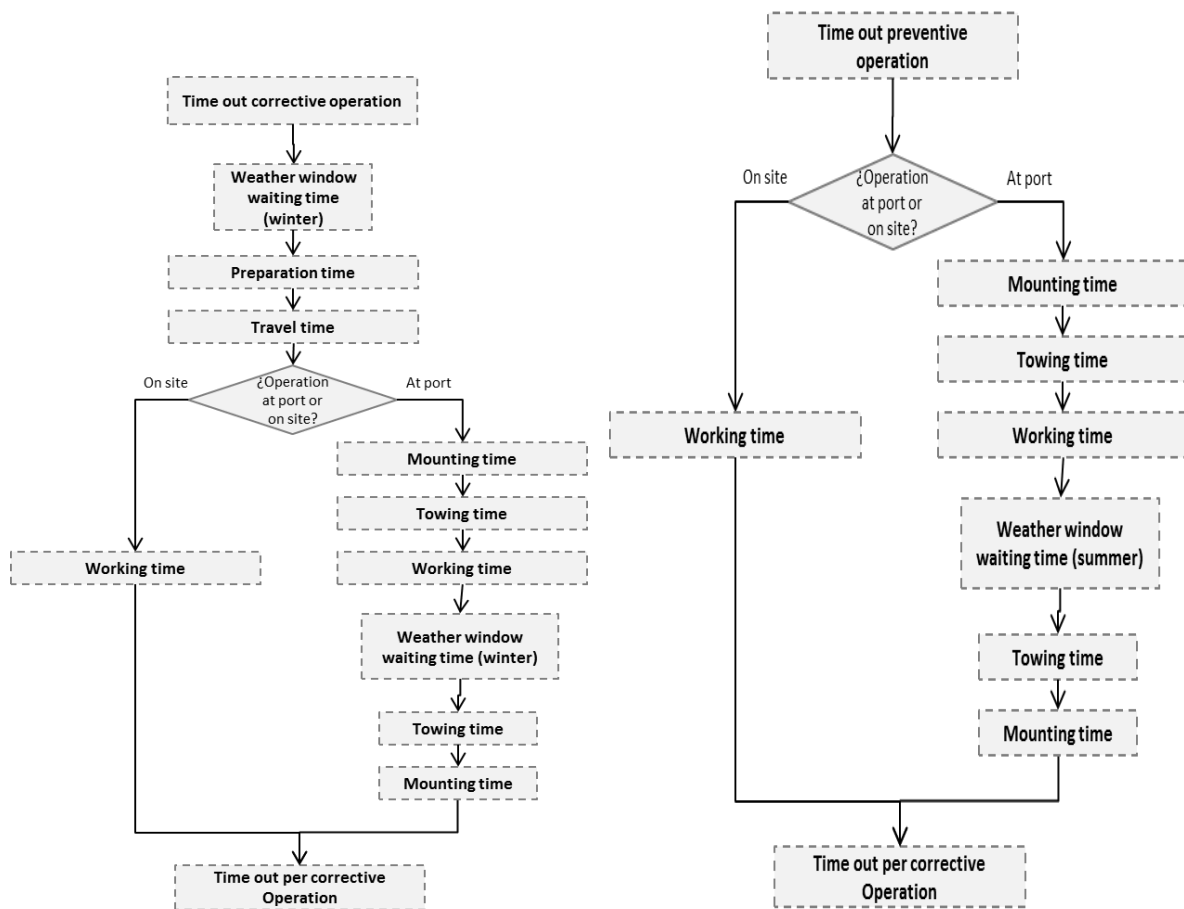
The total time out of the device has been obtained based on corrective and preventive maintenance Operation Times and Weather Window Waiting Times for corrective operation time.

$$TTO = \sum_{N=1}^N (Cm\ WWWT + OT) * Fe_{pp} \quad (8)$$

Where:

- N → Number of operations
- Cm WWWT → Corrective maintenance Weather Window Waiting Time
- Fe<sub>pp</sub> → Failure effect on the power production (0%-100%)
- OT → Operation time

Yearly revenues are obtained considering the total energy production and device availability. Figure 13 show how time out for preventive and corrective operations is obtained.



**FIGURE 13: FLOW CHART REPRESENTING THE TIME OUT ESTIMATION FOR PREVENTIVE AND CORRECTIVE OPERATIONS**

The mean annual power rating of a device is obtained by dividing the AEP value by the number of hours in a year (8766 hours/year). Finally, the capacity factor (sometimes also known as 'load factor') is defined as the amount of energy delivered over a year divided by the amount of energy that would have been generated if running at its rated power,  $P_{rated}$ , throughout all the 8766 hours of a year.

$$CF = \frac{AEP}{8766 \frac{hours}{year} * P_{rated}} \quad (9)$$

CF is usually expressed as a percentage figure.

### 3.5 COMPLEMENTARY ASSUMPTIONS

The techno-economic modelling also includes the following assumptions:

- Timeline:
  - For discounting purposes, the project activities started on year 0.



- AEP:
  - The array generated electricity from year 1 to year 21.
  - Interaction effects among devices were disregarded: i.e. the energy generation for the array equalled the sum of the individual device's generation as if they were alone.
  - AEP varied over time, with the variation of the availability as defined in the OPEX model.
  - The model considered the effect of potential learning (e.g. increased AEP over time because of improved control algorithms of modified operating conditions)
  - Degraded performance due to device aging was neglected or assumed to have a net zero effect.
- CAPEX:
  - All manufacturing costs were assumed to be incurred in year 0 and year 1.
  - All installation costs were assumed to be incurred in year 1 and year 2.
  - Given the size of the arrays, procurement, assembly and installation phases were modelled to occur over two years.
- OPEX:
  - OPEX is incurred during all generation years of the project, i.e. from year 1 to year 21.
  - OPEX costs varied throughout the whole project lifetime.
  - Although the operational period for each device was 20 years, because installation occurred over a period of 2 years, the final OPEX costs were incurred in year 21 of the project. OPEX costs were half of those for the full array in year 1 and year 21 of the project. This staggered effect is shown in Figure 14.
- Decommissioning:
  - Decommissioning costs were assumed to occur at the end of the array lifetime, i.e. in year 21 and 22.
- Discount rate:
  - Discount rate was kept constant over the project lifetime.
- Exchange rate:
  - Where applicable, prices were converted from Stirling Pounds (£) to Euros (€) at an exchange rate of 1.16 Euros to Pounds. This is reflective of the average yearly exchange rate from November 2017 to November 2018, the period during which much of the present report was written.

The project activities are shown on Figure 14.

Year	Project Activities				Devices deployed at end of year	
					Array 1	Array 2
0	Manu					
1		Ins.			20	36
2					40	72
3					40	72
4					40	72
5					40	72
6					40	72
7					40	72
8					40	72
9					40	72
10					40	72
11					40	72
12					40	72
13					40	72
14					40	72
15					40	72
16					40	72
17					40	72
18					40	72
19					40	72
20					40	72
21				Decom.	20	36
22					0	0

FIGURE 14: PROJECT ACTIVITIES

## 4. LCOE RESULTS AND DISCUSSION

This section presents the intermediate and ultimate results of the techno-economic assessment. Section 4.1 presents the availability and resulting AEP results and section 4.2 presents the CAPEX, OPEX and decommissioning values. Section 4.3 sets out the LCOE results of the study and section 4.4 presents the results of the sensitivity assessment. Finally, section 4.5 shows the results of other economic metrics.

### 4.1 ENERGY GENERATION

#### 4.1.1 AVAILABILITY

AEP has been computed by applying the procedure presented in section 3.4. As detailed in Eq. (5), an availability figure is needed for the calculation of AEP. The availability figures are calculated by the OPEX Model. Table 9 lists the availability values calculated by the OPEX model for each of the array scenarios when deployed at EMEC and BiMEP.

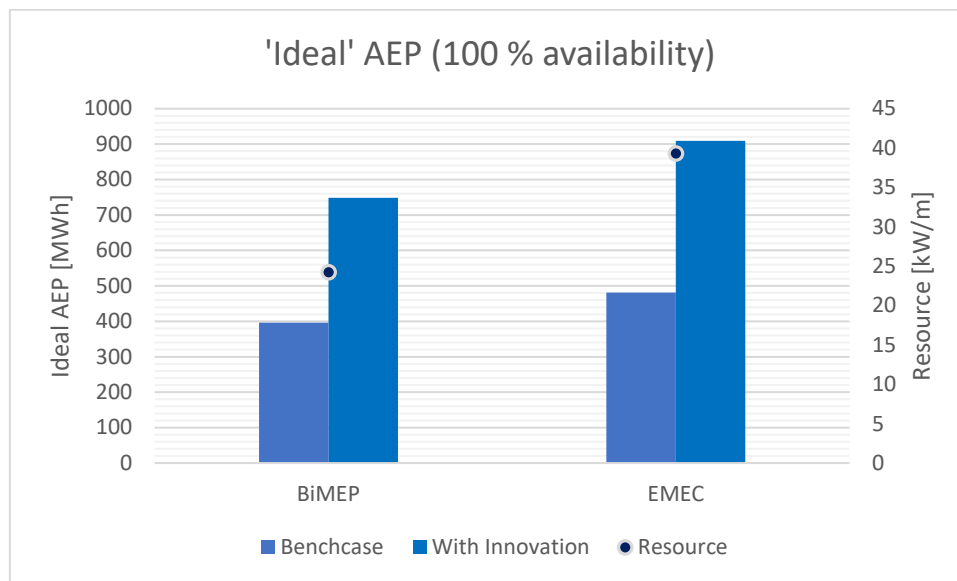
**TABLE 9: AVAILABILITY RESULTS FROM THE OPEX MODEL FOR THE OPERA SCENARIOS.**

Scenarios	EMEC	BiMEP
Single device (250 kW)	75%	88%
Array 1 (10 MW)	79%	90%
Array 2 (18 MW)	79%	90%

The results displayed in Table 9 indicate that availability at BiMEP is higher than EMEC. This is because EMEC has a greater resource, meaning higher limitations during the operational stage and consequently smaller weather windows, which results in lower availability.

#### 4.1.2 'IDEAL' ANNUAL ENERGY PRODUCTION

Figure 15 presents the ideal (i.e. assuming 100% availability) AEP,  $AEP_{ideal}$ , as defined in section 3.4.1, at both of the deployment locations. The figure indicates that AEP is greater at EMEC for both technology level scenarios.



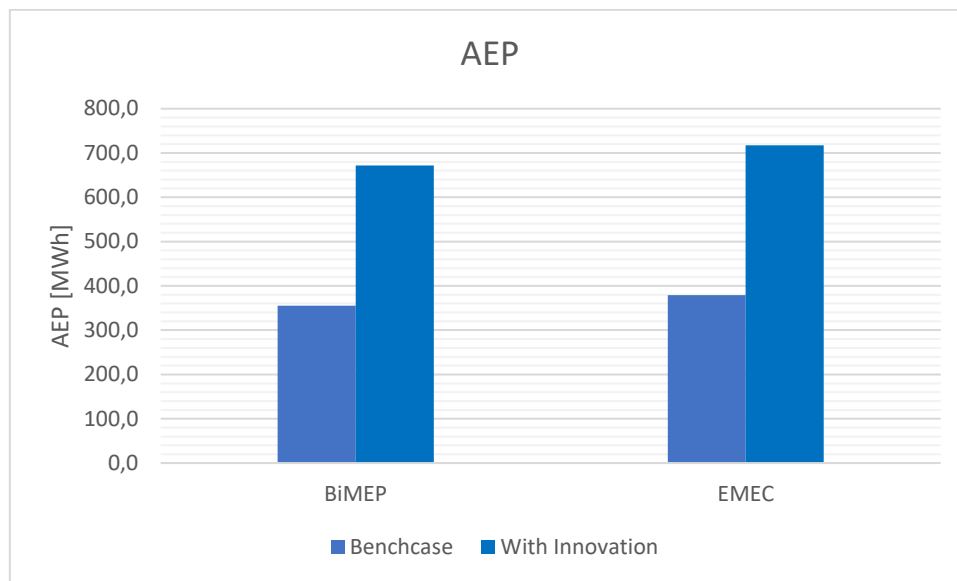
**FIGURE 15: 'IDEAL' ANNUAL ENERGY PRODUCTION (BLUE BARS - LEFT/PRIMARY AXIS) AND WAVE RESOURCE (BLUE DOTS - RIGHT/SECONDARY AXIS) AT EACH DEPLOYMENT SITE.**

In both cases, the With Innovation scenario (bi-radial turbine and the advanced control strategies) offers a better performance than the Bench Case scenario, thanks to its improved efficiency.

Despite EMEC has 62% greater resource than BiMEP (39.3 vs 24.2 kW/m), its generation is only 21% higher (748.8 vs 909.6 MWh for the With Innovation scenario). This highlights how sites with a greater resource do not necessarily mean that the WEC will yield a higher AEP. This is because Idom-Oceantec device has been optimised for BiMEP test site. For EMEC device dimensions would be different to enhance its performance. Due to the larger resource available, it would be smaller for the same power rating.

#### 4.1.3 ANNUAL ENERGY PRODUCTION

As discussed and presented in Eq. (5), the calculation of AEP for both sites is calculated by multiplying the availability figures presented in Table 9 by the ideal AEP values obtained for both sites. The AEP values calculated for the different technology levels at both deployment locations are plotted in Figure 16.



**FIGURE 16: ANNUAL ENERGY PRODUCTION AT EACH DEPLOYMENT SITE. BIMEP CONSIDERED AN AVAILABILITY OF 90% AND EMEC 79%.**

The main change from results displayed in Figure 15 to the ones in Figure 16 is a reduction in the difference between the EMEC and BiMEP AEP figures, which was initially 21%, but by including the availabilities figures reported in Table 9, the difference reduced to 6%.

#### 4.1.4 CAPACITY FACTOR

Table 10 presents the WEC's Capacity Factor (CF) figures, Bench Case and With Innovation, when deployed at both BiMEP and EMEC, derived as per Eq. (9).

**TABLE 10: CAPACITY FACTOR FIGURES CONSIDERED FOR THE OPERA SCENARIOS.**

Capacity factor	Bench case	With Innovation
BiMEP	16%	31%
EMEC	17%	33%

The CF for both sites is almost coincident, even though the 'Ideal AEP' (100% availability) is higher in EMEC. The CF of the With Innovation scenario is higher than the Bench Case, due to the differences in turbine efficiency and improved control strategies, which reflects differences in AEP. Bench case low values are derived from OPEX model in which inputs correspond to the pre-OPERA experience learnings.

The 2015 OES-IEA [7] study suggested that a CF of 30 – 35 % could be expected for second wave pre-commercial projects. The results for the OPERA 'With Innovation' scenario in the present study match the values set out within OES-IEA report and hence outline that the innovations in the OPERA design would facilitate the positioning of the technology at a pre-commercial stage.

## 4.2 EXPENDITURE

### 4.2.1 CAPEX AND DECOMMISSIONING

Table 11 and Table 12 present the CAPEX difference, calculated using the cost factors presented in section 3.2, of WEC array 2 when deployed at the two deployment locations options for both technology levels. Decommissioning totals are also presented for convenience. Costs are normalised with BiMEP and Bench Case scenarios.

Table 11 indicates that moving from BiMEP to EMEC (to a site with smaller distances to shore and higher resources) result in:

- A reduction of the electrical infrastructure costs of 21%, which is directly influenced by the distance to harbour.
- An increase in installation and decommissioning costs by 32%, which is not only influenced by the offshore distances, but also by the waiting time, as described in section 3.3. As discussed, the greater resource results in increased energy production but also increased limitations in terms of access.
- As a result of the previous points, overall, array 2 shows an absolute cost increase of 18 % in relative terms when moving from BiMEP deployment to EMEC.
- The WEC, mooring and PTO costs have been assumed to be site-independent.

**TABLE 11: PERCENTAGE DIFFERENCE IN INDIVIDUAL COST CENTRE CAPEX WHEN TRANSITIONING FROM BIMEP TO EMEC FOR A REPRESENTATIVE WITH INNOVATION SCENARIO, ARRAY 2.**

Cost centres	Difference
WEC structure	-
Mooring system	-
PTO	-
Electrical infrastructure	-21%
Installation	32%
Decommissioning	32%
<b>TOTAL DIFFERENCE:</b>	<b>18%</b>

Table 12 indicates that the OPERA innovations result in:

- A 9% reduction in mooring costs, which is influenced by the shared mooring configuration, cluster arrangement. Section 2.1.1 explains further the assumptions for this calculation. As expected and shown in Figure 10, the more devices the cluster can accommodate, the lower will be the mooring costs per WEC.

