LiftWEC

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

Deliverable D8.1
Cost Database

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EXECUTIVE SUMMARY

This document constitutes Deliverable 8.1 of the LiftWEC project and consists of a cost database gathering all costs related to a wave energy project. A thorough literature review has been performed to compile the cost database. The document is divided into four sections. After a brief introduction, the first section enumerates all costs related to capital expenditure. Costs related to operating expenditure are gathered in the second section. The following section breakdowns the cost in order to visualise easily the relative importance of the different cost centres. A discussion driven by the objective of the LiftWEC project, of developing a cost-effective lift based wave energy converter, is concluding the report.

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1 INTRODUCTION

This document constitutes Deliverable '*D8.1 Cost Database*' of the LiftWEC project. LiftWEC is a collaborative research project funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 851885.

1.1 PROJECT OUTLINE

The LiftWEC project focuses on the development of a novel type of Wave Energy Converter (WEC), called LiftWEC, which is intended to utilise hydrodynamic lift forces to incite device motion and extract wave energy using a rotating hydrofoil, as opposed to the more traditional approach of exploiting buoyancy and diffraction force regimes. This radically different approach to the design of wave energy converters offers the opportunity of making a step-change in the potential of wave energy, and thus leads the way for its commercialisation, where no commercially viable wave energy system currently exists.

1.2 PURPOSE OF THE DELIVERABLE

The cost database is a critical component of the parametric cost model and the Levelized Cost of Energy (LCoE) calculation tool. A successful delivery of a cost database will ensure reliable estimates of the device LCoE, as the costs in the LCoE tool will be updated with the findings described in this document. Upon the completion of the present document, a spreadsheet containing all the costs mentioned here, will be created and populated from all members of the consortium throughout the LiftWEC project.

The focus of this deliverable is to provide cost estimates for a utility-scale power generation technology. Whenever possible, cost data from the different development stages (single prototype and early arrays) has also been provided. This serves to illustrate how costs are expected to decrease as development advances.

The considerations to support preliminary concept development regarding Cost of Energy have been identified as follows:

1. What are likely to be the main cost centres for LiftWEC?
2. How may costs vary with the LiftWEC width and other key dimensions?
3. What "break points" may exist where LiftWEC costs change rapidly?
4. What other key factors may influence the cost of energy for LiftWEC?

Efforts are made throughout the deliverable to provide an answer to these questions.

The learnings from recently finished and ongoing European and national funded projects have been used as part of the literature review carried out to document the costs (Pelamis data from Wave Energy Scotland, lesson-learned from BiMEP test sites, results from the SI Ocean and the OPERA project, etc). Also reference books of the ocean energy sector, such as Pecher / Kofoed (2017) and Greaves / Iglesias (2018) have also been used in the review process.

Please note that costs presented in this document have been adjusted to account for inflation or differences in commodity prices. The costs are mostly from the last 20 years (bibliography years).

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1.3 Structure of the Document

The document is divided into four sections: *Capital Expenditure*, *Operating Expenditure*, *Cost-Centres Breakdown* and *Discussion and Conclusions*. In the first two sections, the cost centres for both capital and operating expenditure are described and detailed in terms of cost. The Cost-Centres Breakdown section summarises and compares all costs. After reviewing the cost centres in the breakdown section, a discussion is formulated based on the objectives of the LiftWEC project and conclusions are drawn.

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2 CAPITAL EXPENDITURE

Capital expenditure (CAPEX) is all expenditure associated with a Wave Energy Converter (WEC) farm development, deployment and commissioning until the operation of the WEC farm starts. It also includes decommissioning at the end of the project life.

According to the findings from the OceanSET project (OceanSET, 2020) upon a survey consultation with technology developers, current average CAPEX of single WEC prototypes at Technology Readiness Level 7 (TRL7) or above is 12.7 MEUR/MW. This survey was answered by seven developers (of the point absorber and oscillating water column type) over TRL 7 and active in 2018, and data was aggregated.

2.1 DEVELOPMENT AND CONSENTING

2.1.1 Description

Costs related to development include the multifaceted process of taking a WEC farm from inception through to the point of financial close or commitment to build, including environmental impact assessment, planning, front end engineering and design (FEED) studies and contract negotiation.

2.1.2 List of costs

Development services

The development services which include project management, design engineering, planning and consenting are normally reported as a percentage of CAPEX. The percentage is expected to decrease proportionally as the installed power capacity of the wave farm increases, and standard procedures are developed (Nielsen, 2001). However, literature review is not fully aligned with this, and estimates (ranging from 2% up to 12% of CAPEX) do not fully converge. This may be due to the fact that these cost are very project specific. Carbon Trust (2006) estimates development services at 2% of CAPEX for a wave energy farm, Fernandez Chozas *et al. (*2014) at 3% of CAPEX for a single WEC, Nielsen *et al.* (2018) in the range of 6.5% to 7.5% of CAPEX for a 200 MW wave farm, depending on the number of WECs installed (20 or 114 WECs, respectively); and Siegel (2012) at 12% of CAPEX for a 200 MW wave farm.

As a comparison, the 40 MW Middelgrunden offshore wind energy farm located 3 km offshore the city of Copenhagen (Denmark), which was the first offshore wind farm built in the MW-scale, reported actual development cost of 6% of CAPEX (Vikkelsø *et al.*, 2003).

Resource monitoring

The cost for wave measuring buoy deployments can vary from 20.000 to 50.000 EUR/year depending on location and buoy measurements capabilities and other characteristics (e.g. directional /non-directional, measurements of currents, insurance included, rented or owned, etc) (DanWEC, 2013), (Kofoed, 2020).

