LiftWEC

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

Deliverable 8.4

LCOE estimates of Baseline Configurations

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EXECUTIVE SUMMARY

In this 3-year funded LiftWEC Project, partners collaborate to determine the economic potential for a new type of wave energy converter (WEC) using lift forces converting wave energy to electricity. The LiftWEC consist of a hydrofoil rotating around a horizontal axis interacting with the incident waves turning a generator generating electricity. The rotor and generators can be mounted on different types of support structures. The final project objective is to propose and evaluate one or more promising LiftWEC configurations.

In this context the LiftWEC Levelised Cost of Energy (LCOE) Calculation Tool has been developed. It is a transparent and simple tool that can assist in the evaluation of the LiftWEC concepts economic feasibility. It has been developed to ensure consistent and transparent calculation methods and to provide a reference framework for performing LCOE analyses. The Tool further facilitates the development of LiftWEC as it allows the identification of the components or cost centres with highest impact on the LCOE.

This deliverable focuses on the economic assessment of four different baseline LiftWEC configurations. These four configurations where selected by consensus by the project consortium. Except for some small refinements, the hydrofoil rotor, power take-off system and its pitch control are essentially the same for all configurations with the difference being in the implementation of the reaction and station-keeping requirements. The first configuration consists of a jack-up tower, the second one of a tension leg platform (TLP), the third one of a semi-submersible structure and the fourth one of a spar buoy.

To carry out a comparative economic assessment for each of the four configurations, the Capital Expenditures CAPEX, Operational Expenditures OPEX over the lifetime of the project and the Levelized Cost of Energy LCOE are utilized. These allow identifying the main economic differences and competitiveness among them. The assumptions used for each cost centre is detailed in the Deliverable.

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1 INTRODUCTION

1.1 BASELINE CONFIGURATIONS

There are four baseline configurations:

- The first configuration consists of a jack-up tower → Tower LiftWEC
- The second one of a tension leg platform (TLP) → TLP LiftWEC
- The third one of a semi-submersible structure → Semi-sub LiftWEC
- The fourth one of a spar buoy → Spar buoy LiftWEC

These four configurations where selected by consensus by the project consortium and represent a full range of considered promising concept implementations.

Except for some small refinements, the hydrofoil rotor, power take-off system and its control are essentially the same for all configurations with the difference being in the implementation of the reaction and station-keeping requirements.

Their main characteristics can be found in the Basis of Design document relevant for each configuration, referenced below. Del 2.8 (Folley and Lamont-Kane, 2022) explains in detail the coordinated and consensus process behind the selection of each of the four final configurations.