- An increase in PTO costs of 231%. Note that even though the PTO cost increase significantly from the Bench case to the With Innovation scenario, the AEP increment is also significant between cases.
- A reduction of the electrical infrastructure costs of 85%. This reduction is due to transitioning from individual cables to each device to cables shared by multiple devices. The particular arrangement of the shared cables has less of an impact on cost reduction. Section 4.3.1 shows the different electrical layouts evaluated.
- As a result of the previous points, overall, array 2 shows an absolute cost saving of 55 % in relative terms due to the four OPERA innovations.
- All the other costs centres, WEC, installation and decommissioning, do not depend on the technology level.

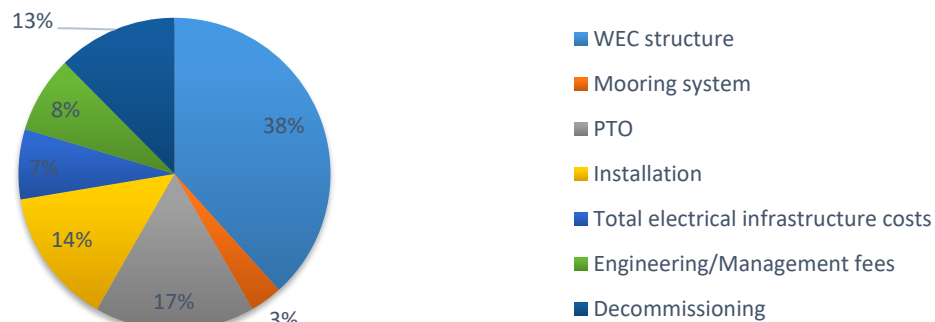
**TABLE 12: PERCENTAGE DIFFERENCE IN INDIVIDUAL COST CENTRE CAPEX WHEN TRANSITIONING FROM THE BENCH CASE WEC TO WEC WITH INNOVATIONS FOR A REPRESENTATIVE SITE EMEC, ARRAY 2.**

Cost centres	Difference
WEC structure	-
Mooring system	-9%
PTO	231%
Electrical infrastructure	-85%
Installation	-
Decommissioning	-
<b>TOTAL DIFFERENCE:</b>	<b>-55%</b>

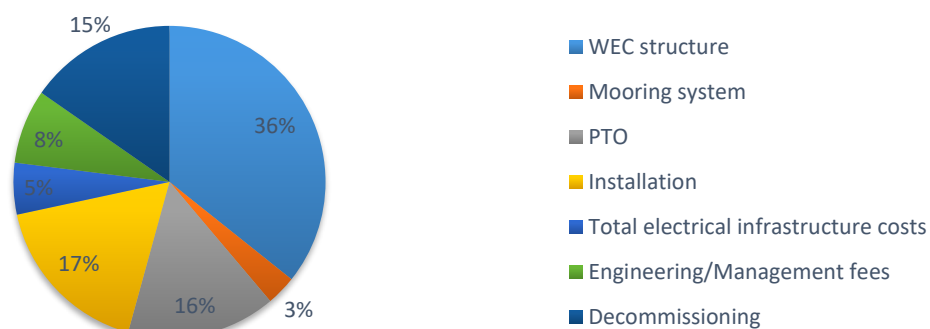
Detailed CAPEX cost breakdowns for the scenarios represented in Table 11 and Table 12 can be seen in Figure 17. For the first comparison between BiMEP and EMEC sites, an almost identical breakdown is observed, with the most significant contribution coming from the WEC structure, PTO and installation costs, which represent around two thirds of the total CAPEX costs, followed by decommissioning, electrical, fees and mooring costs. For the second comparison between Bench Case and With Innovation options, a relatively different breakdown is observed, with the most significant contribution for the Bench Case scenario coming from the electrical infrastructure and WEC structure costs, which represent around 60% of the total CAPEX costs, followed by installation, decommissioning, engineering/management fees, PTO and mooring costs.

Non-discounted values are considered here which means that when discounting these values over time the final contribution on the LCOE at today's price will be different. For example, when decommissioning costs discounted, its percentage will reduce significantly, because decommissioning is planned to happen during the last two years of the project.

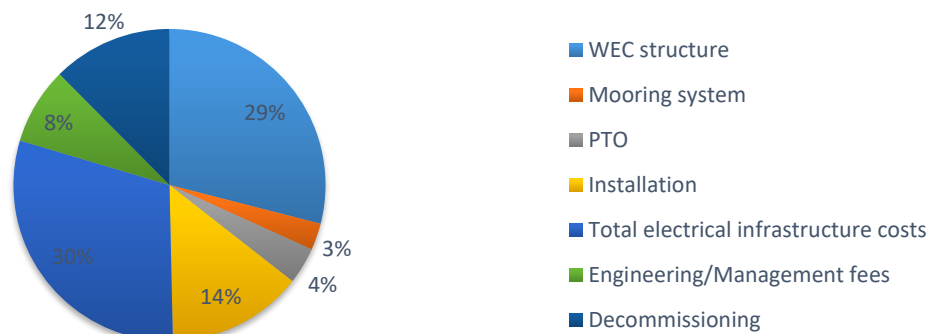
### With Innovation: Nominal CAPEX distribution for Array 2, BiMEP



### With Innovation: Nominal CAPEX distribution for Array 2, EMEC



### Bench Case: Nominal CAPEX distribution for Array 2, EMEC



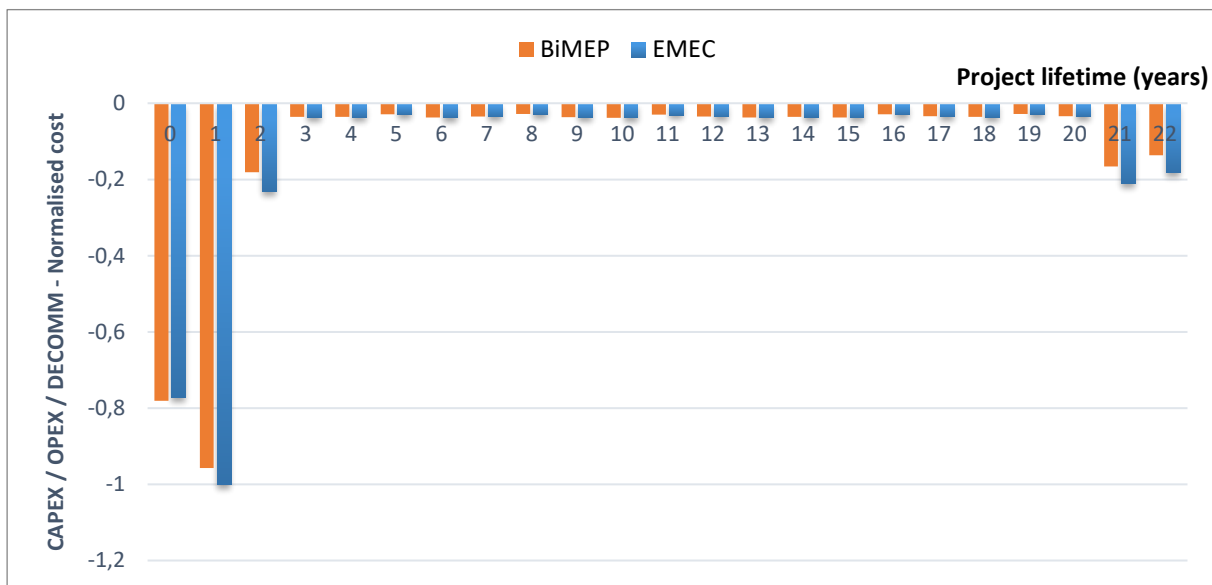
**FIGURE 17: CAPEX COST BREAKDOWN OF ARRAY 2 FOR THE DIFFERENT TECHNOLOGY LEVELS AND DIFFERENT DEPLOYMENT LOCATIONS.**



## 4.2.2 OPEX

The difference in the OPEX for an array of devices deployed in BiMEP vs EMEC is due to the differences on the environmental data, which generates different weather windows, as well as, different offshores distances, defined on Table 3 and Table 5.

These cost differences can be observed in Figure 18. Figure 18 and Table 13 present the results for the Array 2.



**FIGURE 18: TIME SCHEDULING OF THE UNDISCOUNTED EXPENDITURES ASSOCIATED TO THE ARRAY 2 DEPLOYED IN BIMEP AND EMEC.**

As a consequence, the total cumulative lifetime OPEX costs, before discounting, decreases by 1%, when moving from BiMEP to EMEC site, as observed below in Table 13. Again, the presented costs are non-discounted and because OPEX occurs during the project lifetime (O&M stage), when these values are discounted there is a significant reduction on its values.

**TABLE 13: PERCENTAGE DIFFERENCE IN OPEX WHEN TRANSITIONING FROM BIMEP TO EMEC FOR ARRAY 2, WITH INNOVATION SCENARIO.**

Cost centres	Difference
Total OPEX	-1 %

Even though the distance to Harbour is 33% smaller at EMEC, which would result in smaller OPEX, as discussed, EMEC site also has a higher resource, which also means greater limitations, smaller weather windows for intervention and then higher OPEX. Therefore, these two aspects balance out, resulting in this small difference in OPEX when moving from BiMEP to EMEC.

#### 4.2.2.1 LESSONS LEARNT FROM OPEX MODEL

Current assumptions used in the sector for OPEX estimation were revised, a comparison with the OPERA results are presented in this section and recommendations for more accurate OPEX calculation is proposed by OPERA operating experience.

Table 14 shows the relationship in OPERA project between installation costs and total initial costs (IC); OPEX and CAPEX; and finally decommissioning and installation costs. This table aims to demonstrate that these relationships will be different depending on the site as well as on the array size.

**TABLE 14: OFFSHORE COSTS RELATIONSHIP OF OPERA OPEAN SEA EXPERIENCE.**

Site	Rated Power (MW)	Installation Costs (% of TIC)	OPEX (% of CAPEX)	Decommissioning Costs (% of Installation Costs)
EMEC	0.25	30%	2.2%	88%
	10	29%	1.9%	88%
	18	29%	1.8%	88%
BiMEP	0.25	22%	2.2%	88%
	10	22%	1.9%	88%
	18	22%	1.8%	88%

For comparison, in the absence of more accurate O&M models, the costs associated with logistical activities (installation, OPEX and decommissioning costs) are estimated as percentages of the CAPEX.

- **Installation costs** are set to 33% of “initial cost” (IC), being IC the sum of the structure, moorings and PTO cost centres is considered [8].
- **OPEX** are obtained as a fixed yearly percentage of CAPEX, a value of 5% is suggested in [9], [10]. CAPEX considers the IC plus fees and installation costs.
- **Decommissioning cost** is taken as 80% of the installation cost, [11]. Since it is determined as a percentage of a CAPEX cost centre.

The results from OPERA operating experience show reasonable similarities with the assumptions often taken by industry in the absence of an OPEX model. Current assumptions used in the sector assumes that the installation costs should be 33% of the IC, whereas the OPERA experience indicates that installation costs represents between 22-30% of the IC. Current assumptions used in the sector also considers decommissioning costs of 80% of installation costs, whereas the OPERA experience suggest an increase to 88%. These values are based on pre-OPERA experience and OPERA experience points through a significant reduction on installation and decommissioning costs when compared to the simplified industry approaches.

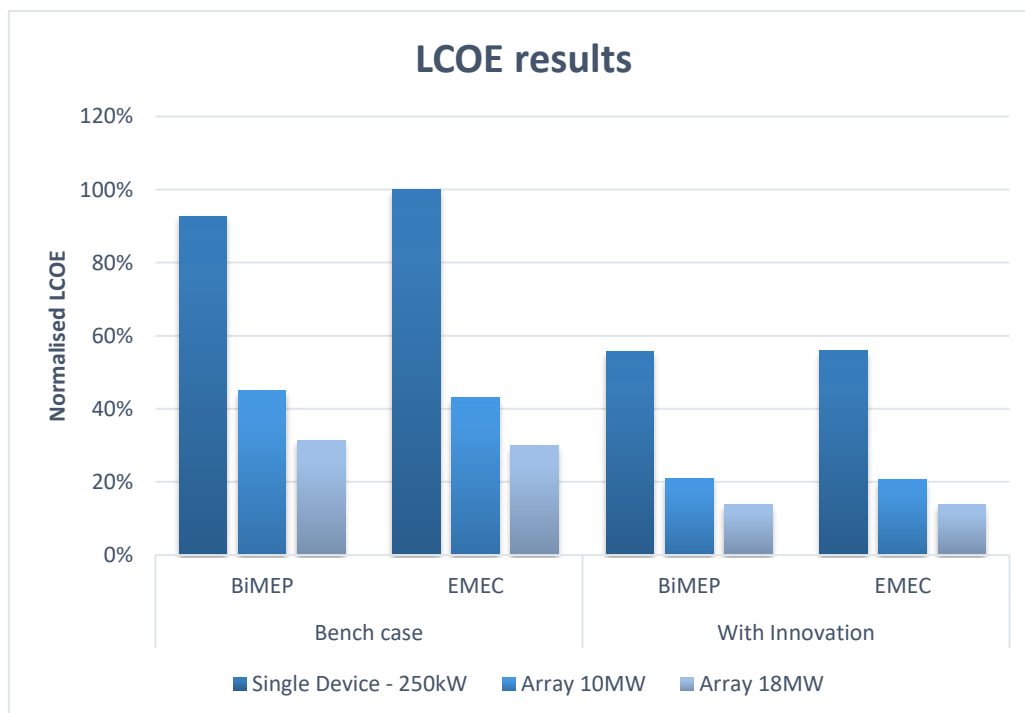
Finally, the current assumptions used in the sector assumes that OPEX should be 5% of the CAPEX yearly, and the OPERA experience shows that O&M can vary between 1.8-2.2% of CAPEX per year, depending on the deployment location and size of the array.

### 4.3 LCOE

Figure 19 and Table 15 summarise the LCOE values calculated for the different technology levels, deployment locations and array sizes considered in this techno-economic study. LCOE values are normalised with the highest LCOE result.

**TABLE 15: NORMLISED LCOE RESULT FOR EACH OF THE DEPLOYMENT LOCATIONS, ARRAY SIZE AND TECHNOLOGY LEVEL.**

LCOE [€/kWh]	Bench Case		With Innovation	
	BiMEP	EMEC	BiMEP	EMEC
Single Device	0.928	1.000	0.558	0.560
Array 1	0.451	0.431	0.209	0.206
Array 2	0.314	0.299	0.139	0.138



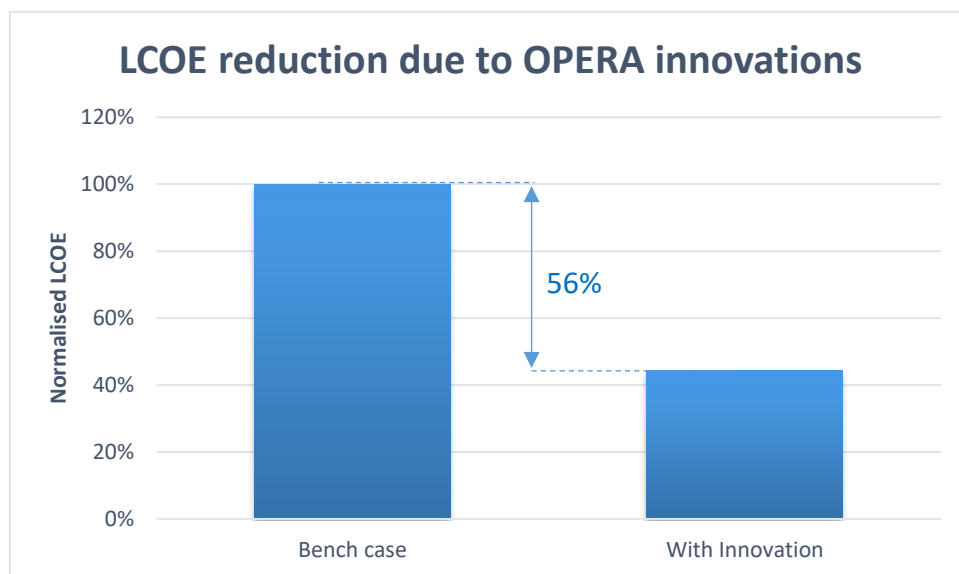
**FIGURE 19: NORMALISED LCOE FOR EACH OF THE DEPLOYMENT LOCATIONS, ARRAY SIZE AND TECHNOLOGY LEVEL. LCOE VALUES ARE NORMALISED WITH THE HIGHEST LCOE RESULT (SINGLE DEVICE AT EMEC).**

The deployment of the 18MW array With Innovations at EMEC, led to the lowest LCOE value. This is an expected result given EMEC's larger resource, as well as its smaller offshore distances and also given OPERA technology improvements.