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Environmental studies

Environmental studies include both environmental surveys as well as geological and hydrological surveys. The cost related to environmental studies have been estimated to between 4 MEUR to 8 MEUR for a 200 MW wave energy farm (Siegel, 2012). ORE Catapult (2019) provides an indicative example for an offshore wind farm and estimates the environmental studies cost to 0.3% of CAPEX.

Certification

The cost of certification for a 200 MW wave energy farm is estimated at 6.5 MEUR (Siegel, 2012).

2.2 Wave energy converter (Structure and Prime mover)

2.2.1 Description

The structure cost includes detailed infrastructure design and supply of all components from the mooring attachment point, excluding the power take-off system. Delivery to a port is also included. Structure and prime mover are the cost centres with higher impact on CAPEX.

2.2.2 List of costs

When looking at the structure and prime mover as a whole, according to Previsic (2004) this cost center accounts for 35.5% of the CAPEX for a case study of the Pelamis WEC deployed off the coast of California, USA, and according to Carbon Trust (2006), structure makes up 27% of a wave farm, and to the OPERA project (OPERA, 2019a and 2019b) 36% for a farm deployed at EMEC, and 38% for a farm deployed at BiMEP.

Structure materials:

Table 1.1 contains the unit cost in EUR/ton for the most common materials used for the structure and prime mover of WECs, according to Nielsen (2003), Meyer *et al.* (2002) and Nielsen *et al.* (2020):

Table 2.1: Cost of raw materials, in EUR/ton

Material	Unit cost (EUR/ton)
Concrete	250
Ballast concrete	70
Steel	3.400
Glass fibre	9.500

Cost of steel:
Steel prices are very variable, as shown in Myhr *et al.* (2014). However, it is important to set a value, as sensitivity analysis of the effect of this variability on LCOE has been extensively researched.

- 1800 EUR/ton (Myhr *et al.*, 2014)
- 3800 EUR/ton (Siegel, 2012).

Cost of fibre glass: The cost of fibre glass ranges from 7.700 to 11.500 EUR/ton of fabricated composites (Siegel, 2012).

Instrumentation and control (cooling system, insulation, drain, wring, PLC-SCADA, Instrumentation and communication, Others)

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Wave Energy Scotland (WES, 2016) compiled the cost of Pelamis P2 WEC. Instrumentation and control accounts for 0.68% of CAPEX (or 3% of the total PTO Primary Transmission Cost, which accounted for 64% of the total PTO cost).

2.3 Balance of Plant

2.3.1 Description

The Balance of Plant costs relate to the power take-off (PTO) system includes supply of all components constituting the PTO system, including the delivery to the port.

2.3.2 List of costs

Total PTO

The total cost of the PTO system (including the PTO itself, the generator, the power electronics, the control and safety system and others) is highly dependent on the WEC and the PTO configuration used. PTO cost account for 31.2% of CAPEX according to Previsic (2004) for a case study of the Pelamis WEC deployed off the coast of California, USA; and in the range of 16%-17% for a fictitious utility-scale case (OPERA, 2019a and 2019b).

For the Mutriku Oscillating Water Column (OWC) pilot plant rated at 296 kW, 1.5 MEUR was spent on the electro-mechanical equipment (Torre-Enciso et al., 2012), leading to 5.000 EUR/kW.

According to Nielsen (2003) and Meyer et al. (2002), a unit cost of 340 EUR/kW can be used for the different PTO systems (mechanical, air, water and hydraulic), if series production is considered. However, this value is not suitable for standalone prototypes and should most likely be updated according to inflation.

According to Ricci (2012) the values shown in Table 2.2 are representative of the different PTO systems.

Table 2.2: Unit cost in EUR/kW for different types of PTO.

Type of PTO	Unit cost (EUR/kW)
Hydraulic	800
Linear generator	600
Mechanical	1.400
Air turbine	1.000

Generator

According to (Siegel, 2012) generator cost varies between 230 and 300 EUR/kW with brake and gear or direct drive. After consultation with generators' supplier ABB, Wave Energy Scotland (WES, 2016b) reports that a cost metric of 60 GBP/kW (about 73 EUR/kW) will give fairly accurate cost of generators.

Mooring

Generally, the mooring cost estimates are given in terms of cost per tonne of mooring system (300 EUR/ton as in (B2B, 2020) or cost per meter of mooring line (from 25 GBP/m to 375 GBP/m or 28 EUR/m to 423 EUR/m) by Harris *et al.* (2004).

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According to Bimep (2018), a mooring system for a single WEC with several anchored lines could cost between 200.000 EUR and 400.000 EUR.

In addition, mooring systems account for between 3% and 10% of CAPEX, depending mainly on the project scale: 3% for a fictitious utility-scale case (OPERA, 2019a and 2019b), 5% according to (Carbon Trust, 2006) and 9.2% of total CAPEX for a case study of the Pelamis WEC deployed off the coast of California, USA (Previsic, 2004). The cost breakdown per main cost centres is also shown in Section 4.

Figure 2.1 shows the price per meter as a function of the minimum breaking load as presented by Harris *et al.* (2004).