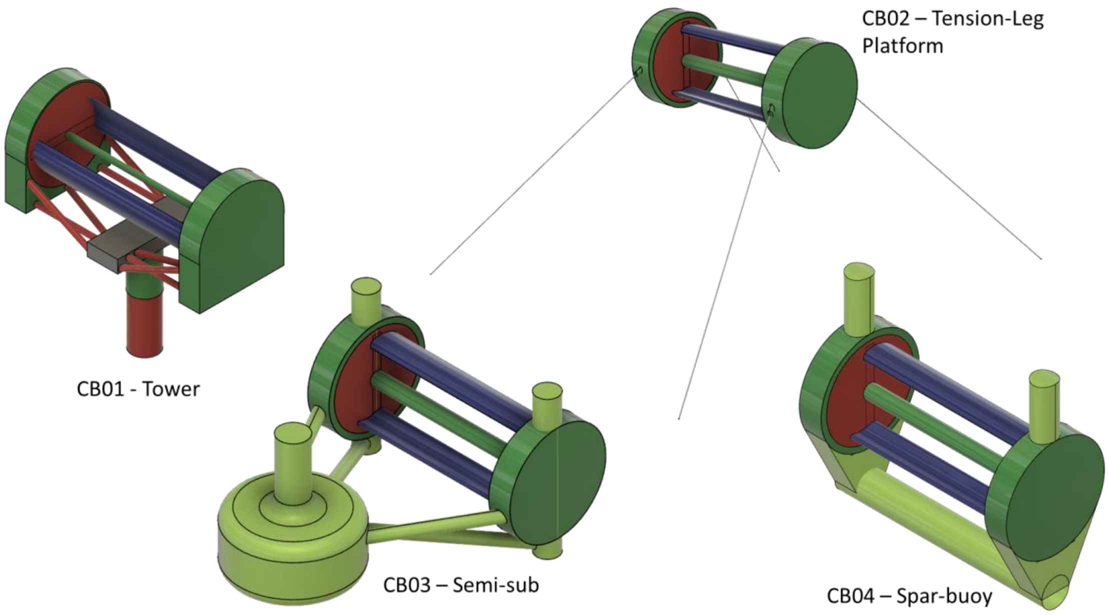

Figure 1.1: The four LiftWEC Baseline Configurations

1.2 METHODOLOGY

This deliverable will compare the Levelized Cost of Electricity (LCOE) of the four concepts using the LiftWEC LCOE Calculation Tool. This takes into account the sum of all accumulated costs for building a plant (CAPEX) and operating it (OPEX), and the annual energy production

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throughout its lifetime (AEP), leading to the Levelized Cost of Electricity (LCOE) in EUR per MWh. This method gives an indication of which concept is more attractive based on the assumptions behind the different technologies comparable.

As a starting point, the specifications for the Tower LiftWEC have been reviewed; and all relevant data has been included as input into the LiftWEC LCOE Tool. The specifications for all the relevant elements are detailed in the document *Tower LiftWEC – Basis of Design*, which is a life document where every WP input new knowledge as it gets available. Discussions on data and parameters have been held if required. When some data has not been available, some estimates have been gathered through internal discussions within WP8 and other project partners – and will be updated when that particular specification is available within the consortium.

Once data has been gathered for the *Tower LiftWEC,* economic estimates have been derived.

As a second step, data for the other three configurations has been reviewed and used as input to the LiftWEC LCOE Calculation Tool. (When data is missing, the approach has been to take the *Tower LiftWEC* data as a reference value, and make estimates on the other configurations relative to that value – by doing this the uncertainties that have been accumulated are consistent in all the four calculations).

1.3 Assumptions

Unless specifically stated, cost estimates have been calculated based on the costs gathered under Deliverable 8.1 (Têtu and Fernandez-Chozas, 2020) and included as default values in the LIftWEC LCOE Calculation Tool (Fernandez-Chozas *et al.*, 2022). It could be discussed whether these default costs, gathered in 2020, are no longer representative of current (spring 2022) prices. For example, steel prices are currently higher (about 20%) than a year ago. In the present exercise, prices before Covid and supply chain issues are considered. This is because we notice that many of the other WECs are showing costs calculated also before 2022, and therefore the relative comparison should be valid. Also, the current volatility of the price of raw materials might not be representative of future long term trends, and therefore caution should be used before using the latest data for R&D project with potential realisation in the medium to long term future.

1.3.1 WEC Structure and Prime mover. Cost Estimates.

In the four configurations the hydrofoils are identical. A hydrofoil span of 30 m is considered, there are two hydrofoils per rotor, their profile is NACA 0012 (curved along hydrofoil path), and have a 6m chord length. The unit volume for each hydrofoil is of 9 m^3 (Arredondo-Galeana *et al*., 2021). If built of **composite**, and assuming an average density of fiberglass of 2000 kg/m^3, total mass of the two hydrofoils is of **36 tonnes**.

The structure of the prime mover (nacelle and rotor) is identical in the four configurations (Figure 1.1). It is a 6 meter diameter rotor, built in steel (assumption of 7850 kg/m^3 density) and has a **total mass of 120 tonnes** (Arredondo-Galeana *et al*., 2021). This includes a centrally rotating shaft the drives the PTO and two lateral supports at both ends of the shaft.

Hence, the WEC structure and prime mover, common of all four configurations, has a total approximate mass of **150 tonnes**.

(note: For structural reasons, the rotor central axis should be bigger for the TLP configuration).

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1.3.2 Deployment Site and Site Lease

For all configurations, the deployment location is the same: off the North Atlantic coast of France (coordinates 47:84° N, 4:83° W), in the Bay of Audierne close to Quimper. Water depth at the selected location is 50 m, distance to shore about 10 km and the wave resource is estimated at 40 kW/m.

1.3.3 Annual Energy Production. Power Matrix.

Current estimates on LiftWEC power performance are based on the results from the 2D, regular waves testing, which has also served to validate the numerical models. The next development step is to carry out 3D testing, which will evaluate the effect on the energy capture of a rotor moving or not; and hence, more certainty on power production estimates. Until those results are available (approx. by end of 2022) it has been decided to use estimates for LiftWEC power production based on the CycWEC device.