It must be stressed though that the LCOE figures should be interpreted with caution given the degree of uncertainty due to the TRL level of the device. In addition to this, the reader should also be reminded of the assumptions made in the calculations of these values. Consequently, the LCOE analysis is complemented with a sensitivity study, which is described in section 4.4.

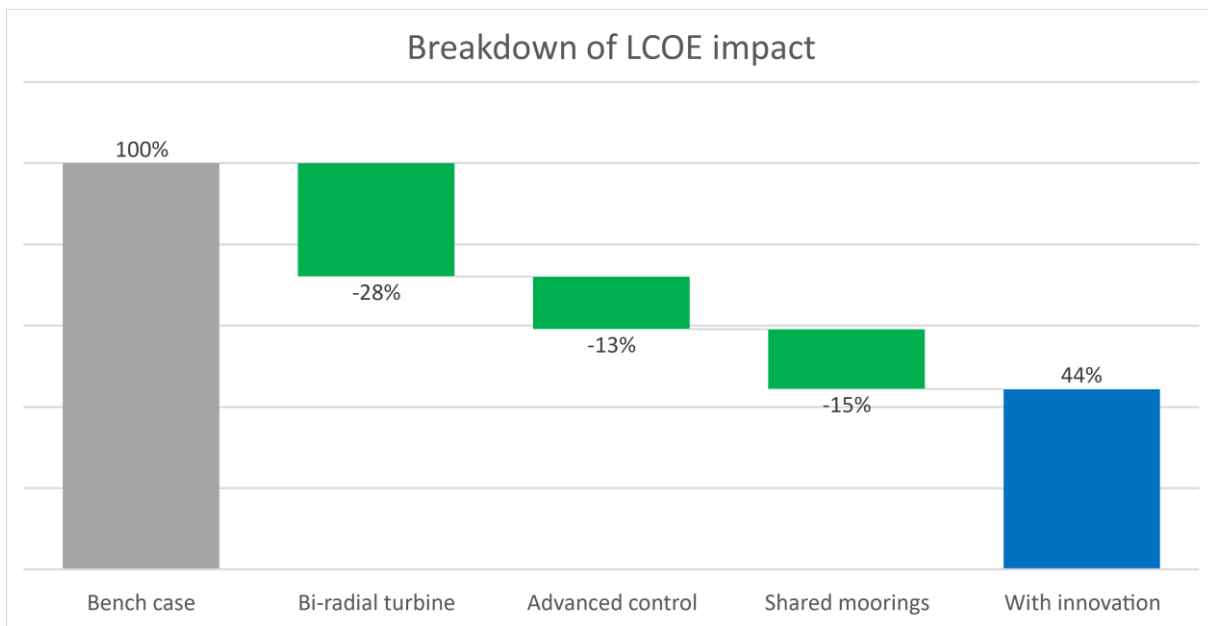
#### 4.3.1 BENCH CASE VS WITH INNOVATION

LCOE results for the array cases exceed the initial target of a 50% reduction in LCOE when transition from the Bench Case to the With Innovation scenario that had been highlighted in the project proposal. Thanks to the improvements brought about by the OPERA technological solutions, such as novel bi-radial turbine, advanced control strategies and shared mooring configuration, the results obtained when evaluating the With Innovations case studies reach about 52 – 56 % reductions in both locations for the array cases. Figure 20 shows the LCOE reduction for the array of 18MW deployed in BiMEP.



**FIGURE 20: NORMALISED LCOE IMPACTS OF OPERA INNOVATIONS (NOVEL BI-RADIAL TURBINE, PREDICTIVE AND LATCHING CONTROL SYSTEM AND SHARED MOORING SYSTEM).**

For the sake of clarity, the breakdown of LCOE reductions due to the OPERA solutions will be presented only for the 18MW array deployed at BiMEP. This analysis can be repeated for other sites in order to estimate the LCOE for different site and environmental conditions.



**FIGURE 21: LCOE IMPACTS OF THE OPERA SOLUTION AT BIMEP SITE.**

Figure 21 is a waterfall chart presenting a breakdown of how each of the tested innovations impact on LCOE. The present techno-economic analysis has identified and quantified such impacts as follows:

- **Bi-radial turbine** improved efficiency by 55% (see D3.3) but also marginally increased the CAPEX due to the novel turbine costs, which when fed into equation (4), resulted in a 28% LCOE reduction.
- **Advanced control strategies** led to a higher AEP figure (22% mean value and 31% maximum, see D4.2), which again, when fed into equation (4), resulted in a LCOE reduction of 13%.
- **Shared mooring configuration** resulted in a LCOE reduction of 15%, due to the mooring cost reduction as well as electrical infrastructure cost reduction.

If different electrical layouts were considered (see Case 2 and Case 3 on section 3.2.4), different LCOE reduction would be observed when moving from the Bench Case to the With Innovation scenario. When considering an offshore substation and consequently one export cable to shore (Case 2), instead of an onshore substation and one export cable for each cluster, an LCOE reduction of 51% was observed and a final LCOE value close to Case 1 was achieved. When considering one kilometre of rock coverage for every 8 devices (Case 3), instead of one kilometre of rock coverage for each cluster, a LCOE reduction of 49% was achieved and again a final LCOE value close to Case 1 value was achieved. Therefore, the LCOE of Bench Case is smaller for Cases 2 and 3 when compared with the LCOE of the Case 1 electrical configuration.

Table 16 presents a comparison between the present results (Array 18MW, BiMEP) and the expectations that were outlined at the time of writing the proposal for OPERA project. Results

of the LCOE modelling are aligned with the initial objectives. It shows further LCOE reductions could be achieved if the assumption on the increased reliability target is accomplished.

**TABLE 16: COMPARISON OF LCOE (PRESENT RESULTS VS PROJECT PROPOSAL) FOR ARRAY 18MW AT BIMEP.**

Innovations	Present results	Proposal projections
Novel Bi-radial turbine	- 28%	- (33%)
Advanced control strategies	- 13%	- (16% / 23%)
Shared mooring configuration	- 15%	- (1% / 10%)
Elastomeric mooring tether	(1)	- (3% / 8%)
<b>TOTAL LCOE reduction</b>	<b>- 56%</b>	<b>- 50%</b>

<sup>(1)</sup> The elastomeric mooring tether accounts with the improvement of reliability, which was proved during the OPERA experience. The improvement on reliability also has an impact on the capital cost of the WEC structure due to a reduction of reduction of peak loads. The load spectrum should improve when moving from the traditional mooring system to the elastomeric one, reducing both peak and fatigue loads. D2.2 reports a reduction on the mooring lines' extreme loads of 50%. However, at this stage of the project the impact of this innovation on LCOE was disregarded as there are too many layers of uncertainty to estimate how CAPEX reduces with the new mooring, but it has shown the potential to reduce the cost of the floater, mooring system itself and ancillary system, such as mooring connectors.

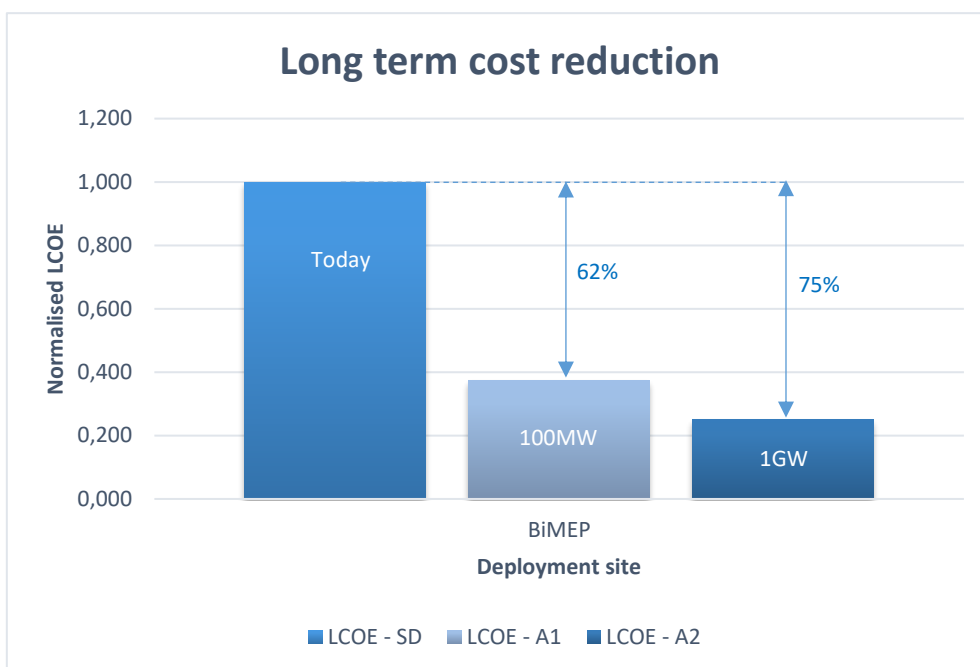
#### 4.3.2 SINGLE DEVICE VS ARRAYS

The cost of energy will come down further as the industry progresses to the stage of a global market maturity, benefiting from cost reductions thanks to learning effects (both learning-by-researching and learning-by-doing), economies of volume, and economies of scale. This section shows results from the third scenario group, defined on item 2.1.3, which considers the three scenarios for different array capacities and industry stages:

- Single device (SD): device of 250kW (prior installed capacity 5MW)
- Array 1 (A1): installed capacity of 10MW (prior installed capacity 100MW)
- Array 2 (A2): installed capacity of 18MW (prior installed capacity 1000MW/1GW)

The OES/IEA report (2015) [7], also performed an LCOE evaluation considering different industry phases: first pre-commercial array, second pre-commercial array and first large commercial-scale array/projects.

Due to the level of maturity of the wave energy sector, energy costs are expected to be initially high and drastically reduce with the sector development. The initial costs represent only the start of the learning curve. Figure 22 shows the OPERA results for the BiMEP site. OPERA's LCOE assessment shows a 62% reduction in cost when comparing single device deployed to 100MW installed and a 75% cost reduction when comparing a single device deployed to 1GW installed. The LCOE results for the array cases match the Bench Case that had been highlighted in the project proposal (long term cost-reduction of over 50%). These long term cost reductions are also in line with the IEA OES report, 2015 [7]: "The LCOE is expected to be drastically reduced from the first deployment to the first full commercial project (around 75% based on developers and 50% based on reference studies)".



**FIGURE 22: LCOE LONG TERM PROJECTIONS WITH LEARNING RATES AND BULK DISCOUNT. LCOE VALUES ARE NORMALISED WITH THE HIGHEST LCOE RESULT (SINGLE DEVICE AT EMEC).**

The LCOE values achieved by the OPERA arrays (With Innovation scenarios deployed at both BiMEP and EMEC sites), are aligned with the values of the "second demonstration projects" in [7], the LCOE's of which, when converted to Euros and inflation-adjusted to present values, range from 0.160 to 0.515 €/kWh .

Figure 24 shows a graph taken from IEA OES report, 2015 [7] onto which LCOE values calculated in OPERA are superimposed. Figure 24 highlights (blue circle) that the OPERA LCOE results for the arrays deployed at BiMEP match the [7] trend line defined within the sector, for the cost reduction of wave energy. A conversion rate of 0.88€/€ was used.

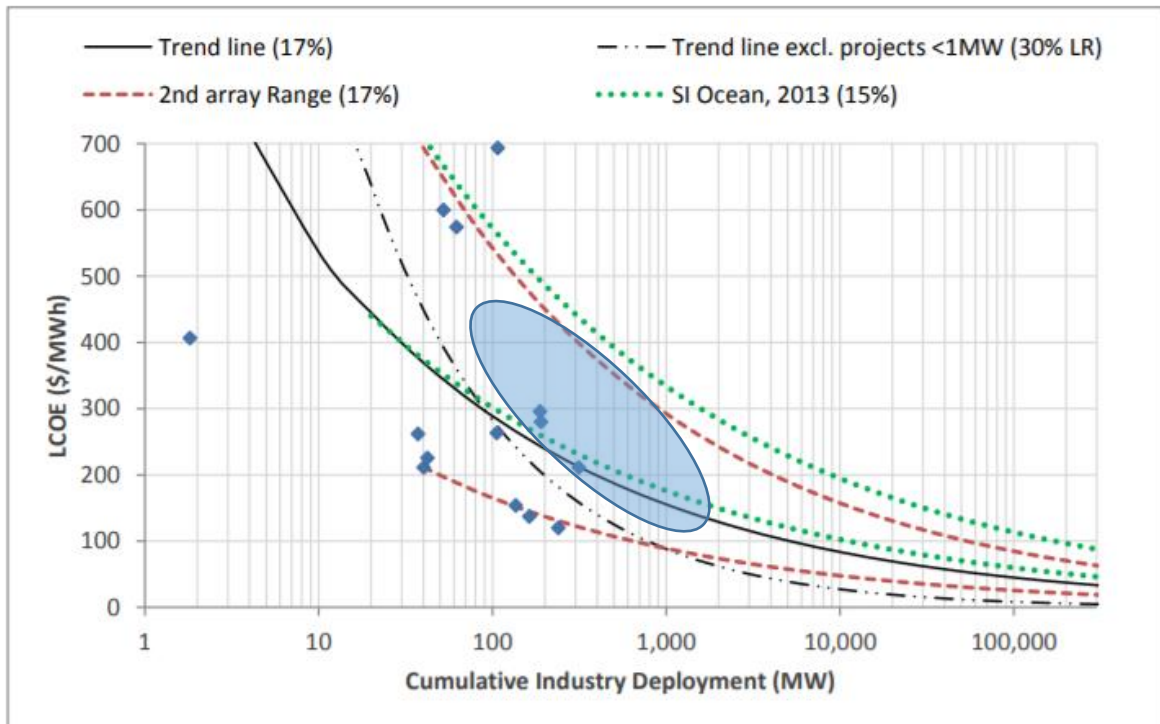


FIGURE 23: OPERA LCOE PROJECTION RESULTS PLOTTED AGAINST IEA OES 2015 [7] PREDICTIONS WITH POSSIBLE LEARNING TRENDS FOR THE WAVE ENERGY SECTOR.

### 4.3.3 EMEC VS BIMEP

Figure 24 shows the LCOE calculated for the two different locations: BiMEP and EMEC. The LCOE difference between sites is extremely small, 0.5% smaller at EMEC.

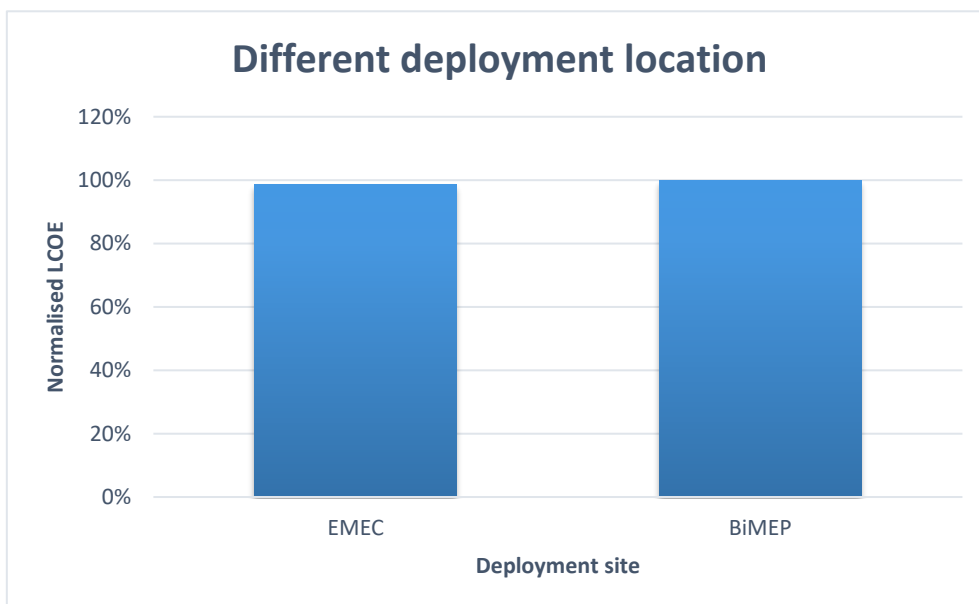


FIGURE 24: LCOE IMPACTS OF DIFFERENCE DEPLOYMENT LOCATIONS (EMEC AND BIMEP SITES), 18MW ARRAY.