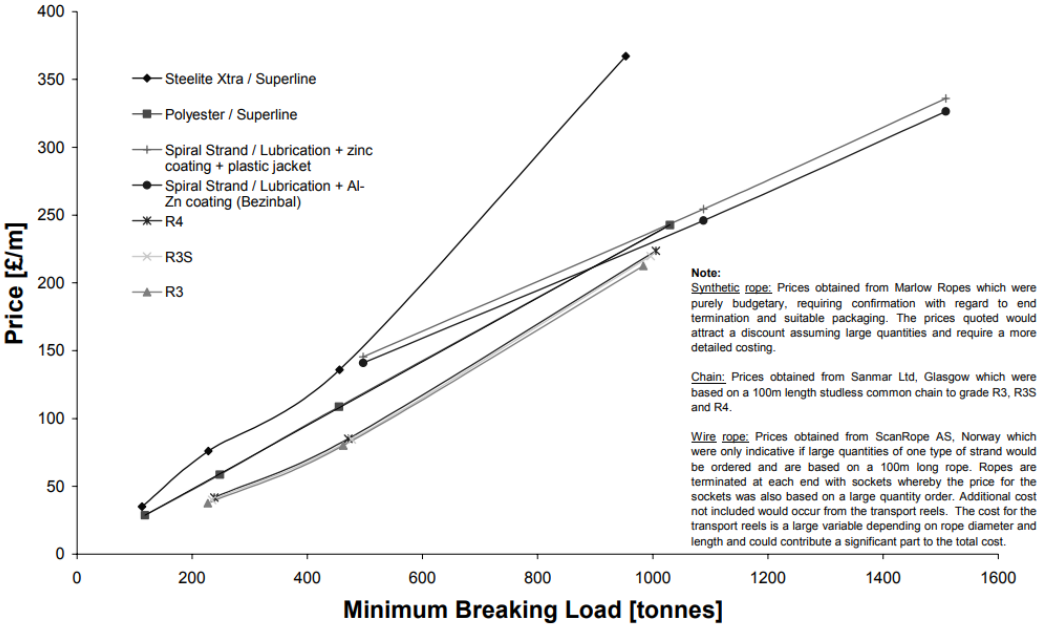

Figure 2.1: Price per meter as a function of the minimum breaking load for different mooring lines. Taken from (Harris et al., 2004).

Foundations

One way to calculate the cost related to foundations (C_F in MEUR/MW installed) is to look into the offshore wind sector. According to Serrano Gonzalez (2011) the foundation cost for offshore wind is estimated at 15-25% of CAPEX. The range for this cost is related to the water depth at the deployment location, as the costs are highly dependent on both the type of foundation and the amount of material used. The following relation can be used to estimate the cost of the foundation based on the water depth (d) (Serrano Gonzalez, 2011):

$$d = \begin{cases} [\,0, 30] \ m\text{:} & C_F = 0.15 + 10^{-5} d^3 \\ [30, 60] \ m\text{:} & C_F = 0.35 + 4 \times 10^{-5} d^3 \\ [60, \infty \ \ m\text{:} & C_F = 0.15 + 0.016 d \end{cases} \quad \text{MEUR/MW installed}$$

For shallow water conditions ([0, 30] m) monopile or gravity foundations are commonly used. At intermediate water depths ([30, 60] m), tripods, jackets and trusses are the appropriate foundation. Floating foundations become the best option in deep water. For a monopile foundation at 30 m water depth, the relation above leads to 0.42 MEUR/MW installed per foundation; which can be compared to the low and high estimates of 0.14 MEUR/MW installed and 0.23 MEUR/MW installed, respectively

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for a single WEC foundation at 30 m water depth of a monopile steel construction type as detailed by Siegel (2012).

Electric Cables (Inter array, export)

According to Previsic (2004) subsea cables account for 4% of the CAPEX for a case study of the Pelamis WEC deployed off the coast of California.

O'Connor *et al.* (2012) provides a list of supply cost depending on the installed capacity and the voltage of the cable, as shown in Table 2.3.

Table 2.3: Range of cable costs (O'Connor et al., 2012).

Range MW	kV	Supply cost per EUR/m
[0.25, 75]	20	59
[8.1, 20]	38	173
[21, 110]	110	288

According to Bimep (2018), the umbilical cable cost depends on power, voltage, length, etc., corresponding to an average cost of 70 EUR/m. (B2B, 2020) estimates umbilical cable costs at 100 EUR/m for the connection of a single 1 MW wave energy converter, and at 400 EUR/m for the connection of a 4 MW one. Siegel (2012) estimates the cost for cables from WECs to connecting point and from connecting point to shore in the range of 380 to 580 EUR/m.

When calculating the cost of the subsea cable network of a farm of WECs, the knowledge and experience from the offshore wind industry could be useful. The voltage of three-core submarine AC cables between the wind turbines and between the turbines and the transformer platform is in general 33 or 34 kV. Unit costs (without installation) of a 34 kV XLPE 3-core submarine AC cables with steel wire armour (copper conductor) with varying cross sections (between 95 mm^2 and 630 mm^2) were provided by Ørsted (DONG Energy at that time, in Beels *et al.* (2011)) and range from 106,67 EUR/m to 313,33 EUR/m, respectively. For offshore wind, the inter-array electrical cable costs, including installation, is 114.000 EUR/MW or 1.300 EUR/m (Vikkelsø *et al.*, 2003).

The cost of submarine intra-array cables is detailed in Iglesias *et al.* (2018). The cost is calculated as a function on the layout of the array, the distance to the transformer, the voltage of the cable and the maximal current.

Offshore substation (electrical, other)

The offshore substation cost accounts for 5.3% of CAPEX according to ORE Catapult (2020). In Siegel (2012) the cost of the subsea connecting point is estimated at between 750.000 EUR (6% of CAPEX) and 1.500.000 EUR (8% of CAPEX).

Onshore electrical (electrical, other)

Onshore substation was costed at 20.000 EUR/MW by O'Connor *et al.* (2012). The cost was estimated from a standard price list for components (ESB, 2009).