The power matrix depicted in Figure 1.3.3 has been extracted from (Siegel, 2019), which corresponds to a 60 m span hydrofoil and 5 m chord length cycloidal wave energy converter. LiftWEC baseline configurations have two, 30 m hydrofoils. Accordingly, the same power matrix as in Siegel (2019) divided by two has been chosen for the calculation of the TLP LiftWEC, which shares overall structural similarities to CycWEC device.

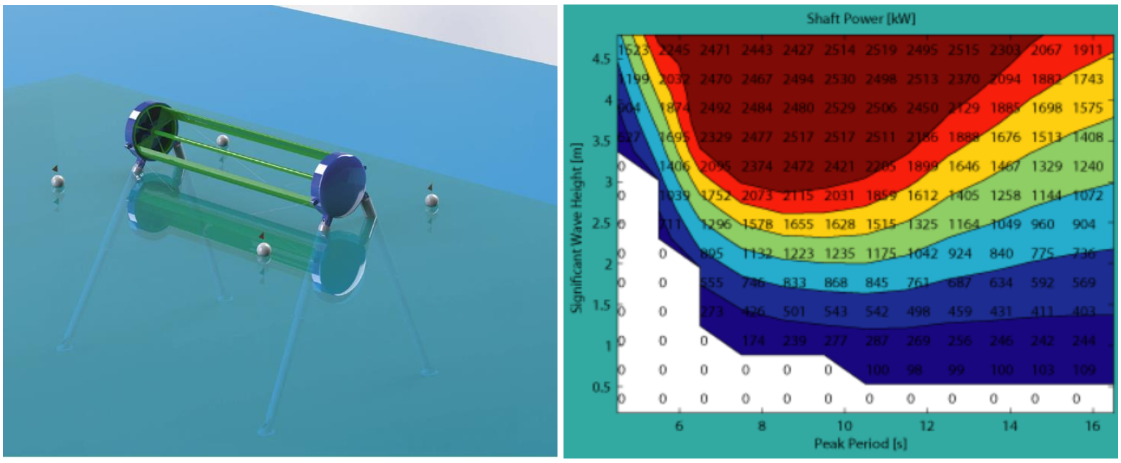

Figure 1.3.3: The Cycloidal Wave Energy Converter (CycWEC) in maintenance position (left) and its power matrix (right). Dimensions: 6-meter radius, 5m chord length, 60m hydrofoils span, 2.5 MW designed power output) (Siegel, 2019).

The down-rated power matrix operating at Ifremer site provides an **annual energy production 2.7 GWh/y** (2722 MWh/y). This value is taken as a reference for the TLP LiftWEC.

1.3.4 Development costs

Development and consenting costs are considered the same for the four configurations, and equal to 6% of CAPEX of the Tower LiftWEC configuration. This amounts to **approx. 0.5 MEUR.**

1.3.5 Control Cost Estimates

The control of each LiftWEC configuration differs. The common control elements for all configurations are the following:

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

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- There is no rotor radius control.

To calculate the costs of control the following is assumed: Siegel (2012) provides a low and high estimate for the elements allowing the control of the monopile CycWEC, with a designed power output of 5 MW. Control includes pitch, yaw and lift. An estimate of 385 to 580 kEUR is provided (500 to 750 kUSD) (Siegel, 2012).

Assuming an average value of 500 kEUR corresponding to a 5MW device, it can be a fair approximation to estimate half of the costs for a 1.5 MW device, about 250 kEUR. It is the assumption that each of the three systems of control (submergence, pitch and yaw) correspond to the same part of the total costs, giving an **approximation of 75.000 EUR per control system**.

The cost of **phase control** is considered to be included within the costs of the PTO.

1.3.6 Installation Cost Estimates

Many types of installation vessels exist, which vary greatly on capabilities and daily rates (Table 1.3.6.). Generally, as components get larger, vessels become more expensive. Vessels maximum operational limits (wave height, current) are also a key factor.