The LCOE equation (4) involves three main inputs: costs, AEP and discount rate. This section highlights the equation inputs that are different between sites, which are: offshore costs (installation, OPEX, decommissioning and electrical) and AEP ('Ideal AEP' and availability).

### Offshore costs

As observed on Table 11, electrical infrastructure costs are higher in BiMEP because the offshore distances are higher. However, it is also observed that, even though the BiMEP case study has a greater distance to port, the installation and decommissioning costs are higher at EMEC. This is because the calculation of offshore costs (calculated by the OPEX model) takes into account the costs accrued during the weather window waiting time (see section 3.3). Therefore, with higher resources at EMEC, which means a higher limitation for offshore operation (lower weather windows), the EMEC costs are higher.

### AEP

The 'Ideal AEP' values were provided by Idom-Oceantec, as explained in section 3.4. Figure 15 shows that EMEC 'Ideal AEP' is 21% higher when compared to BiMEP. However, when applying equation (5), which considers availability, the AEP difference reduces to 6% (as seen in Figure 16). This is because the availability is higher at BiMEP (see Table 10), due to its lower resource, in other words, its lower limitation on the weather windows.

### LCOE

The representative scenario, array 2 (18MW) With Innovation, shows that offshore costs in EMEC are 18% higher than BiMEP (see Table 11), which contributes to an increase of the LCOE. However, AEP in EMEC is 6% higher than BiMEP, which contributes to a reduction of the LCOE. This balance between costs, AEP, resources and offshore distances, combined with the model assumptions, result in a similar LCOE between EMEC and BiMEP.

### Discussion

This work shows no preference between EMEC or BiMEP for the deployment of the Idom-Oceantec device. There is a small difference, EMEC is marginally better, but its improvement is within the uncertainty levels of the assumptions. This result is based on the assumptions made for the OPERA project and some of them are highlighted below.

- The Idom-Oceantec device was optimized for BiMEP. If the WEC was designed for EMEC instead its design would be tailored to the characteristics of that site, resulting in an increase of the 'Ideal AEP'.
- The OPEX model assumes that vessels are hired daily, which results in a significant cost increases when there are limitations due to lack of weather windows. For locations with higher resources (such as EMEC), this assumption could be re-evaluated and

considerations of fixed costs for hiring vessels could take place, avoiding the waiting time tariff.

#### 4.4 SENSITIVITY ANALYSIS - LCOE

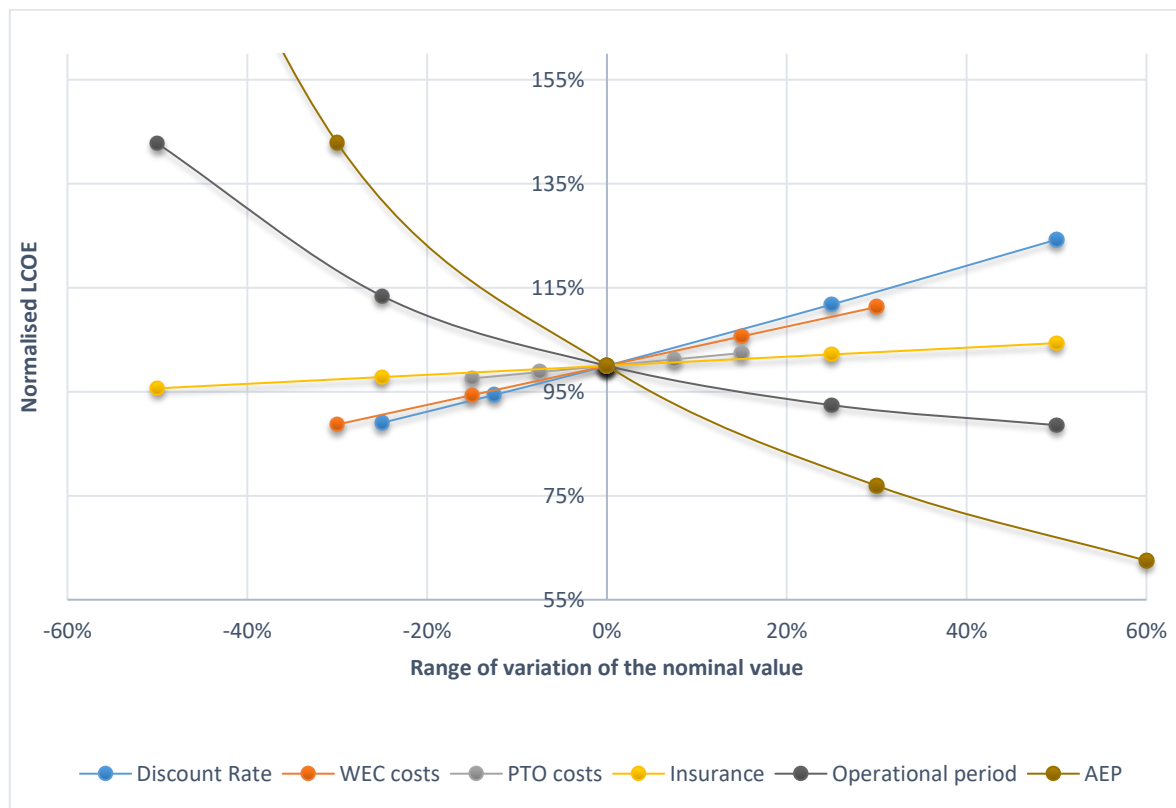
As discussed, the calculation of LCOE, especially for future scenarios, relies on many assumptions and estimates due to the early stage of WEC technology and the wave energy industry in general. These assumptions often contain many uncertainties, which eventually result in a high level of uncertainty being contained within the calculated LCOE value. For this reason, this section presents plausible alternative values for some input parameters.

The variables chosen for this sensitivity study, together with the values used in the analysis, are presented in Table 17.

**TABLE 17: SUMMARY OF PARAMETERS CONSIDERED IN THE SENSITIVITY ANALYSIS.**

Variable / input parameter	Nominal value	Range of variation of nominal value
WEC costs	-	+ / - 30%
PTO costs	-	+ / - 15%
AEP	909.6 MWh	+ / - 60%
Operational period	20 years	+ / - 50%
Discount rate	8%	+ / - 25%
Insurance	1% CAPEX	+ / - 50%

The values not varied have been taken from the scenario in which an 18MW array of WECs was deployed at BiMEP. Due to the sensitivity analysis essentially presenting the characteristics of the LCOE equation, the results presented here can be extended to the other scenarios. WEC and PTO costs are not shown because are confidential. The results of the sensitivity analysis are presented in Figure 26.



**FIGURE 25: SENSITIVITY ANALYSIS FOR THE LCOE OF THE ARRAY OF 18MW AT BIMEP.**

Figure 26 indicates that the steeper the curve, the more impact an uncertainty in that variable has on LCOE. As per the graph, the input parameters could be ranked in terms of impact on LCOE, from largest to smallest, as follows: AEP (steepest curve), discount rate, WEC costs, operational period, PTO costs and insurance costs.

**TABLE 18: LCOE VARIATION OBTAINED IN THE SENSITIVITY ANALYSIS.**

Inputs	Parameters	Var.1	Var.2	Var.3	Var.4
AEP	input variation	-60%	-30%	+30%	+60%
	LCOE variation	250%	143%	77%	63%
Discount rate	input variation	-25%	-12.5%	+12.5%	+25%
	LCOE variation	89%	94%	112%	124%
WEC costs	input variation	-30%	-15%	+15%	+30%
	LCOE variation	89%	94%	106%	111%
Operational period	input variation	-50%	-25%	+25%	+60%
	LCOE variation	143%	113%	92%	89%
PTO costs	input variation	-15%	-7.5%	+7.5%	+15%
	LCOE variation	98%	99%	101%	102%
Insurance	input variation	-50%	-25%	+25%	+60%
	LCOE variation	96%	98%	102%	104%

The sensitivity analysis shows that the AEP has the most significant effect on LCOE. Increasing efficiency and maximising AEP should be a focus for development. Efforts should be made to reduce parameters whose uncertainty has greater impact on LCOE, AEP being the most relevant one. Therefore, work should focus on increasing device WEC power absorption.

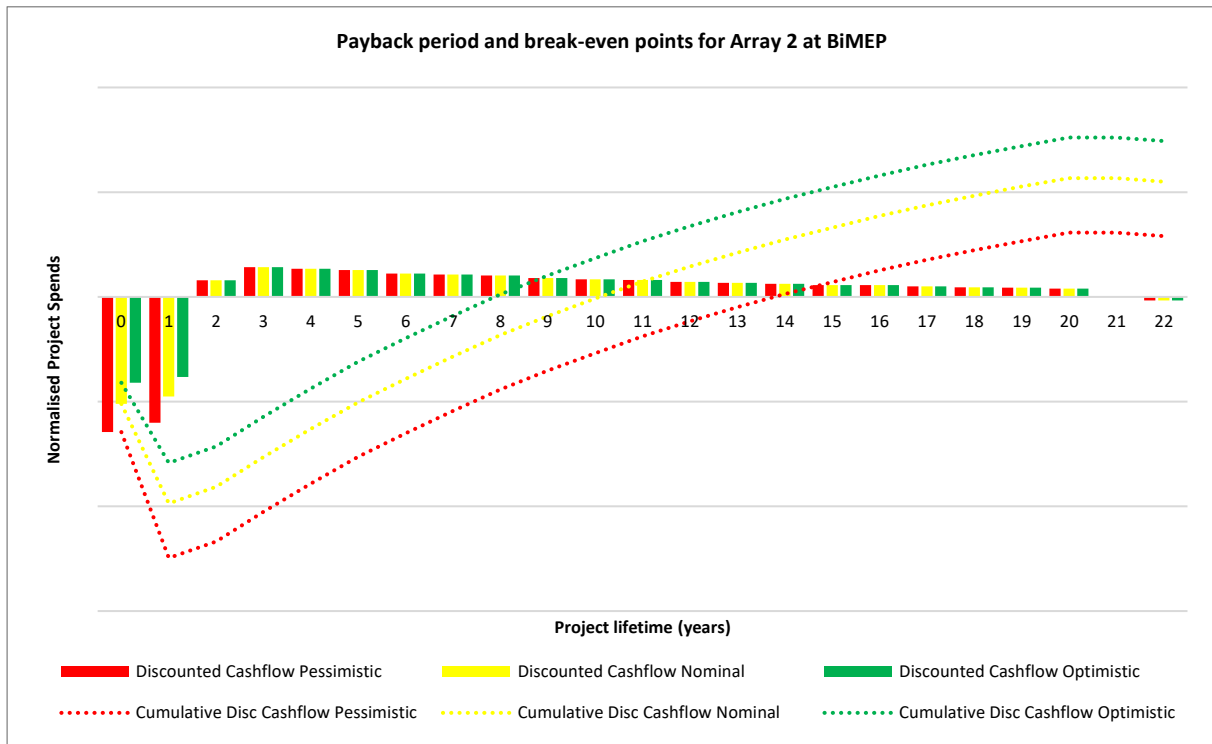
The other parameter that showed a significant impact on LCOE was the discount rate. The discount rate reflects how the investment risk is perceived by investors. Beside finance availability and market factors, developers need to prove the reliability of components through established mechanisms, like certification to minimise the risk as perceived by the potential investors, in order to lower the discount rate.

## 4.5 OTHER METRICS

The techno-economic assessment of OPERA also considered the evaluation of financial indicators such as the Net Present Value (NPV), the Internal Rate of Return (IRR) and CAPEX per MW. The NPV is the difference between the cash inflows and outflows, discounted to the present time, over a certain period, and is an indicator of the profitability of an investment (the higher, the better). Positive values of NPV indicate the project/investment under consideration would bring a value gain for the investors, whereas negative values would lead to value loss or subtraction. The IRR is the discount rate that would lead to an NPV equal to zero at the end of the project.

Figure 27 shows the discounted cashflows for the array 2 deployed at BiMEP site. To facilitate the interpretation of the graph, the reader should take into account the following considerations:

- The colours indicate the three different uncertainty scenarios: red – pessimistic, orange/yellow – neutral, green – optimistic.
- The bars represent the net cashflow (i.e. income minus expenses) for that year, discounted to present value, at a discount rate of 8 %.
  - Incomes are driven by the AEP, which is assumed to be sold to the grid at an electricity price equal to the current strike price under the Contracts for Difference scheme for current wave and tidal projects in the UK, i.e. £0.305/kWh [12].
  - Expenses comprise: CAPEX, OPEX and decommissioning.
- Dotted lines represent the cumulative discounted cashflow. The right end of the dotted lines represents the NPV of that scenario. Should the final value of NPV stay under the horizontal axis (i.e. NPV with a negative value), the project would not be viable.
- The payback period is defined by the year in which the cumulative discounted cashflow turns positive, i.e. the year in which the dotted line crossed the horizontal axis.



**FIGURE 26: DISCOUNTED CASHFLOWS AND PAYBACK PERIODS FOR THE ARRAY 2 DEPLOYED IN BiMEP.**

The following observations can be extracted after analysing Figure 27:

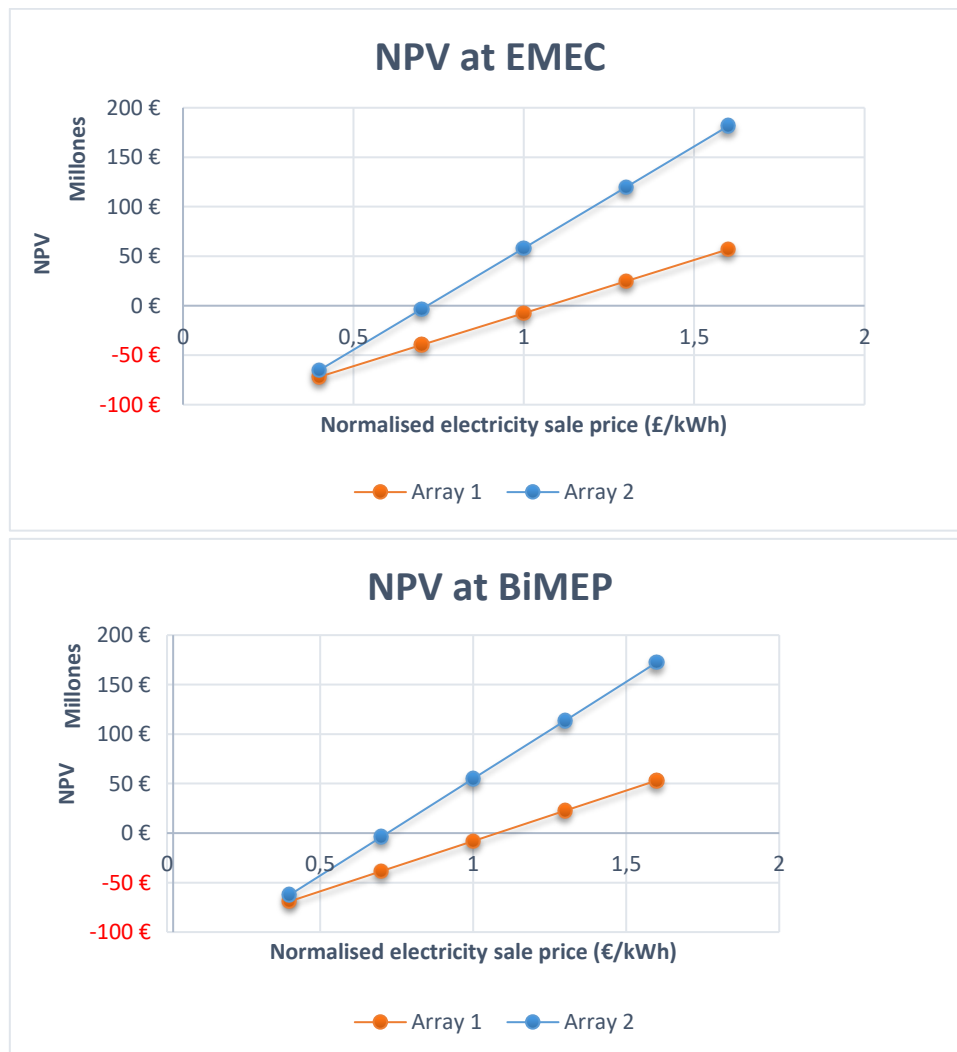
- The cumulative cashflow starts at very low negative values in year 0 and 1 due to the upfront CAPEX.
- From year 2 onwards, the cumulative cashflow starts to rapidly increase due to the increase associated to the energy generation.
- As the reader moves right in the graph, the steepness of the cumulative cashflow curve diminishes and the height of the cashflow bars decreases. This is caused by the discounting, which reduces the weight of cashflows happening far in the future when compared to present or near future flows.
- Each of the NPV values are positive when array 2 is deployed at BiMEP. The associated value for IRR is 14% (neutral condition) with uncertainty ranging from 11% (pessimistic) to 18% (optimistic).