According to Previsic (2004) onshore transmission and grid interconnection account for 1.5% of CAPEX for a case study of the Pelamis WEC deployed off the coast of California.

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2.4 Installation and Commissioning

2.4.1 Description

Installation costs include installation of the WECs on site and commissioning of these to a fully operational state, up to point of issue of any take over certificate. Installation cost are driven by vessel chartering costs. Installation methods requiring smaller/cheaper vessels are to be preferred. Installation in port followed by towing is viewed as optimal.

2.4.2 List of costs

When looking at the installation cost as a whole, according to Previsic (2004) and for the case study of a single Pelamis deployed off the coast of California it accounts for 7.8% of CAPEX. Carbon Trust (2016) estimates that for a wave array installation makes up 13% of CAPEX, and the OPERA project (Opera, 2019a), 14% and 17% of CAPEX, depending on the deployment site at BIMEP or at EMEC, respectively. Unfortunately it is not always clear whether the costs of the installation of the electrical connection and the moorings are included in the direct costs of the components or as installation costs.

Foundations/mooring installation

According to Carcas (2011) the renting cost for an anchor handler vessel ranges from 4.500 to 140.000 EUR/day. According to Bimep (2018), the renting cost is 10.000 EUR/day. When taking into account that the effective installation period of 4 days is spread over 10 days due to mobilisation/demobilisation and weather window, the mooring installation cost is estimated at 100.000 EUR for a single device (Bimep, 2018).

Offshore substations installation

See offshore substation in balance of plant.

WEC installation

According to Bimep (2018) the towing and hanging up of the device manoeuvre can be relatively cheap if the mooring system has been designed in order to optimize the installation process, and therefore reducing the cost. It is also influenced by the size of the device and the number of towing vessels that are needed.

- Cost of a towing vessel: 7.500 EUR/day, normally 2 days are required for installation.
- Cost of diving work required for operations or supervision: 2.500 EUR/day, normally 2 days are required for installation.

Installation costs represents between 22-30% of the “initial cost” (where initial cost stands for the sum of the costs related to the structure, the moorings and the PTO cost centres), as shown by experience in the OPERA project (Opera (2019a)). In O’Connor *et al.* (2012) installation costs are estimated to 33% of the initial cost.

Cable installation

According to Bimep (2018) the total cost for cable installation / assembly from test berth for a WEC is about 120.000 EUR, including:

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- 80.000 EUR for specialist team to assemble the connector to the umbilical cable and to assemble the connectors between them (this includes mobilisation, demobilisation, 3 to 4 working days, 7 people and related equipment).
- Dynamic Positioning vessel class 1 (DP1) costing about 10.000 EUR/day, normally 2 days needed.
- Insurance 20.000 EUR.

In O'Connor *et al.* (2012) the cost for the installation of the cable is specified as a function of the seabed requirements, as shown in Table 2.4

Table 2.4: Cable installation costs (O'Connor et al., 2012).

	Installation cost in EUR/km
Cable laying trenched	282.000
Cable laying untrenched	100.000
Cable coverage (rock coverage)	939.000

2.5 DECOMMISSIONING

2.5.1 Description

Decommissioning costs include all cost related to the removal of the WEC, the foundation or mooring system and the electrical cables according to the legally binding contract.

2.5.2 List of costs

According to Bimep (2018), for a single device, decommissioning activities sum up to about 200.000 EUR, including:

- Device decommissioning: one day at 7.500 EUR/day.
- Mooring system: 5 days at 10.000 EUR/day, in total 50.000 EUR.
- Grid disconnection: 8 days at 10.000 EUR/day, in total 80.000 EUR.
- Umbilical disconnection insurance: 20.000 EUR.
- Vessel to disconnect and remove cable: 20.000 EUR.
- Diving works: 2 days, in total 5.000 EUR.

On top of the costs listed, 10.000 EUR are normally spent in pre-decommissioning work (Bimep (2018)).

Based on the open-water experience of the OPERA project (Opera (2019a)) decommissioning cost reached 88% of the installation cost, which corresponds to 25/13% of the installation costs based on a 5/8% discount rate over 25 years.

The experience from the wind sector can also be used to estimate the cost of decommissioning. According to Myhr *et al.* (2014), decommissioning cost at 70% of the installation cost can be estimated for offshore floating wind turbines and at 80% for bottom-fixed wind turbines. Those costs are excluding the decommissioning of the mooring system and the subsea cables. In Maslov *et al.* (2015) those costs were estimated at roughly half of the installation costs. According to Kaiser *et al.* (2012) decommissioning costs are found to range from 115.000 USD/MW to 135.000 USD/MW (or 90 EUR/MW to 105 EUR/MW), approximately 3–4% of estimated CAPEX.

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3 OPERATING EXPENDITURE

Operating expenditure (OPEX) is all expenditure associated with the operation of a WEC farm for the moment a takeover certificate is issued, including the cost of all operation and maintenance activities as well as the cost associated to site leasing and insurance. It is usually measured on an annual basis, although it increases with time.

When data is scarce, annual OPEX can be estimated as a percentage of CAPEX. As shown in literature, estimates of total OPEX per year roughly range from 1% to 10% of CAPEX. This is due to different factors (e.g. single prototype or utility-scale project, distance to shore, floating or submerged WEC, innovative O&M techniques applied, etc).