Table 1.3.6. Typical Installation vessels and indicative daily rates (Flannery, 2020a), (Flannery, 2020b)

Name	Vessel Type	Operational Day rate / Day rate at port	Mobilization / Demobilization rates	Max. Hs positioning
Crew transfer		1.200 EUR		
Multicat		2.000 EUR		
Diving work		2.500 EUR		
50-ton tug	also towing vessel	8.000 EUR		
DP1 vessel	Dynamic Positioning 1	10.000 EUR		
Anchor handling		10.000 EUR		
70-ton tug		12.000 EUR		
OCV 250	Small Offshore Construction Vessel (OCV)	35.000 EUR		
Viking Neptune (OCV 400)	Large construction vessel	95.000 EUR		
Rambiz	Installation. Lift Vessel.	60.000 EUR	120.000 EUR	1.5 m
Multicat tug	Tug	25.000 EUR	50.000 EUR	2 m
Svanen	Installation. Heavy lift Vessel	180.000 EUR	360.000 EUR	2 m
Isaac Newton	Cable Laying. Offshore Support vessel	180.000 EUR	360.000 EUR	2.4 m

It can initially be assumed the same towing-to-site procedure for the prime movers of the four configurations. For this, Flannery (2020b) indicates the use of two multicat tugs at a daily rate of 12.500 EUR per tug. Hence, a **towing-to-site cost for the prime movers of 25.000 EUR** is assumed.

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This is a slightly higher estimate (as well as an additional vessel) than that used for the Pelamis WEC (estimated at approx. 5.000 EUR (Gray et al, 2017). A higher estimate has been chosen to be on the conservative side, and because although Pelamis was a heavy device, it had a shape and draft that was conducive to towing.

As a generic estimate, a 3-day weather standby is assumed in the installation of the four configurations (Lacal Arantegui *et al*, 2017). This waiting time takes into account that daily rates of vessels at port or offshore in operation are the same.

The installation of the foundation (of Tower LiftWEC) and the moorings (of the TLP, spar and semi-sub) is discussed in sections 2.1.4, 3.1.4, 4.1.4 and 5.1.4.

1.3.7 Maintenance Strategy overview and OPEX estimates

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

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

According to [Correia da Fonseca, 2021], the O&M port shall be as close as possible, and ideally below a 2-hour transit.

LiftWEC maintenance will be primarily on a return-to-base (RTB) strategy for all but the simplest procedures. Tug boats will be used to recover individual power capture units. These will be repaired and then re-deployed with i.e. 50-ton tug vessels. This maintenance strategy is essentially the same for the four baseline configurations.

It is understood that to attach/de-attach the Tower LiftWEC from the foundation (the monopile) a lift vessel will be needed. The simplest attach/de-attach procedures will be for the semi-sub and the spar buoy thanks to the single-point connection, which allows for a quick and fast operation, which can also be carried out at higher wave heights (and thus, requires for less waiting for weather windows). The attachment procedure for the TLP configuration will involve more operations than for the semi-sub and the spar, as there are 4 anchors to connect and the dynamic cable too. On the other hand, a smaller tug vessel could be needed to tow the prime mover of the TLP.

Due to the limited data available on OPEX, an indicative 8% of CAPEX (before contingencies) has been assumed for the TLP; which amounts to about 250 kEUR/year.

Taking the above assumptions as a baseline, it is assumed that the maintenance (and hence OPEX) of the Tower LiftWEC will be twice as expensive as the maintenance of the TLP configuration. The semi-sub and the spar would have similar OPEX; estimated twice as cheap as the TLP. Thus, OPEX for Tower LiftWEC is estimated at 500 kEUR/year, for TLP LiftWEC at 250 kEUR/year, and for the two floating configurations, the spar and the semi-sub, at 125 kEUR/year. As a reference, OPEX estimates for the Tower corresponds to 6% of CAPEX, OPEX represents 3.8% of the CAPEX for the semi-sub configuration, and 4.2% in the spar buoy option.

1.3.8 Uncertainties

There are uncertainties associated both to the input as well as the output values. The economic assessment is subject of several assumptions that will be verified as the development process evolves. It is estimated that at the current stage of development of LiftWEC, results have an uncertainty that varies between [-30% to 80%].

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2 Tower LiftWEC Economic Assessment

The Tower LiftWEC configuration consists of the two-hydrofoil rotor set atop a previously installed Jack-up Tower. The connection between the power capture unit and the Jack-up Tower is via a self-aligning transition piece. The Jack-up Tower is mounted atop a monopile foundation (monopile not shown in the Figure 2.1).

The transition piece facilitates deployment and recovery as well as enabling yaw control. The Jack-up Tower is used both during deployment and recovery activities, and to control the rotor submergence in accordance with the wave conditions and water level.