Results were obtained for all array levels (A1 and A2) and locations (EMEC and BiMEP). The NPV was found to be negative under array 1 scenarios. The LCOE values calculated for these scenarios were higher than the assumed electricity price of 0.305 £/kWh, hence leading to unprofitable investments. Amongst the positive figures of NPV, the highest was found at EMEC in the Array 2 case, with an associated IRR of 15%.

It needs to be stated that NPV and IRR metrics assumes a specific sale price of electricity, which is very variable; 0.305 £/kWh is unrealistic and won't be awarded. In 2019, in the UK, the Department for Business, Energy & Industrial Strategy [13] defined a new Contract for

Difference (CfD) administrative strike prices for wave energy between 291-268 £/MWh. In Spain, in 2007, the *Agencia Estatal - Boletín Oficial del Estado* [14] defined an electricity price of 306 €/MWh, whereas in 2017 the *Boletín Oficial del Estado* [15] reduced the support for renewables to 40 €/MWh or 150 €/MW.

Figure 28 presents a sensitivity evaluation of the NPV for different electricity sale prices.



**FIGURE 27: NPV SENSITIVITY ASSESSMENT FOR EMEC AND BIMEP. ELECTRICITY SALE PRICE IS NORMALISED WITH THE ELECTRICITY SALE PRICE CURRENTLY ASSUMED ON THE MODEL.**

Figure 28 shows that for the Array of 18MW at EMEC the electricity sale price currently assumed on the model produces positive NPV, while for the Array of 10MW the electricity sale price should be higher. A similar behaviour is observed for the arrays deployed at BiMEP.

## 5. LCA MODELLING

An introduction to Life Cycle Assessment (LCA) was previously presented in D7.2. It highlighted Global Warming Potential (GWP), Energy Payback in Time (EPBT) and Energy Return of Investment (EROI) as the main outputs by the LCA process. As such, this section directly focuses on the calculation process of the mentioned metrics, its assumptions and the corresponding results.

### 5.1 SCOPE OF ASSESSMENT AND BOUNDARIES

This LCA analyses the incoming and outgoing materials and processes required and produced during the life cycle of a representative array of Idom-Oceantec WECs with the 4 OPERA innovations. The array lifetime has been set as 20 years and the studied array is composed of 72 devices (18 MW). The WECs have bi-radial turbines with advanced control and share moorings in a 4x2 cluster arrangement. The array's grid connection was included, as well as installation and operations fuel consumption during the lifetime of the array. Decommissioning and disposal were also considered in the presented analysis. Deployment at EMEC was considered in the analysis.

This study considers a cradle-to-grave boundary. This means that the study considers all energy input on, and carbon emissions from, the extraction of raw materials from their natural state through the manufacturing process to the complete disposal of the devices at end-of-life.

The energy and emissions associated with the manufacturing of plants and machinery used has been excluded. This approach is in line with previous studies and assessments on the LCA of ocean energy converters.

In the present study, the functional unit (i.e. the reference to which the inputs and outputs can be related) was established at one kilowatt-hour of energy output (1 kWh).

### 5.2 LIFE CYCLE INVENTORY ANALYSIS (LCI)

#### 5.2.1 PROCEDURE

The inventory 'foreground data' used for the LCA presented here was provided by Kymaner, Idom-Oceantec and University of Exeter. Regarding installation, O&M, decommissioning and the vessels required, this information was based on the OPEX model developed by Tecniaia.

Information on the 'background data', i.e. the embodied energy and carbon for each unit of material/process, was obtained mainly from Inventory of Carbon & Energy [16] and ecoinvent [17] databases.

## 5.2.2 RAW MATERIALS

Oceantec-Idom have indicated that the WEC has a mass of 842 tons, 96% of which is attributed to its structure with 4% due to the bi-radial turbine. The total mass of the clustered mooring system is 1,144 tons (for 8 devices, 4x2 arrangement). The main components of the mooring system (chain, anchor and cable) are made of steel.

The material breakdown of the WEC structure and bi-radial turbine can be observed in Figure 29 and Figure 30. Steel accounts for 64% of the WEC structure's mass, and the rest is mostly concrete. Carbon steel accounts for 89% of the bi-radial turbine's mass, followed by stainless steel and glass, with 5% and 4%, respectively. The rest of the materials represent less than 2% of the turbine's total.

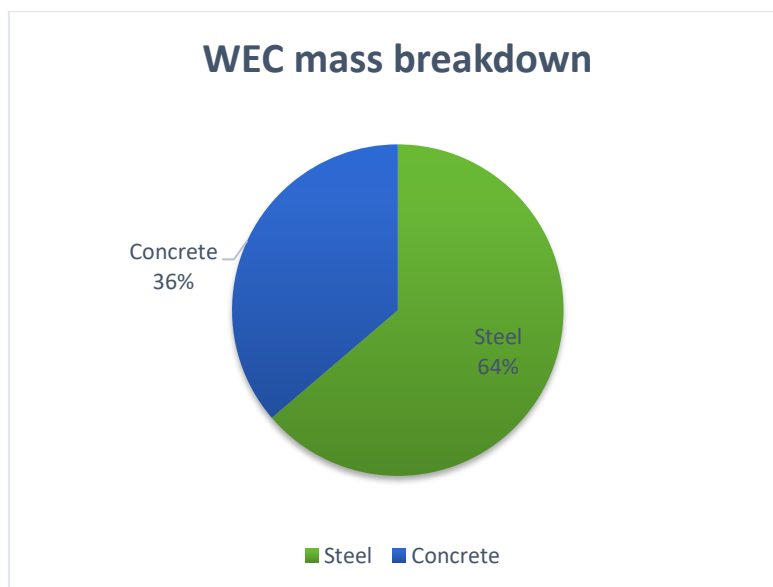
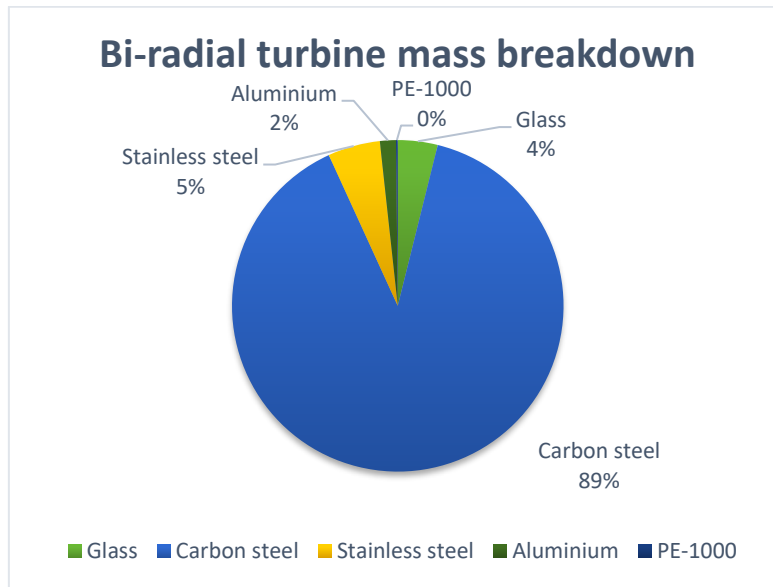


FIGURE 28: MASS BREAKDOWN OF WEC STRUCTURE BY MATERIAL.





**FIGURE 29: MASS BREAKDOWN OF BI-RADIAL TURBINE BY MATERIAL.**

Data for material embodied energy and carbon are given in Table 19. The databases utilised provide cradle-to-gate information, which covers the material's lifetime from the exploration and extraction of the raw and feedstock materials to readiness for collection at the factory gate. Carbon and energy associated with the remainder of the material's life, i.e. from gate to grave, needs then to be accounted for separately and added in order to be able to compute the final cradle-to-grave result.

The present study considered and quantified the recycling of materials at end of the project lifetime activities. Consequently, when sourcing the ICE database, 'primary' values of embodied carbon and energy were employed, in order to avoid double crediting recyclability. 'Primary' here means virgin materials, i.e. as if totally extracted from the natural source, without any recycled content.

**TABLE 19: SUMMARY OF EMBODIED CO<sub>2</sub> AND ENERGY FOR OF THE MAIN MATERIALS.**

Material	Embodied carbon [kg CO <sub>2</sub> /kg]	Embodied energy [MJ/kg]
Steel	2.71	35.40
Concrete	0.035	0.95
Glass	8.10	100
Stainless steel	6.15	56.7
Aluminium	9.16	155.0
PE-1000	1.7	73.7

## 5.2.3 MANUFACTURING

### 5.2.3.1 PROCESSES

Table 20 summarizes the energy requirements and CO<sub>2</sub> exhausted for the selected manufacturing processes considered in the present study.

**TABLE 20: SUMMARY OF EMBODIED CO<sub>2</sub> AND ENERGY FOR THE MANUFACTURING PROCESSES.**

Process	unit	Embodied carbon [kg CO <sub>2</sub> /unit]	Embodied energy [MJ/unit]
Welding	m	1.80	15.10
Surface treating (Sandblasting)	m <sup>2</sup>	0.05	1.00
Surface treating (Painting)	m <sup>2</sup>	2.43	31.90
Machining (carbon steel)	cm <sup>3</sup>	0.0011	0.0093
Machining (stainless steel)	cm <sup>3</sup>	0.0006	0.0052
Machining (aluminium)	cm <sup>3</sup>	0.0001	0.0011

### 5.2.3.2 COMPONENTS

#### Electrical components:

Each cluster is connected to the offshore substation and the substation is connected to the network via a subsea cable to shore. The electrical components include the umbilical cable, bend restrictor, bend stiffener, offshore station and transmission cable.

Table 21 summarizes the energy and CO<sub>2</sub> requirements for the selected electrical components considered in the present study.

**TABLE 21: SUMMARY OF EMBODIED CO<sub>2</sub> AND ENERGY FOR THE ELECTRICAL COMPONENTS.**

Component	unit	Embodied carbon [kg CO <sub>2</sub> /unit]	Embodied energy [MJ/unit]
Umbilical cable	m	20.90	462.00
Bend restrictor	m <sup>3</sup>	13.30	3890.00
Bend stiffener	kg	4.31	97.50
Offshore station	MW	51.10	985.00
Transmission cable	m	20.90	462.00

## 5.2.4 ONSHORE AND OFFSHORE OPERATIONS

Table 22 summarizes the energy and CO2 requirements due to the fuel consumed during marine operations and road transport.

**TABLE 22: SUMMARY OF EMBODIED CO2 AND ENERGY FOR MARINE OPERATIONS.**

Process	unit	Embodied carbon [kg CO <sub>2</sub> /unit]	Embodied energy [MJ/unit]
Road transport	ton*km	0.067	0.94
Fuel consumption	litre	2.65	45.29

The OPEX model calculates the litres of fuel consumed during installation, O&M and decommissioning stages. The OPEX model calculates the fuel consumed in the aforementioned activities for one device. For the array scenarios, this was scaled up by multiplying the results by the number of devices in the array and a learning rate to simulate increased efficiency due to improvements in the logistic process.

As per [18]: “Eurostat freight transport statistics show that, for almost all member states, more than 50% (by mass) of ‘Other non-metallic mineral products’ travel less than 50 km per trip”. The OPERA case study assumes that the distance from the assembly/manufacturing plant to Dockyard is 50 km which represents national distances. However, two other cases are added to understand the increment in CO2 emission coming from onshore transportation in case the assembly/manufacturing plant is located in Europe or China [19].

### 5.2.4.1 FUEL CONSUMPTION CALCULATION

Litres of fuel consumed have been obtained taking into account the number of trips, speed and the type of vessel for each trip. The formula used is the following one:

$$\text{Liters consumption year} = \sum_{N=1}^N \gamma * \sum_{V=1}^{V=3} \left\{ V_{np} * V_{CF} * V_c * \frac{D}{V_s} + V_{np} * V_{CF} * V_c * DT \right\} \quad (10)$$

Where:

- $\gamma$  → Number of same Operations
- $N$  → Number of operations
- $D$  → Distance from port to offshore site (km)
- $V$  → Number of vessels (maximum 3)
- $V_s$  → Vessel speed (km/h)

$V_c$	→ Vessel consumption (kG/kWh)
$V_{np}$	→ Vessel nominal power (kW)
$V_{CF}$	→ Vessel Capacity Factor (0-1)
DT	→ Duration (h)

## 5.2.5 DISPOSAL

Past LCA studies on offshore renewable energy have shown that the recycling stage of the life cycle has a relevant impact on embodied carbon and energy [20], [21]. Thanks to recycling, the energy input and carbon emissions associated with the raw material extraction and primary processing can be avoided, and hence credited or subtracted from the total carbon and energy footprint figures.

Percentages of recyclability for the different materials are listed in Table 23. All non-recycled materials are deposited in landfill, except aluminium, which is assumed to be incinerated.

**TABLE 23: REMOVAL SCENARIO FOR MATERIALS.**

Material	recyclability
Steel	90%
Stainless steel	90%
Aluminium	90%
Concrete	20%
Glass	0%
PE-1000	0%

Carbon and energy intensities of waste treatment processed are shown in Table 24.

**TABLE 24: SUMMARY OF EMBODIED CO<sub>2</sub> AND ENERGY FOR THE WASTE TREATMENT ACTIVITIES.**

Process	unit	Embodied carbon [kg CO <sub>2</sub> /kg]	Embodied energy [MJ/kg]
Steel: landfill	kg	0.00571	0.168
Concrete: landfill	kg	0.00571	0.168
Aluminium: incineration	kg	0.0767	2.36

## 5.3 RESULTS AND DISCUSSION

For the sake of clarity, results will be presented for the array of 18MW installed at EMEC site. Similar conclusions can be drawn for the array of 18MW deployed at BiMEP, since results are relatively location independent.

### 5.3.1 ENERGY CONSUMPTION AND CO<sub>2</sub> EMISSIONS

Results on embodied CO<sub>2</sub> emissions and energy for the life cycle of the OPERA 18MW array deployed in EMEC are displayed in Figure 31. Figure 31 (left) indicates that the most significant stage was manufacturing, which accounts for 67% of lifetime gross energy consumption. This was followed by O&M. The gross life cycle production of CO<sub>2</sub> is again with the greatest shares represented by manufacturing with 73%, see Figure 31 (right).

The credit offered by recycling is significant with the 40% credit lowering the net embodied energy. The recycling credits are higher than the 30% values for wind turbines [22]. The LCA study for the Seagen technology indicates recycling credits of 35% for energy and 42% for carbon [20].