For example, Carbon Trust (2005) indicates annual OPEX of 1.3% of CAPEX for a nearshore OWC (based on the Isle of Islay nearshore LIMPET device). Nielsen et al. (2018) estimate lifetime OPEX for a 200 MW wave energy farm based on the KNSwing device as 50% of CAPEX, which translates as annual OPEX of 2% of CAPEX for a 25-year project lifetime. Previsic (2004) indicates annual OPEX of 5% of CAPEX for the deployment of Pelamis WEC off the coast of California, which is aligned with the value provided by the COE Calculation Tool (Fernandez Chozas *et al.*, 2014) that estimate annual OPEX as 6% of CAPEX for a single WEC.

When specific O&M innovations are applied, OPEX can be directly reduced. The OPERA project (Opera, 2019) has shown by the experienced gained throughout the project that annual OPEX can vary between 1.8% to 2.2% of CAPEX, depending on the deployment location and size of the array. In this case, innovative O&M techniques have been studied and applied. These O&M techniques, such as advance control algorithms, shared mooring systems, elastomeric mooring tether and O&M scheduling, have enabled a more than 60% reduction in OPEX from a baseline assumed of annual OPEX at 5% CAPEX. In Nielsen *et al.* (2018b) innovative mooring system solutions have shown to have the potential of reducing the total cost by 10 to 30% depending on the technology, where the biggest impact of those innovative solutions was on the reduction of OPEX.

Upon international consultation of wave energy developers carried out during 2018, the following estimates were found (OES, 2019): for a single device, annual OPEX in the range of 6% to 9% of CAPEX, for a small array 6% of CAPEX, and for a utility scale project 4% to 5% of CAPEX. Those estimates are more conservative than the ones demonstrated within the OPERA project.

The numbers for the single device can be compared to the recent published findings from the OceanSET project (OceanSET, 2020) also upon consultation with technology developers, where data from seven wave energy projects over TRL7 and active in 2018 was aggregated, and showed current annual average OPEX of 0.7 EUR/W for a single prototype device at TRL7.

The offshore wind energy sector has also used this way of presenting the operational expenditures. Pecher and Kofoed (2017) show annual OPEX as 4.5% of CAPEX while IRENA (2017) indicates annual OPEX as 3% of CAPEX.

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3.1 Operation and Maintenance

3.1.1 Description

Operation and maintenance costs include servicing of the WEC(s), mooring system and electrical connection from the take-over, on completion of building and commissioning of all part of a WEC farm.

Depending on the available information and the developer's experience, annual cost of operation and maintenance can be calculated with different degree of detail. In the following general estimates that can be used when data is scarce, and a more detailed list of cost are presented. A comparison to the offshore wind energy sector is also provided.

According to Iglesias *et al.* (2018) and Waveplam (2010) O&M tasks can be estimated at 30 EUR/MWh. This can be compared to the numbers provided by Milborrow (2010) for the wind energy sector, which ranged from 15 to 26 EUR/MWh in 2006 to 7 to 26 EUR/MWh. It shall be noted that offshore wind deployments at that time was still low, so these numbers mostly refer to onshore O&M tasks, however, the numbers do serve for illustration purposes.

Alternatively, Fernandez Chozas *et al.* (2014) estimate annual O&M as 4% of CAPEX. For comparison, Blanco (2009) estimated O&M for offshore wind as 30% of CAPEX. For a 25-year project, the annual OPEX is then 1.2% of CAPEX.

3.1.2 List of costs

Remote Operation (inspection) and Maintenance

The cost for remote inspection and maintenance depends largely on the type of vessel (small or large) required, as well as the number of days planned and needed.

From real sea-experience shared by different established actors of the wave energy sector, we know that small vessels can cost around 100 EUR/trip (Bimep, 2018), a multicat workboat from 2.300 EUR/day to 3.400 EUR/day (Carcas, 2011), a towing boat about 12.500 EUR/day (McAdam, 2012) and a large vessel in the range of 15.000 EUR/day to 23.000 EUR/day (Siegel, 2012).

Bimep (2018) estimates 7.000 EUR for remote inspection of a single WEC carried out in 20 trips a year (100 EUR/trip with a small vessel) and where diving work for inspection is done twice a year (at a cost of 2.500 EUR/inspection).

Siegel (2012) allocates one week per year for inspection, and one month every 5 years for maintenance.

Alternatively, de Andrés *et al.* (2017) use an average cost of intervention of 11.500 EUR based on private communication with vessel owners.

Operation (local), Maintenance (local), Port activities (remote, local)

No cost values were found for that particular category.

Other

Other cost that should be considered within this cost-centre are the ones related to travel and subsistence of personnel. According to Bimep (2018) this amounts to 36.000 EUR/year for 2 people.

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3.2 Site Lease and Insurance

3.2.1 Description

Costs related to site lease and insurance are self-explanatory. Insurance covers the replacement of faulty/broken components or defective work. When data is scarce, these costs are given as a percentage of CAPEX (as in Fernandez Chozas *et al.* (2014), where site lease and insurance are estimated as 2% CAPEX)

3.2.2 List of costs

Site lease

The cost of a site lease depends highly on the project scope, and whether the project encompasses the sea trial of a single prototype, first array, or a utility scale project in the range of 200 MW, for example.

In the first case, the cost of a site lease to carry out a test campaign varies a lot depending on the chosen location. There are several established test sites in Europe that enable "plug-and-play" characteristics, where environmental permits and the grid connection are in place, and resource assessment is well-documented (Marinet network (2020)). The price for the site lease usually depends on the services included in the test site (e.g. allocated area of sea, grid connection, data export to operating station, 24/7 surveillance of the device, emergency response, administrative licenses & permits, onshore offices), although O&M has been generally excluded from the total fee (Bimep, 2018).