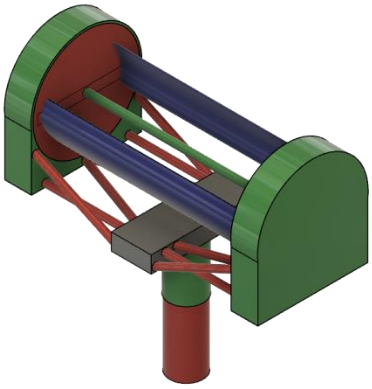

Figure 2.1: Tower LiftWEC

2.1 Input Values

2.1.1 Main dimensions: dry weight and foundation costs

The monopile is a hollow structure, about 53 m height (suitable for a 50 m water depth). Due to possible loads from the rotor and vibrations, Ramboll suggests to assume a diameter of 4.5 m (Ø=4.5 m, perhaps tapered from the seabed up). Assuming a conservative diameter to thickness ratio of 100, a thickness of 45 mm is suggested. This gives 33 m^3 of steel, hence **260 tonnes only for the monopile**.

Year 2020/2021 prices of steel for this application were around 1500 EUR/ton. Now (2022) costs are higher, and possibly around 2000 to 2020 EUR/ton. For this exercise, a rough estimate of 2000 EUR/ton is assumed – only for the monopile, giving a **cost estimate of 520.000 EUR**.

Note the unit cost of steel for all other more complicated structural steel parts including painting and corrosion protections etc. is estimated at 3400 EUR/ton.

Arredondo-Galeana *et al*. (2021) calculates a steel support bracket atop a monopile to have a mass of 103 tonnes. In this case, a jack-up structure able to provide submergence capabilities placed on top of the monopile together with a transition piece; is assumed to require **about 260 tonnes of steel.**

Total dry weight of the tower LiftWEC, excluding the monopile, is hence 420 tonnes (260 tonnes for jack-up tower and transition piece, 120 tonnes for the nacelle and rotor, and 36 tonnes for the hydrofoils).

If it is assumed that the monopile will be embedded into the sea bottom about a third of its height (around 20 m), the monopile will sit about 30 meter above sea bottom. On top of it, the jack-up structure holding the rotor and nacelle will be placed.

The Jack-up Tower is used both during deployment and recovery activities, and to provide submergence control of the rotor on a sea-by-sea basis. This is often termed slow-control. A deadlock style locking system is employed to maintain position between jack-up operations (similar to SeaGen). Consequently, the actuators used to perform the lifting/lowering

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operations are not used to maintain the tower height during operation or between jack-up activities.

The primary objective of the rotor submergence control of this configuration is to maximise the power capture, whilst avoiding excessive loads on the structure. An additional objective of submergence control is to protect the device from wave slamming or wave impact loads during storms by increasing the rotor submergence depth. A final objective of rotor submergence control is to facilitate particular marine operations.

2.1.2 Annual Energy Production.

It is expected that Tower LiftWEC will have better performance than TLP since it is a fixed structure and has yaw control. A total 10% increase in AEP (relative to TLP performance) is hence assumed, leading to an estimate of **annual energy production 3 GWh/y** (2994 MWh/y) at Ifremer site (this is before 3D tank test validations).

2.1.3 Control Cost Estimates

The tower LiftWEC allows for full-control, including:

- Pitch control of the hydrofoils enabled by two actuators per hydrofoil, one at each end.
- Phase control implemented by direct drive generators, one in each stator.
- There is no rotor radius control.
- Submergence control enabled by jack-up tower (following the sea states).
- Yaw control provided in transition piece.

The cost of pitch, submergence and yaw is estimated at 75.000 EUR each, **in total 250.000 EUR**.

2.1.4 Installation Cost Estimates

One third of the length of the monopile (in total estimated at 53 m long) will be inserted into the seabed during installation activities (Arredondo-Galeana *et al.*, 2021). Hydraulic impact hammers are required be utilised for this operation (Li *et al.*, 2016); which are expensive, heavy lift vessels. There are few vessels that could handle the necessary height and weight, and for this activity the *Svanen* heavy lift vessel (Figure 2.1.4, Table 1.3.6) is assumed (Flannery, 2020b).

Then, a smaller lift vessel (for example *Rambiz, see Table 1.3.6*) is assumed to lift the structures (jack-up tower, transition piece and prime mover) onto the monopile, after towing it to site.