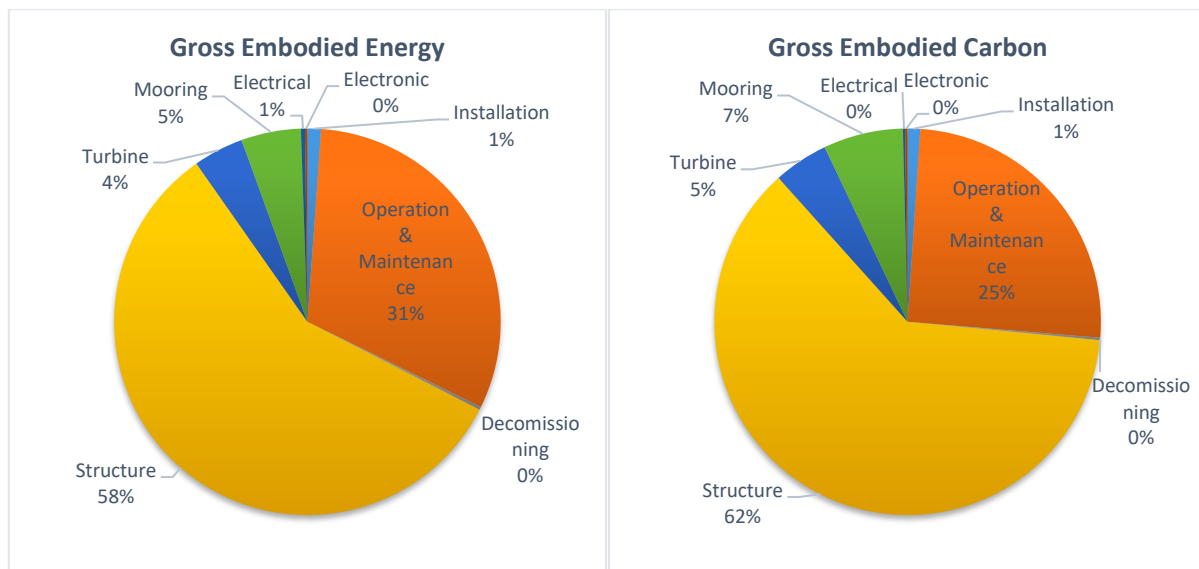
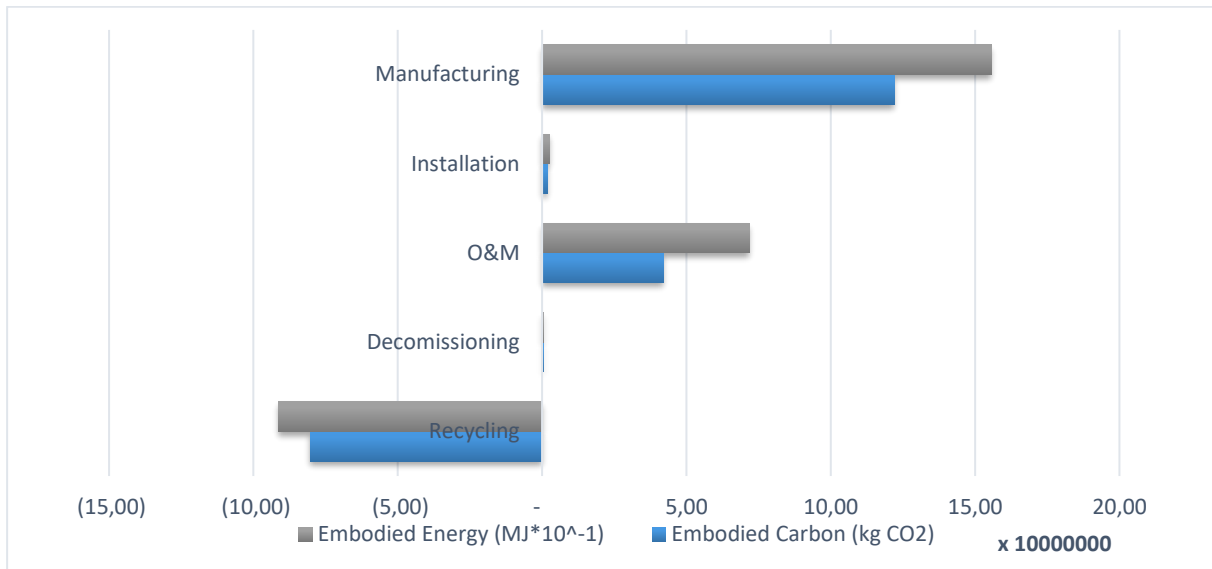
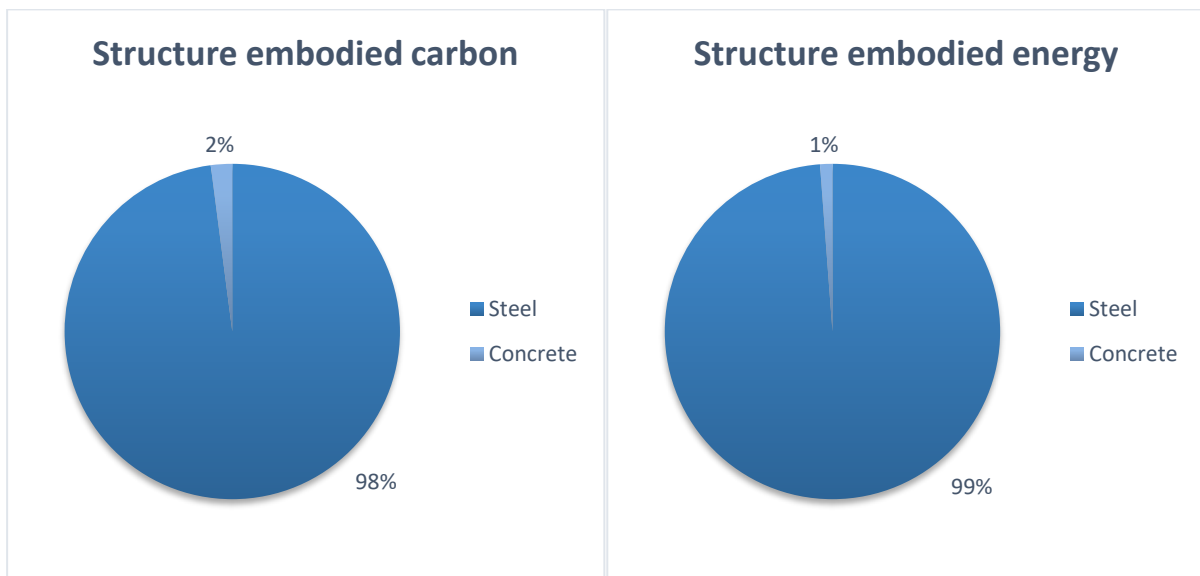


FIGURE 30: GROSS EMBODIED ENERGY (LEFT) AND CARBON (RIGHT) BREAKDOWN OVER THE LIFE-CYCLE.



**FIGURE 31: ENERGY CONSUMPTION AND CO<sub>2</sub> EMISSIONS PER LIFE-CYCLE STAGE.**

Although the WEC structure's mass is divided between concrete and steel (Figure 29), the latter is the main contributor to embodied carbon and energy. This disproportion is especially noticeable for instance when comparing the embodied breakdown by material of WEC structure (Figure 33). It can be observed that the relative figures are greater for steel than concrete.



**FIGURE 32: EMBODIED BREAKDOWN BY MATERIAL OF WEC STRUCTURE (LEFT EMBODIED CARBON, RIGHT EMBODIED ENERGY).**

### 5.3.2 METRICS

In order to facilitate comparisons of LCA performances between different electricity generation technologies, lifetime carbon emissions need to be normalised by dividing them by the lifetime electricity production figure. This allows the derivation of the so-called CO2 ‘intensity’ or Global Warming Potential (GWP).

$$GWP = \frac{\text{Embodied carbon over lifetime}}{\text{Lifetime energy production}} \quad (11)$$

At the EMEC site (our reference case in the LCA modelling), the AEP for a single device was calculated to be 909.6 MWh/year (remember Figure 15). The array’s energy production over its 20-year lifetime is estimated at 1,234.4 GWh. Dividing the net life cycle CO2 emissions by the lifetime production indicates a carbon intensity of 69.4 gCO2/kWh. Omission of the recycling credits raises the intensity to 135 gCO2/kWh.

The LCA performance of the representative array can also be measured in terms of energy payback period (EPBT), which provides an indication on how rapidly embodied energy is ‘recovered’ by the carbon-free electricity generated by the project. Derivation of energy payback periods is shown in Equation (12).

$$EPBT = \frac{\text{Embodied energy over lifetime}}{AEP} \quad (12)$$

The EPBT for the present study is around 6.6 years. Omission of the recycling credit from the calculation increases the payback period to almost 11 years.

The Energy Return of Investment (EROI) can be found using the equation below:

$$EROI = \frac{\text{Lifetime energy production}}{\text{Embodied energy over lifetime}} \quad (13)$$

The EROI of the present study is around 3.2. Omission of the recycling credit from the calculation reduces the return of investment to almost 1.9.

### 5.3.3 COMPARISON WITH OTHER SOURCES OF ELECTRICITY

LCA metrics of the OPERA 18MW array can be compared with other marine renewable energy technologies.

### 5.3.3.1 GLOBAL WARMING POTENTIAL (GWP)

Figure 34 presents a comparison of the WEC array analysed through OPERA with a range of other devices from a study completed in 2016 [23], in which the LCA performance of different anonymous ocean energy concepts was evaluated and classified by technology. The OPERA array's carbon intensity result is positioned in the higher three-quarters of all concepts considered, but lower than the point absorber technology, which is the most comparable device with the WEC tested in OPERA. The lower the GWP, the lower the environmental impact. There is a UK target for renewable energy technologies to achieve GWP values smaller than 50gCO<sub>2</sub>/kWh by 2030 [24]. OPERA shows a GWP of 69.4 gCO<sub>2</sub>/kWh.

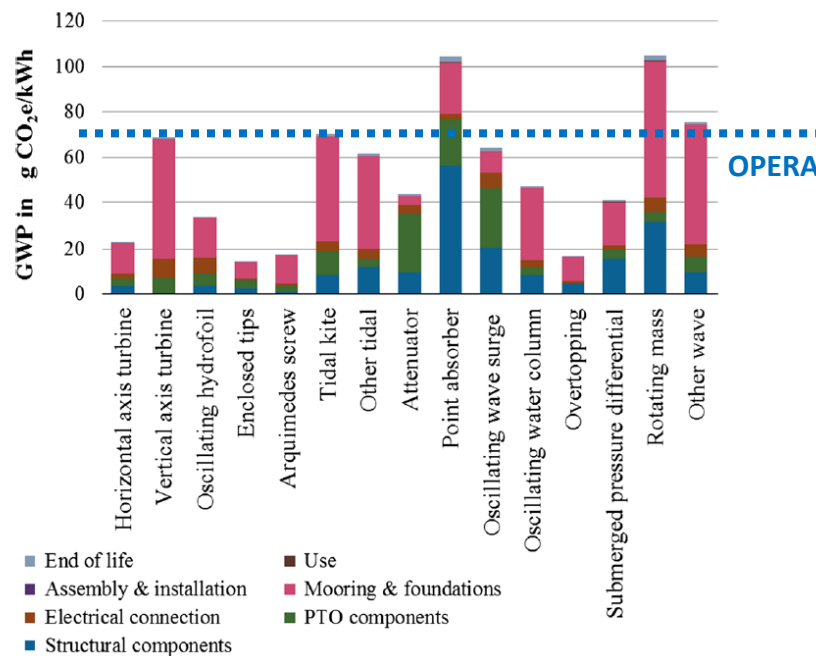
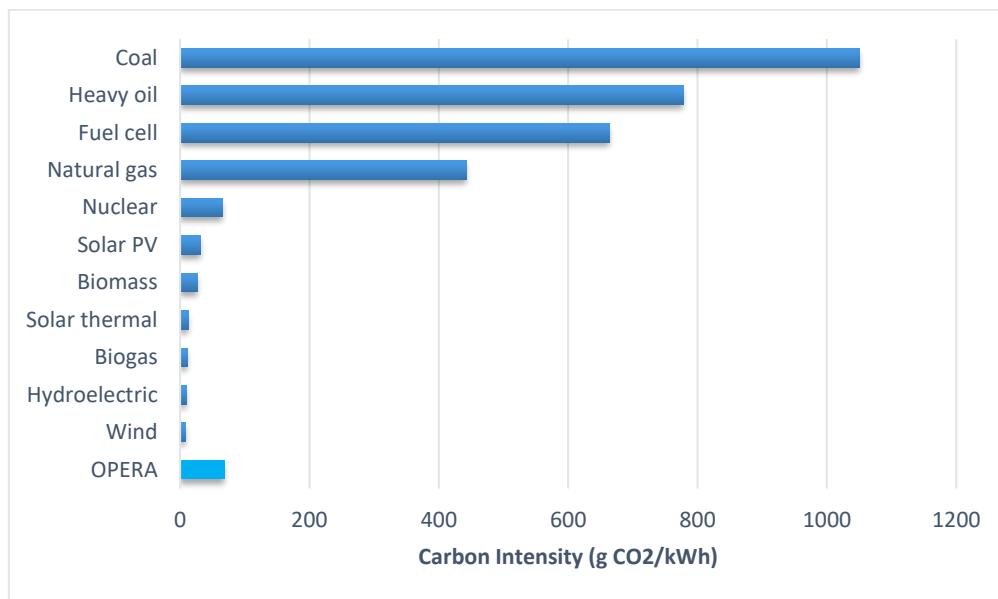


FIGURE 33: CARBON INTENSITY ACCORDING TO LIFE CYCLE STEP (ADAPTED FROM [23]).

It must be highlighted, as stated in [20], that “direct comparison with values from other LCA studies can be problematic, as the assumptions may be different and often non-conservative as well as issues regarding compliance with the ISO standards”. The OPERA scenario considers recycling credit and a detailed fuel consumption calculation coming from the open sea experience, which is disregarded in [23].

The OPERA array becomes especially environmentally-beneficial when compared to more traditional electricity generation alternatives such as fossil fuels, see Figure 35. It also shows a good performance against better-established renewable technologies such as solar PV or geothermal [25].





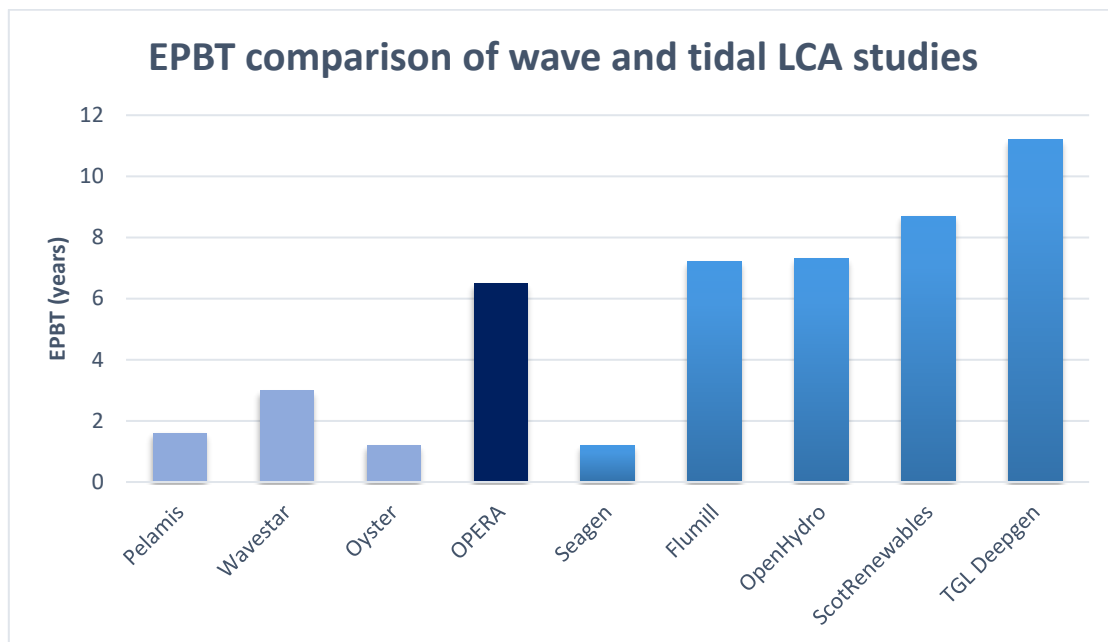
**FIGURE 34: LIFE CYCLE CARBON INTENSITIES OF OPERA AND ALTERNATIVE ENERGY GENERATION TECHNOLOGIES, AFTER REFERENCE [25].**

Every kWh of power generated by OPERA device saves 981g CO<sub>2</sub> when compared to the same power from coal, 709 CO<sub>2</sub> when compared to heavy oil and 374g CO<sub>2</sub> when compared to gas. This is relevant considering that the energy industry is required to be almost completely decarbonized by 2030 [26]. In the UK, electrification is the focus for emissions' reduction. The government is dedicated to eliminating coal power by 2025 [26]. This transition to renewables will assist on carbon savings.

Based on OREC study, 2018 [26], wave energy has the potential to reduce emissions by 1MtCO<sub>2</sub> per year in 2040, which accounts with ocean energy savings of 937g CO<sub>2</sub> when compared to the same power from coal and 394 CO<sub>2</sub> when compared to gas. Therefore, the carbon savings by the OPERA device is in line with the reduction in emissions foreseen by OREC, 2018 [26]. Therefore, OPERA device has the potential to contribute to the reduction in carbon emissions.