After direct consultation with different test sites carried out in 2014 (Fernandez Chozas, 2014), it was found that the cost for the site lease for benign test sites (not grid-connected site, excluding O&M) is in the range of 3.000 EUR/year to 7.000 EUR/year. Open-sea test sites (grid connected sites also excluding O&M) have higher costs, from 250.000 EUR/year to 350.000 EUR/year (Bimep (2018) and Fernandez Chozas (2014)).

For a utility scale project of a 200 MW wave energy farm, Siegel (2012) estimates the cost of the site lease to be in the range of 3 MEUR to 4 MEUR for the total project lifetime. For a 20-year project, this equals 150.000 to 200.000 EUR/year, in the same order of magnitude as the site lease of established test sites.

Alternatively, Iglesias *et al.* (2018) assess this cost to 3.3 EUR/MWh or 2.5% of CAPEX.

Insurance

The cost of insurance is small compared to other project costs. Bimep (2018) estimates annual insurance cost of a single WEC as 1% of CAPEX, to be paid every year during the design life, and Iglesias *et al.* (2018) as 2% of CAPEX (or alternatively as 37 EUR/MWh).

Carbon Trust (2006) estimates insurance cost of a wave energy farm as 14% of OPEX. Considering OPEX estimates as summarised at the beginning of Section 3 (1.8% to 9% of CAPEX) this leads into the range of 0.3% to 1.3% of CAPEX, in the same order of magnitude as the two previous estimates.

Bimep (2018) also points out to add into the insurance cost the civil liability insurance, which is about 40.000 EUR/year.

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Licenses

Carbon Trust (2006) estimates the licenses of a wave energy farm as 1% of OPEX. By carrying out the same exercise as before (annual OPEX in the range of 1.8% to 9% of CAPEX) licenses are in the range of 0.018% to 0.09% of CAPEX.

Others

Other expenses that have not been directly listed above but that influence final project cost are, among others (Bimep, 2018):

- Sea bed anchor point inspection
- Marine contractor and sea operations director
- Financial statement
- Transport insurances

4 COST-CENTRES BREAKDOWN

The breakdown of cost centres is used to identify which costs centres have the most and the least influence on the total cost of project (a single WEC, a first wave energy array or a utility-scale project). The cost breakdown highly depends on the type of WEC: offshore, onshore or nearshore; floating or submerged, the type of absorption principle or PTO, and other intrinsic characteristics of the WEC. Therefore, the numbers shown below have been compiled to provide current and projected order of magnitudes rather than for comparison.

The results from the UK Marine Energy Challenge: CAPEX and OPEX breakdown

Based on data gathered during the Marine Energy Challenge[1] of the UK (Carbon Trust, 2006), the following breakdown of capital costs and of operational and maintenance costs for a wave farm were done (Figure 4.1). As indicated by the Carbon Trust:

> "*The charts refer to specific types of wave energy converter and are not representative/typical of wave energy technologies as a whole. There are considerable variations between different technologies, project locations and project sizes (numbers of machines installed). Also, future design improvements, performance/cost optimisations and learning effects could change the relative weighting of some cost centres*".

Decommissioning costs were not included in the breakdown as, according to Carbon Trust (2006) they fall at the end of a project. The present value in a discounted cash flow analysis is low and has only a marginal effect on cost of energy (Carbon Trust, 2006).

[1] The Marine Energy Challenge was designed by the Carbon Trust. It was a 3.0 MGBP, 18-month programme of targeted engineering support. Eight technology developers were selected through an open tender: AquaEnergy Development UK, Clearpower Technology, Ecofys, Embley Energy, Lancaster University, Ocean Power Delivery, Seavolt Technologies and Wave Dragon (Carbon Trust, 2006).

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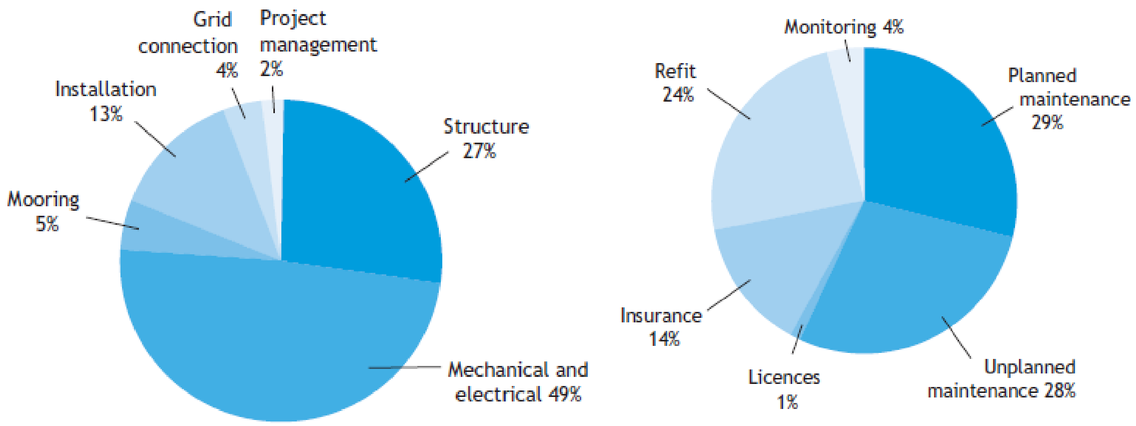

Figure 4.1: Breakdown of capital costs (chart on the left) and of operational and maintenance costs (chart on the right) for a wave farm. The O&M chart shows annual average costs evaluated over the entire life of a wave farm (Carbon Trust, 2006).