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***Figure2.1.4**: Left: Van Oord's Heavy lift vessel Svanen [source ("Vesselfinder.com," 2020)]. Right: Rambiz positioning the SeaGen at Strangford narrows (Ireland), at a water depth of 25m +-2m, on a jacket foundation (Fraenkel, 2009).*

Assuming a 1-day installation for the monopile, and 3-day delay due to weather windows, total costs of installation of the monopile are:

- Mobilisation: 360.000 EUR
- 4-day operation / at port: 180.000 * 4 = 720.000 EUR
- De-mobilisation: 360.000 EUR
- Total **monopile Heavy lift Vessel: 1.4 MEUR**

Assuming that the prime mover, jack-up tower and transition piece are assembled onshore at harbour facilities, and afterwards are towed out to site with only one vessel (Arredondo-Galeana *et al.*, 2021), costs are as follows. Assuming a distance of 10 km, it would take from 1 to 3 hours to get to deployment site with a towing speed ranging from 1.5 m/s to max. 4.5 m/s (14 km/h).

- Mobilisation: 50.000 EUR
- 4-day operation / at port: 25.000 * 4 = 100.000 EUR
- De-mobilisation: 50.000 EUR
- Total **prime mover, jack-up tower and transition piece tugboat: 200.000 EUR**

To lift the power capture unit and remaining structures (jack-up tower and transition piece assembled together) onto the monopile, a 3-day service of a small lift vessel (for example the Rambiz) is assumed, and a 3-day delay due to weather windows:

- Mobilisation: 120.000 EUR
- 6-day operation / at port: 60.000 * 6 = 360.000 EUR
- De-mobilisation: 120.000 EUR
- **Total: 600.000 EUR**

Total Installation for the Tower LiftWEC (no electrical connection included) of 2,2 MEUR.

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2.2 Output Values

LiftWEC LCOE Calculation Tool

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The development of the COE Calculation Tool has been previously funded by the Danish funded projects "The COE tool for WECs – Improvement and Dissemination" (grant agreement 2013-1-12135, 2013-2014) and "Beton til Bølgeenergi" (64018-0600).

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

Project summary

Project name	Tower LiftWEC
Deployment location	France - Ifremer
Power density at the location	40 kW/m
Project lifetime	25 years

Main dimensions and characteristics

Main active dimension	30,0 m
Secondary dimension (length/width)	12,0 m
Total dry weight (excluding monopile)	420 ton
Station keeping type	Bottom-fixed
PTO type	Direct drive
PTO average efficiency	98%
Generator rated power	1240 kW

Economic Assessment for Tower LiftWEC

Development stage: Phase 1 / TRL 3 — [-30 to 80%] Uncertainty

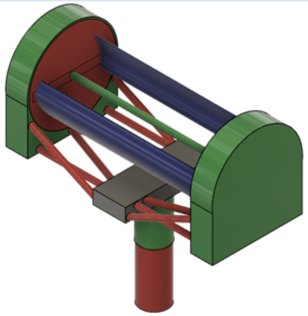
Total CAPEX	8,27 MEUR	**[CAPEX / MW]**	6,7 MEUR/MW
Annual OPEX	500 kEUR/year	**[annual OPEX / CAPEX]**	6%

Discount rate	0%	3,5%	5,0%
LCOE (25 years, in EUR/MWh)	277	334	362

Performance Assessment for Tower LiftWEC

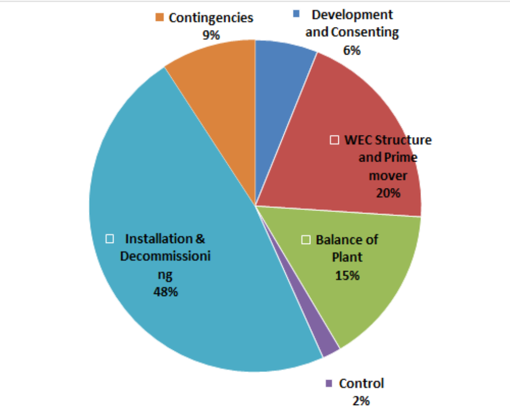
WEC rated power	1240 kW	**Average annual electricity production**	342 kW
Annual Energy Production	3000 MWh/y	**Average annual Capture width**	9,7 m
Capacity factor (C_f)	28%	**Average annual Capture width ratio**	32%