#### 5.3.3.2 ENERGY PAYBACK IN TIME (EPBT)

Figure 36 displays a comparison of the EPBT calculated for the OPERA array with other marine renewable energy technologies. The other technologies with available LCA include, Pelamis [27], Wavestar [28], Oyster [29], Seagen [20], Tidal Generation (TGL) Deepgen, OpenHydro, ScotRenewables and Flumill [25].



**FIGURE 35: ENERGY PAYBACKS OF MARINE (WAVE [LIGHT BLUE] AND TIDAL [DARK BLUE]) ENERGY GENERATING TECHNOLOGIES.**

In terms of energy payback, the OPERA array's performance is within the range of other LCA studies. The contrast between the results is partly caused by the different energy yield performances for each technology. For the same value of embodied energy, the higher AEP, the lower the energy payback, as can be concluded from Equation (19).

For instance, on the left-hand side of the graphs, studies on Pelamis and the Oyster considered equivalent CF of 45% and 55% respectively, while studies on the last four tidal stream technologies on the right-hand side were based on CF figures ranging from 18% to 24%. This results in a poorer (i.e. longer) energy payback for the latter with respect to the former. OPERA presents CF of 33% for the EMEC site (as seen in section 4.1.4) and shows an EPBT value in between Pelamis / Oyster and Flumill / OpenHydro / ScotRenewables / TGL Deepgen.

As stated, direct comparison with values from other LCA studies can be challenging. Different studies consider different boundaries. The absence of stricter guide makes the results comparison difficult.

### 5.3.4 SENSITIVITY ASSESSMENT

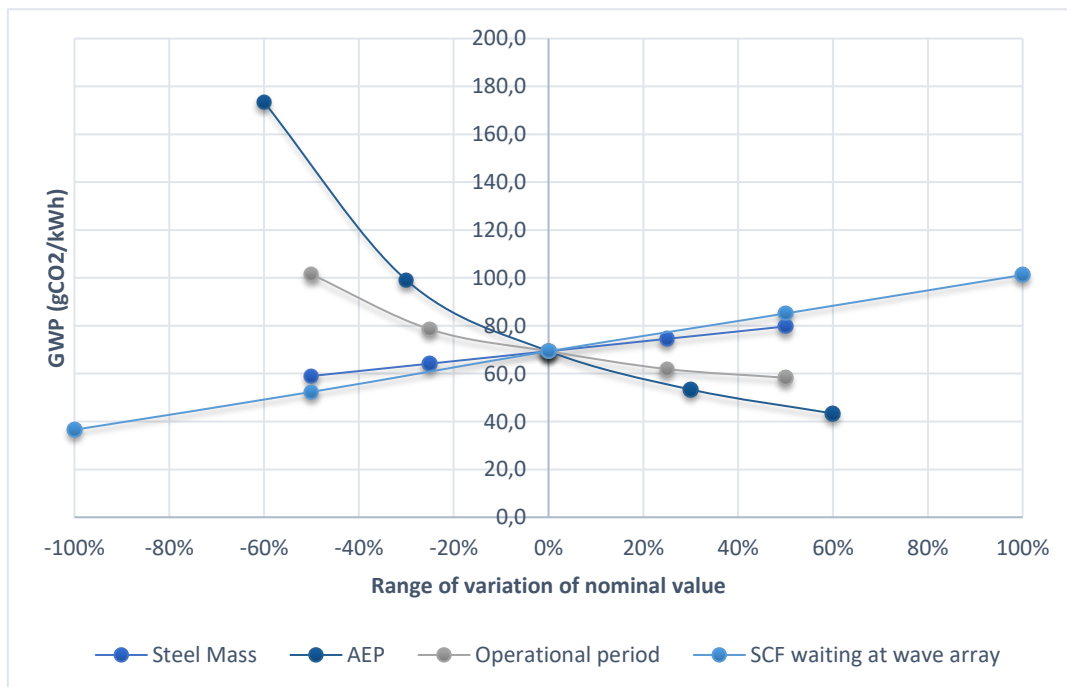
The calculation of the LCA metrics for the OPERA array relies on many assumptions and estimations due to the early stage of development of the WEC and the wave energy industry as a whole. These assumptions often contain many uncertainties, which eventually result in a high level of uncertainty being contained within the calculated LCA results. For this reason, this section presents plausible alternative values for some input parameters. This study will focus on the GWP metric.

The variables chosen for this sensitivity study, together with the values used in the analysis, can be seen in Table 25.

**TABLE 25: SUMMARY OF PARAMETERS CONSIDERED IN THE SENSITIVITY ANALYSIS.**

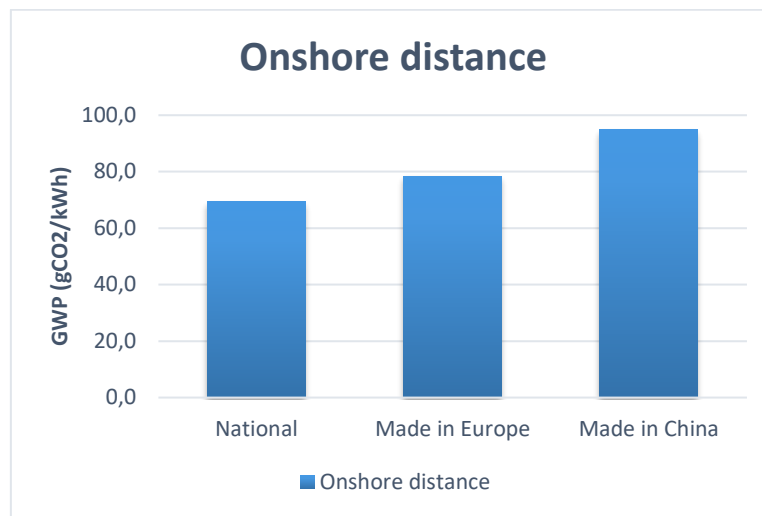
Variable / input parameter	Nominal value	Range of variation of nominal value
Steel mass (kg)	516,279.51	+ / - 30%
AEP (MWh)	909.6	+ / - 60%
Ship capacity factor (SCF) waiting at wave array (%)	5	+ / - 100 %
Operational period (years)	20	+ / - 50%
Onshore distance (km)	50	2,000 km (Europe) 8,000 km (China)

Figure 37 presents the results of a sensitivity analysis of the LCA calculation. Each curve is obtained by modifying just one variable in Table 25 at a time, and keeping the nominal conditions for the rest of them.



**FIGURE 36: SENSITIVITY ANALYSIS FOR THE LCA (GWP) OF THE ARRAY OF 18MW AT EMEC.**

The sensitivity results due to the variation of the onshore distance is shown in Figure 38.



**FIGURE 37: SENSITIVITY ANALYSIS FOR THE LCA (GWP) OF THE ARRAY OF 18MW AT EMEC FOR DIFFERENT ONSHORE DISTANCES.**

Some interesting conclusions can be drawn in light of Figure 37. The steeper the curve, the more impact the uncertainty in that variable has on LCA. As per Figure 37, the input parameters could be ranked in terms of impact on GWP, from largest to smallest, as follows: AEP (steepest curve near the nominal conditions); SCF waiting at wave array; operational period; and steel mass.

**TABLE 26: GWP VARIATION OBTAINED IN THE SENSITIVITY ANALYSIS.**

Inputs	Parameters	Var.1	Var.2	Var.3	Var.4
AEP	input variation	-60%	-30%	30%	60%
	GWP variation	250%	143%	77%	63%
SCF waiting at wave array	input variation	-100%	-50%	50%	100%
	GWP variation	53%	75%	123%	146%
Operational period	input variation	-50%	-25%	25%	50%
	GWP variation	146%	113%	89%	84%
Steel Mass	input variation	-50%	-25%	25%	50%
	GWP variation	85%	93%	107%	115%
Onshore distance	input variation	-	-	Europe	China
	GWP variation	-	-	113%	137%

The sensitivity analysis of LCA shows that the AEP has the most significant effect on the GWP. Increasing AEP should be a focus for development to reduce environmental impacts. This is a similar conclusion made during the LCOE sensitivity assessment. Figure 38 shows that if produced in Europe emissions could increase by 13%, whereas if the WECS were made in China the emissions could increase by 37%.

## 6. SCOE MODELLING

A high-level outline of the global economic model's Socio-Economic Cost of Energy (SCOE) module and its operation was provided in OPERA deliverable D7.2 [30]. Consequently, this present section primarily focuses on the SCOE calculation process, its assumptions and results.

Socio-economic analyses evaluate externalities to determine the social benefits of undertaking particular projects. The OPERA global economic model's SCOE module focuses on the impact of an OPERA array deployment on the increasing regional economic activity and jobs supported. The model's results are useful for highlighting, to policy makers and public funding bodies, the alternative benefits of investing in a project.

The main elements (i.e. inputs/outputs and methodology) of the SCOE procedure carried out in task T7.3 are described in the section 6.1. The results of a case study in which an 18 MW array of OPERA devices are deployed at EMEC (Scotland) are presented in section 6.1.4.

### 6.1 MODELLING METHODOLOGY

#### 6.1.1 DEFINITION OF REGIONS OF INTEREST

The first step in a regional SCOE study is to indicate the region, or regions, of interest. The regions determine the industry capacity characteristics and the Industry by Industry (Ixl) Input-Output (IO) tables used in the calculation of the Gross Value Added (a measure of additional economic activity, GVA) and employment effects/multipliers. IO tables describe the sales and purchase relationships between producers and consumers within a regional economy. In the specific case of Ixl IO tables, they show the flows of final and intermediate goods and services defined according to industry outputs.

Within OPERA, two different regions were selected for the socio-economic analysis: Scotland and the Basque Country. The two cases were selected with the intention of highlighting the different socio-economic benefits in different regions of interest. However, due to high levels of uncertainty in the analysis, and in the interests of brevity, the results of only one of the case studies will be presented here; those obtained for Scotland. The differences between the GVA and jobs supported calculated for both sites are within the uncertainty ranges of the analysis and therefore this study cannot explicitly identify the differences. Instead, the results present the approximated benefits of a large array of wave energy converters to the deployment region.

#### 6.1.2 DEFINITION OF PROJECT TIMELINE

Once the regions of interest are identified, the project timeline needs to be established. The project timeline indicates when project spend is invested. In this case, the project timeline is

global economic model's project timeline, see Figure 14. Recall, the key project periods during which cost is accrued are considered to be manufacturing, installation, O&M and decommissioning.

### 6.1.3 DETERMINATION OF GROSS SPEND

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The cost centre breakdowns for each project period are presented in Table 27 to Table 30. The cost centre breakdowns specify the gross spend invested in each cost centre,  $GS_{cc}$ , and also which industries are engaged in the cost centre's activities. Note, where two or more industries were expected to be engaged in activities on a cost centre, gross spend was divided evenly amongst the industries involved. This is not correct as spend won't be evenly distributed, however, without any evidence it is a reasonable assumption as any other estimate of the spread of spend would also be as incorrect. It would also be incorrect to claim that all the cost centre spend should be spent on one industry.

Different ready reckoners (see section 6.1.4) and GVA and employment effects (see section 6.1.5) are calculated for each industry sector engaged as they each have different supply chains. Values for leakage (the ready reckoner used in this study) and the GVA and employment effects for each industry are also presented in Table 27 to Table 30.



TABLE 27: INDUSTRY DATA ESTIMATED FOR THE MANUFACTURING PERIOD OF THE SCOE CASE STUDY.

Project period	Cost centre	SIC codes and industry	Ready Reckoner: Leakage (%)	GVA effect (Type II, GVA/€M)	Employment effect (Type II, jobs/year/€M)
Manufacturing	WEC structure	25 Fabricated metal	50	0.8	12.6
		24.1-3 Iron & Steel	62	0.6	7.3
		23.5-6 Cement lime & plaster	39	0.8	13.2
		23OTHER Glass, clay & stone etc.	42	0.8	11.7
	Mooring system	25 Fabricated metal	50	0.8	12.6
		22 Rubber & Plastic	52	0.7	11.4
	PTO	23OTHER Glass, clay & stone etc.	42	0.8	11.7
		24.1-3 Iron & Steel	62	0.6	7.3
		24.4-5 Other metals & casting	55	0.6	6.9
		27 Electrical equipment	61	0.7	9.0
		28 Machinery & equipment	58	0.6	11.8
	Engineering management	41-43 Construction	36	0.8	14.4
		71 Architectural services etc.	40	0.9	14.5
		72 Research & development	38	1.0	16.7





Project period	Cost centre	SIC codes and industry	Ready Reckoner: Leakage (%)	GVA effect (Type II, GVA/€M)	Employment effect (Type II, jobs/year/€M)
	Offshore cable	27 Electrical equipment	61	0.7	9.0
		24.1-3 Iron & Steel	62	0.6	7.3
		22 Rubber & Plastic	52	0.7	11.4
		28 Machinery & equipment	58	0.6	11.8
	Rock coverage	06-08 Oil & gas extraction, metal ores & other	44	0.6	10.0
		41-43 Construction	36	0.8	14.4
		50 Water transport	55	0.7	9.0
	Offshore cable treatment	27 Electrical equipment	61	0.7	9.0
		50 Water transport	55	0.7	9.0
	Onshore substation	27 Electrical equipment	61	0.7	9.0
	Onshore cable	27 Electrical equipment	61	0.7	9.0





**TABLE 28: INDUSTRY DATA ESTIMATED FOR THE INSTALLATION PERIOD OF THE SCOE CASE STUDY.**

Project period	Cost centre	SIC codes and industry	Ready Reckoner: Leakage (%)	GVA effect (Type II, GVA/€M)	Employment effect (Type II, jobs/year/€M)
Installation	Installation	33 Repair & maintenance	52	0.9	11.3
		41-43 Construction	36	0.8	14.4
		50 Water transport	55	0.7	9.0
		52 Support services for transport	0	0.9	13.2

**TABLE 29: INDUSTRY DATA ESTIMATED FOR THE OPERATION PERIOD OF THE SCOE CASE STUDY.**

Project period	Cost centre	SIC codes and industry	Ready Reckoner: Leakage (%)	GVA effect (Type II, GVA/€M)	Employment effect (Type II, jobs/year/€M)
O&M	Insurance	65 Insurance and pensions	46	0.7	6.9
	Operation and maintenance	33 Repair & maintenance	52	0.9	11.3
		50 Water transport	55	0.7	9.0
		52 Support services for transport	0	0.9	13.2





TABLE 30: INDUSTRY DATA ESTIMATED FOR THE DECOMMISSIONING PERIOD OF THE SCOE CASE STUDY.

Project period	Cost centre	SIC codes and industry	Ready Reckoner: Leakage (%)	GVA effect (Type II, GVA/€M)	Employment effect (Type II, jobs/year/€M)
Decommissioning	Decommissioning	33 Repair & maintenance	52	0.9	11.3
		38, 39 Waste, remediation & management	48	0.7	9.8
		41-43 Construction	36	0.8	14.4
		50 Water transport	55	0.7	9.0
		52 Support services for transport	0	0.9	13.2



#### 6.1.4 DETERMINATION OF NET SPEND – READY RECKONERS

The net spend, in the region of interest, on a particular cost centre,  $NS_{cc}$ , is calculated through equation (14).

$$NS_{cc} = GS_{cc} * [(1 - L) * (1 - D_w) * (1 - D_p) * (1 - S)] \quad (14)$$

Equation (14) includes four ready reckoners which convert the gross spend on a cost centre to the net spend invested in the region of interest. The ready reckoners are: Leakage ( $L$ ), Deadweight ( $D_w$ ), Displacement ( $D_p$ ) and Substitution ( $S$ ). In this study, the ready reckoners were estimated using the Ixl IO tables and by comparing the gross spend invested in each industry with the “Total output at basic prices” for the each of engaged industries, which is also obtained from the Ixl IO tables.

Leakage reflects how much of the spend on a cost centre is invested in the region of interest; a high leakage value would indicate that a large amount of the cost centre spend was invested outside the region of interest. Deadweight accounts for the fact that spend on cost centre activity may prevent alternative additional economic activity from occurring in the region of interest; a high deadweight value would indicate that alternative investment would have been made in the region where the cost centre’s activities not to occur. Displacement accounts for industrial activity in the region shifting from existing work to work required on the cost centre; a high displacement value would indicate that the cost centre’s activity takes a large market share from existing firms in the region of interest. Substitution indicates how existing industry might change their operations to better serve the cost centre activity; a high substitution value would indicate that the cost centre requires a significant focus shift by industries in the region from their existing operations to those of the cost centres.