Contribution of different cost centres to the overall LCOE

Carbon Trust (2011) analyzed collected data to present the indicative levelized cost of energy components for wave energy converters in an early commercial farm (Figure 4.2). The coloured segments are capital costs, while the grey segment (above 45%) represents O&M costs and includes all other expenses including insurance and leases. Note that O&M has the same influence on the total costs as the WEC structure.

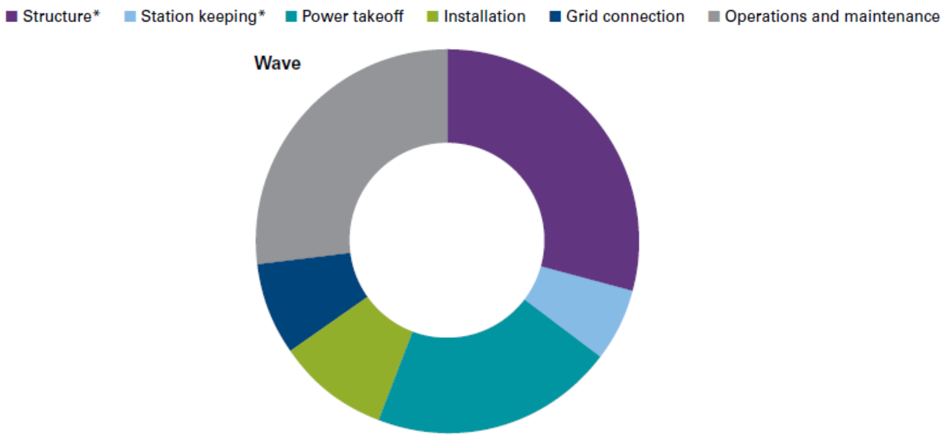

Figure 4.2: Typical cost breakdown for early wave arrays. A discount rate of 12% and lifetime of 20 years are assumed (Carbon Trust, 2011).

Results from the SI Ocean Project: all costs breakdown

The SI Ocean project (SI Ocean, 2013) compiled a range of estimates of the breakdown of costs of an early array of wave energy converters (Figure 4.3). Note that OPEX are included in the same chart as CAPEX. Results indicate that the structure and prime mover makes up on average 31% of lifetime costs for a wave array, the foundation or moorings 6%, the power take off 22%, installation 18%, operating and maintenance 17%, and other costs, including project management costs and the site development costs 6% of lifetime costs for a wave array.

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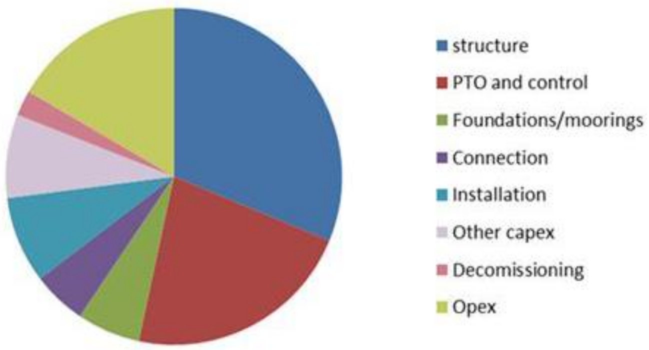
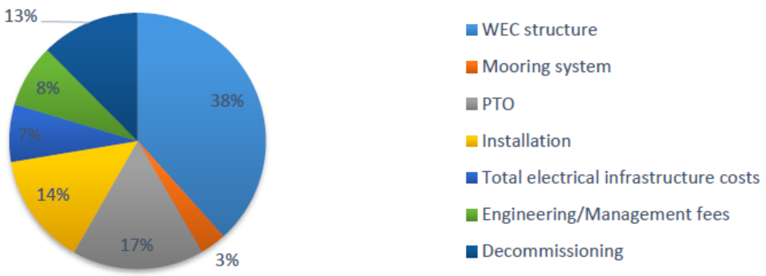


Figure 4.3: Wave early array cost breakdown (SI Ocean, 2013).

CAPEX and decommissioning breakdown result from the OPERA project at BiMEP and EMEC

The two pie charts below (Figure 4.4) illustrate the non-discounted CAPEX breakdown obtained through the OPERA project where a fictitious utility scale case is deployed at BiMEP and at EMEC, first and second chart in Figure 4.4, respectively. The cost breakdown shown for an installed capacity of 18 MW is when innovations are considered (the innovations have been detailed in the previous section). In both cases the larger contributions come from the structure, the PTO, and the installation, all three representing two thirds of the total CAPEX. Plots of each of the scenarios are presented in Opera (2019a) and (2019b).



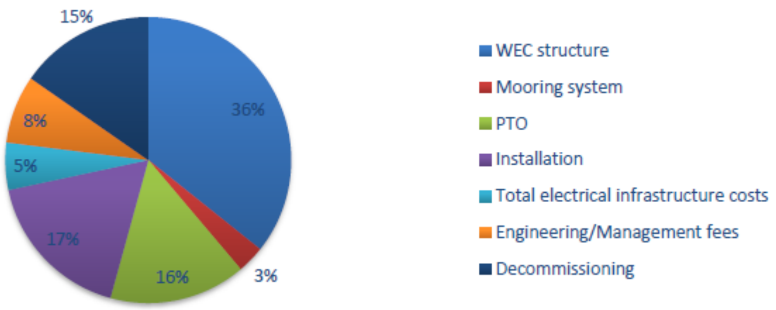


Figure 4.4: CAPEX breakdown of array 2 for "with innovation scenario" when deployed at BiMEP (first pie) and at EMEC (second pie), (Opera, 2019a), (Opera, 2019b).

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Offshore wind energy cost breakdown

For comparison, a detailed breakdown of cost centres for a 3.6 MW offshore wind project as given by BVG (2010) is also presented.