In the present study, deadweight, displacement and substitution have been set to 0 %. Displacement and substitution have been set to 0 % because of the relatively low spend of the project, i.e. the values spent in the project are low relative to the overall value of the industries in Scotland that would potentially be involved in the deployment and operation of the WEC array. Deadweight is also 0 %, i.e. where the project not undertaken, no added economic activity would have occurred in the region.

Leakage values can be nonzero as it is acknowledged that spend would most likely be invested outside Scotland during the project. For the majority of cost centres, leakage for the industry involved in a particular activity was estimated as being the ratio of “Total domestic use” to the sum of “Imports from the rest of UK” and “Imports from rest of world”. In a number of cases, leakage was forced to be 0 % as it was determined that spend would be invested in Scotland. One example of this: the leakage for the “52 Support services for transport” industry engaged during O&M (which is used to account for warehouses and storage during O&M) is forced to

0 % as it is assumed that equipment and devices will be stored at the harbours near to the deployments in the region of interest. The activities/industries for which leakage was forced to zero are highlighted in tables Table 27 to Table 30 with shaded grey leakage cells.

Note, it is conceivable that leakage figures could reduce for large arrays or if a sector was to build up in the regions of interest for the development and support of WECs. However, for the scale of the array considered in this case study, it is envisaged that the supply of goods and services would continue to arise from existing and established industry sites outside of the regions of interest.

### 6.1.5 GVA AND EMPLOYMENT EFFECTS AND MULTIPLIERS

The IxI IO tables were obtained for the regions of interest from [31]. Type II GVA and employment effects were used in this analysis. Type II GVA and employment effects are calculated through the manipulation of IxI IO tables. Type II effects are used in the calculation of the GVA and jobs supported that result from direct, indirect and induced activity. Direct GVA/jobs supported are those created within the project developer to undertake the project. Indirect GVA/jobs supported are those created in the supply chain to meet the increased demand of the project developer. Induced GVA/jobs supported are those created in the region of interest due to the increased spending of employees throughout the supply chain.

As opposed to Type II, Type I effects account for only direct and indirect activity. Type II effects were used in this study to obtain a wider picture of how the projects impacted the regions of interest.

## 6.2 RESULTS AND DISCUSSION

### 6.2.1 METRICS

As previously outlined, the main metrics presented in this SCOE analysis are GVA and jobs supported. GVA indicates the increase in economic activity to an area of interest. It is usually defined as the difference between output and intermediate consumption for a given sector or firm. As stated in the Scottish Government's Input-Output Methodology Guide, "broadly speaking, it is simply the sum of each company's outputs (sales) less inputs (purchases)" [32]. GVA represents, in this study, the net spend that is invested in the region due to a WEC array's deployment and operation.

Jobs supported is estimated in job years. This acknowledges that jobs supported by the project will have a finite time. For example, jobs supported by the manufacturing of the WECs are likely to only last as long as the manufacturing phase, unless the same employees are engaged in alternative activities at later stages.

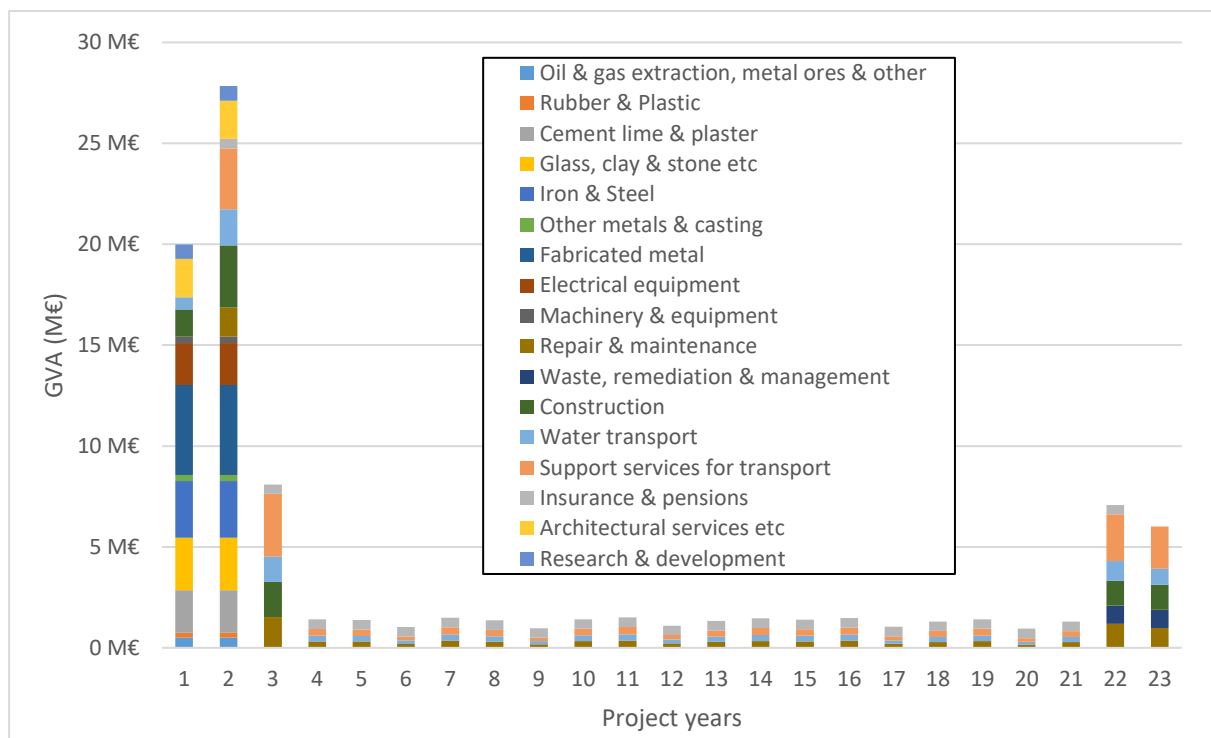
### 6.2.1.1 GVA

GVA is calculated through equation (15),

$$GVA = \sum_{cc,ind=1}^J NS_{cc,ind} * g_{cc,ind}, \quad (15)$$

where  $NS_{cc,ind}$  is the net spend on a project cost centre industry.  $g_{cc,ind}$  is the GVA effect for the corresponding project cost centre's industry. As previously discussed, the GVA effect is calculated through manipulation of the IxI IO tables, see OPERA D7.2 for further details [30]. The GVA effect coefficient calculates the GVA arising from a change in final demand for a given industry's output of £1 [32].  $g_{cc,ind}$  enables the calculation of GVA due to activity in a particular cost centre's industry.  $J$  in equation (15) is the number of cost centre industry activities considered. Ultimately, equation (15) yields GVA for the whole project, though it is possible to obtain the GVA due to activity in each cost centre,  $GVA_{cc}$ .

The undiscounted GVA to the Scottish economy throughout the project lifetime of an 18 MW array of OPERA devices was estimated to be roughly £92M, or £5M per MW. Figure 38 shows the contribution of each of the Scottish industries, estimated to be involved in each project stage, to the overall GVA due to the project.



**FIGURE 38: GVA TO SCOTLAND DUE TO THE 18 MW ARRAY PROJECT WHEN DEPLOYED AT EMEC.**

### 6.2.1.2 JOBS SUPPORTED

The number of jobs created by the project is calculated using equation (16).

$$Jb = \sum_{cc=1}^J NS_{cc,ind} * E_{CC,ind} \quad (16)$$

Note, equation (16) is exactly the same as equation (15) except that it includes  $E_{CC,ind}$ , the employment effect for a cost centre, instead of  $g_{CC,ind}$ . The employment effect calculates the impact upon employment, in job years supported, throughout the region's economy arising from a change in final demand for a given industry's output of £1.

Within Scotland, the total job years supported along the project lifetime was estimated to be roughly 1,309, or 72.7 job years per MW. Figure 39 shows the job years supported by the different Scottish industries assumed to be engaged in the development and support of the 18 MW array of OPERA devices deployed at EMEC.

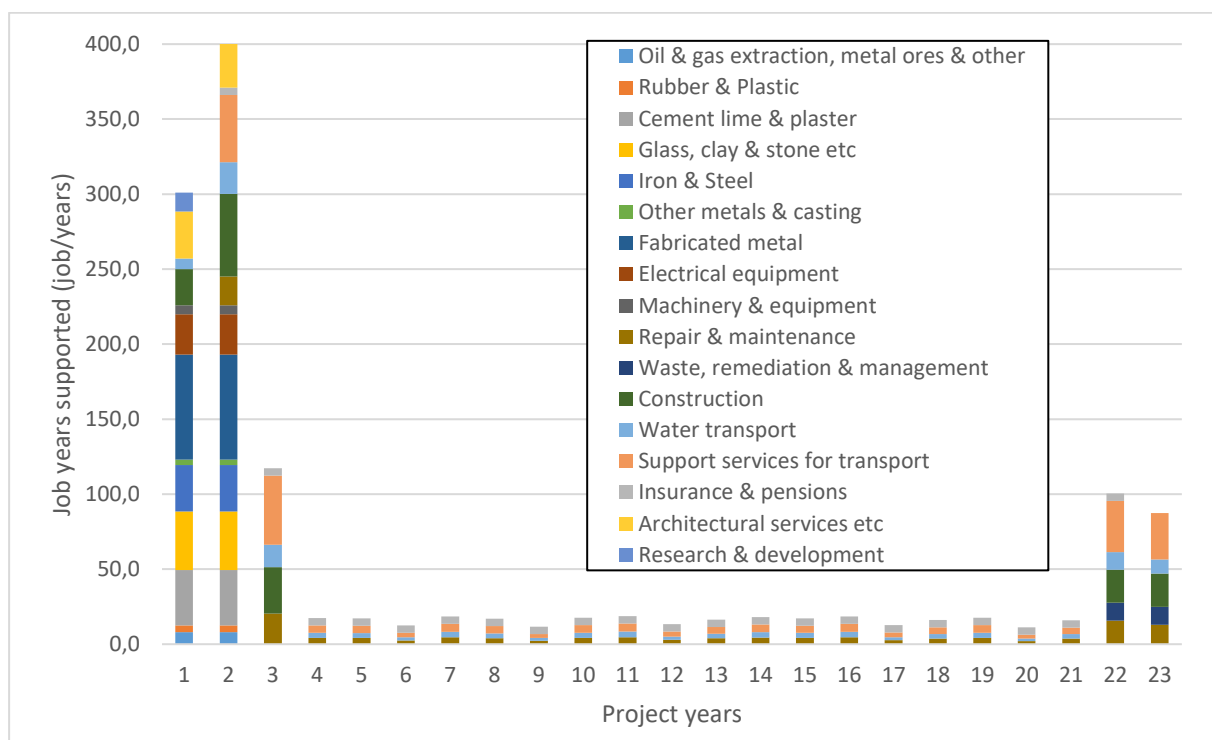


FIGURE 39: JOBS SUPPORTED IN SCOTLAND DUE TO THE 18 MW ARRAY PROJECT WHEN DEPLOYED AT EMEC.

### 6.2.1.3 DISCUSSION

The SCOE analysis has presented an estimate of the GVA that a WEC array's deployment could contribute to the deployment region. Further to this, it has also presented an estimate of the number of jobs that could be supported as a result. The figures presented in this study contain

high levels of uncertainty ( $\delta_{SCOE}$ ), owing to uncertainties associated with WEC array costs ( $\delta_{WEC\ costs}$ ; CAPEX, installation, O&M and decommissioning), estimates of cost breakdown ( $\delta_{CB}$ ), industry assignment ( $\delta_{Ind}$ ), ready reckoners ( $\delta_{RR}$ ) and effects ( $\delta_E$ ), see equation (17).

$$\delta_{SCOE} = \delta_{WEC\ costs} + \delta_{CB} + \delta_{Ind} + \delta_{RR} + \delta_E \quad (17)$$

Due to these uncertainties, it isn't possible to estimate an accurate figure of the benefits, however, the figures do serve the purpose of highlighting how the deployment of an array of WECs would generate income for regions adjacent to deployments and support jobs.

It should be noted that the undiscounted GVA and job supported impacts presented in this study are representative of a single project. This is demonstrated graphically by Figure 38 and Figure 39 where a short period spike in GVA and job years supported is seen at the start and end of the project (manufacturing and decommissioning). The development of a commercial industry would result in more significant and sustainable GVA and job support impacts, particularly to whichever region takes the lead in the development of the wave energy sector and establishes the industry and supply chain expertise necessary to support it. Further to this, a peculiar quirk of the methodology adopted here is that, were the technology to improve performance and reduce costs, by focussing on a standalone project, the regional socio-economic benefits would reduce; due to the lower spend. This further emphasises the need to undertake a socio-economic analysis of a commercial industry, in which, improvements in technology would lead to an increase in demand, which in turn would be reflected in improved socio-economic impacts due to the wave energy sector.

Other studies, such as [26], have estimated the potential socio-economic benefit that a competitive wave, and tidal, energy industry could have for the UK. [26] estimated that in 2040, in a positive scenario, that the wave energy industry could support up to 8,100 jobs. Further to this, [26] also estimated that the wave energy industry could benefit the UK economy through a GVA of £1,500m.

As discussed, the outcome of the present SCOE study is useful for highlighting the added benefits of investing in a marine renewable energy project to policy makers and potential funders, either public funding bodies or private investors.

## 7. CONCLUSIONS

### 7.1 LCOE

This study has evaluated the techno-economic performance of several arrays of OPERA WECs. Arrays including four technological innovations (shared mooring, bi-radial turbine, control system and elastomeric tether) tested through the OPERA project were compared against the performance of array of devices of the Bench Case scenario without the innovations. The primary metric used to evaluate the device was Levelised Cost of Energy (LCOE). The study also evaluated the techno-economic performance of OPERA arrays for two locations (EMEC and BiMEP) and for different array sizes (250kW, 10MW and 18MW).

LCOE was observed to reduce by more than 50% for the arrays when considering the four OPERA innovations. Competitive LCOE values [7] could be achieved in both deployment locations for the array scenarios With Innovation. The lowest LCOE values were calculated for deployments at EMEC, largest array. Considering the projected reductions of LCOE due to learning, OPERA's LCOE is on a trajectory towards consolidating a commercially competitive cost of electricity generation by the time the industry reaches global market maturity.

The sensitivity analysis showed that the most influential variables in the LCOE calculation were AEP, the discount rate and the operational period. This means that uncertainties in other parameters such as PTO cost, insurance, etc, had less of an impact on uncertainty in LCOE.

### 7.2 LCA

The present LCA study covered the materials, components and life cycle stages that contribute to energy input and carbon emissions of an OPERA array of 18MW. The most significant contributors were identified. Both the manufacturing and the O&M phases were found to be important in terms of carbon footprint associated. The OPERA open sea experience allowed a detailed calculation of the fuel consumption during offshore operations, which is often disregarded in LCA studies. Results show that the O&M stage has a significant impact on overall project carbon emissions. The WEC structure was found to be the component with the highest representation in associated energy input and carbon emissions, due to its mass. Steel is the main contributor to the OPERA embodied energy and carbon. At the same time, steel also provides most of the recycling credit, which reinforces the importance of its waste and disposal management.

It was found that, by yielding a GWP of 69 g CO<sub>2</sub>/kWh and EPBT of 6.6 years, the LCA performance of the OPERA technology can compete with alternative ocean electricity generating technologies and offers many environmental advantages compared to fossil-fuelled generation. Every kWh of energy generated by OPERA device saves 374-981 g CO<sub>2</sub>



compared to the same energy from coal, heavy oil and gas, which is extremely important once the energy industry requires to be almost completely decarbonized by 2030. Wave energy has the potential to reduce emissions by 1MtCO<sub>2</sub> per year in 2040. This is a good reference to see that OPERA would be within the range expected by the sector. Taking into account the early stage of development of the OPERA technology, the fact that the LCA results compare well with alternative and more established technologies is very encouraging.

## 7.3 SCOE

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The socio-economic study complemented the economic analysis with insights of the potential additional benefits of an 18 MW OPERA project array in terms of undiscounted GVA and jobs supported. The outcome of the present SCOE study is useful for highlighting the added benefits of investing in a marine renewable energy project to policy makers and potential funders, either public funding bodies or private investors.

Results estimated an undiscounted GVA of £92M and around 1,309 job years supported. The discussion section highlighted that large uncertainties are contained within the calculated results due to the large number of uncertainties that arise in the methodology followed. It also highlighted the need to investigate the socio-economic benefits of a commercial wave energy industry to present sustainable job support and economic benefit.

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