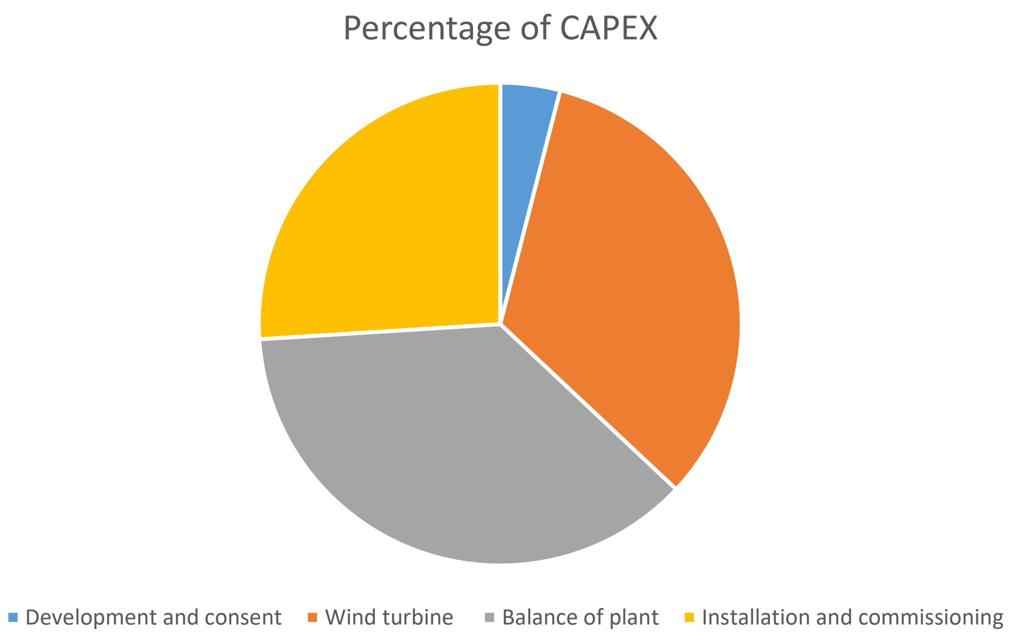

Figure 4.5: Cost breakdown for a 3.6 MW offshore wind (BVG, 2010).

5 Discussion and Conclusions

Here we seek to provide an answer to the four questions posed at the introduction to the document:

- What are likely to be the main cost centres for LiftWEC?

The main cost centres influencing LiftWEC are, within CAPEX category, the WEC structure and prime mover (material and width chosen), the balance of plant, specially the mooring or foundation type chosen, and the installation and decommissioning. In OPEX, O&M tasks will largely affect the final costs.

- How may costs vary with the LiftWEC width and other key dimensions?

Increasing the width or any other key dimensions would increase the costs but also the power absorption, so no major effects on LiftWEC key dimensions on the LCOE are envisaged. However, larger units lead to larger installed capacity per unit, meaning fewer units to be installed, which in turn would decrease installation and O&M costs.

- What "break points" may exist where LiftWEC costs change rapidly?

Due to the intrinsic characteristics of a lift-based type of WEC, the structure and the prime mover will be mostly submerged. This will be more costly than developing, installing, operating and maintaining a floating structure and prime mover.

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The type of maintenance strategy chosen (e.g. onsite submerged maintenance involving divers or onsite maintenance at the surface) will have a major influence on the costs.

The water depth and distance offshore will also have a big impact on the cost of the foundation.

- What other key factors may influence the cost of energy for LiftWEC?

Firstly, the capabilities of the structure to be manufactured in an industrialised way can have a big impact on the costs. If the manufacturing of the main components of the device (the structure and the mooring or the foundation) could be industrialised, this would largely drive the cost down. This has been showcased by the larger supplier of wind towers today (Welcon). Based in Denmark, it keeps up its leading position due to an optimised manufacturing process of steel wind towers. It would be interesting to investigate how LiftWEC could benefit of industrialised processes already in place within the wind energy sector; and the TetraSpar (Andersen *et al.*, 2018) concept could inspire some discussions.

Secondly, installation procedures have also a major impact on costs. Being able to assemble all parts of the WEC in the harbour and tow it to the site would save all the costs associated to large vessels, specialised labour force, multiple trips to harbour, weather windows, etc.

Thirdly, due to the fact that OPEX make up around a quarter of the project levelized cost of energy (Carbon Trust, 2011), and are incurred annually throughout the whole project lifetime (and indeed increases along lifetime), it is largely agreed that it is the cost centre where most cost reduction opportunities are. Indeed, by minimising (and optimising) OPEX and particularly the O&M tasks, the operations or installation and decommissioning will also benefit of this, and their associated costs will be reduced.

Carbon Trust (2011) concludes that the development of efficient O&M strategies must be a priority:

> *"innovative O&M strategies or technologies can significantly reduce lifetime costs at the device level, primarily by increasing the range of sea conditions in which O&M can be undertaken, and by reducing the time required for operations. At the array level there are also opportunities for reducing O&M costs by developing efficient deployment and recovery strategies for multiple devices, and by exploiting economies of scale for planned maintenance. The simplest way to achieve low O&M costs is to build extremely reliable devices that need very little maintenance. Costs are also expected to reduce as new intervention techniques are developed, particularly involving retrieval rather than on site-intervention, or purpose-built offshore servicing platforms."*

The SI Ocean project (2013) described O&M cost reduction opportunities through: increased reliability, modular components, simpler access, specialist vessels, far offshore O&M strategy, intelligent predictive maintenance, and improved ROV and autonomous vehicles.

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