Concept picture



Breakdown of costs

Total CapEx	**8,27 MEUR**
Development and Consenting	500 kEUR
WEC Structure and Prime mover	1634 kEUR
Balance of Plant	1264 kEUR
Control	150 kEUR
Installation & Decommissioning	3894 kEUR
Contingencies	752 kEUR
Annual OpEx	**500 kEUR/year**



3 TLP LiftWEC Economic Assessment

The Tension Leg Platform or TLP LiftWEC configuration consists of the two-hydrofoil rotor held in place by four tension-leg cables. Each cable is reacted at the seabed by a micro-piled foundation (Figure X).

The tension-leg mooring winch system is used both during deployment and recovery operations and to provide submergence control of the rotor.

There are two drums outside the nacelle allowing the moorings lines to be like a yo-yo, adjusting the tension and the water depth / submergence of the rotor.

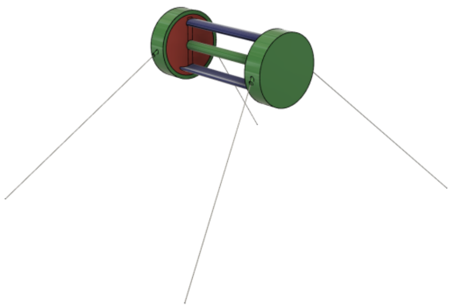


Figure 3.1: TLP LiftWEC

Each cable has a total length of 80m (65m required to bring the power capture unit to the surface plus spare). When the device is submerged to 14m submergence, 55m of tension leg cable per tether is expected to be exposed. Each tension-leg cable terminates at a mechanical winch mounted within a disparately sealed section of the nacelle units. A set of mechanical locks restrict cable motion between winching activities.

The anchoring system consists of four structural footing elements, each of which is independently micro-piled to the sea floor using 12 inclined micro-piles. The micro-pile foundations are used to transmit the fundamental reaction forces and hydrofoil reaction torques to ground.

3.1 Input Values

3.1.1 Main dimensions: dry weight and mooring costs

The tension leg configuration has a more complex mooring than the spar and the semi-sub. Four steel cables, at a water depth of 30 meter, 50.4 mm diameter each (Pecher and Kofoed, 2017), with a weight of about 50 tonnes per line, are assumed; in total **200 tonnes for the mooring lines**. 200 tonnes at a cost of 3400 EUR/ton (cost of steel), provides an estimate of **680.000 EUR for the mooring system**.

The power absorption mechanism needs extra buoyancy in the nacelle part, estimated at about 20 tonnes.

Thus, **total dry weight of the TLP LiftWEC,** excluding the mooring, is estimated at about 180 tonnes (120 tonnes for the nacelle and rotor, 36 tonnes for the hydrofoils, and extra 20 tonnes of buoyancy for the drums).

3.1.2 Annual Energy Production.

Annual energy production for the TLP LiftWEC has been estimated at 2.7 GWh/y at Ifremer site.

3.1.3 Control Cost Estimates

The TLP LiftWEC allows for the two common controls (pitch and phase control):

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- Pitch control of the hydrofoils enabled by two actuators per hydrofoil, one at each end.
- Phase control implemented by direct drive generators, one in each stator.
- There is no rotor radius control.

Submergence is enabled by the moorings, and there is no yaw.

Cost of pitch control is estimated at **75.000 EUR**.

3.1.4 Installation Cost Estimates

The expected installation procedure for the TLP LiftWEC has been detailed in the *Basis of Design document* describing that *"the micro-piled footings and tension-leg mooring cables are installed using surface-based micro-piling vessels and light weight lift vessels. The power capture unit is transported to and from site using tug boats. At the point of deployment, mooring cables are detached from their placeholder buoys and attached to the 4 corners of the power capture unit. The nacelle-mounted winching mechanisms then submerge the device to the desired depth for operation".*

For the micro-pilling activities, estimates on the conservative side assume the use of a small Offshore Construction Vessel (i.e. OCV 250) at 35.000 EUR daily rate, during 4 days (1 working and 3 days waiting).

- Mobilisation: 70.000 EUR
- 4-day operation / at port: 35.000 * 4 = 140.000 EUR
- De-mobilisation: 70.000 EUR
- Total **micro-pilling 280.000 EUR**

Assuming the tension-leg mooring cables are installed with a light weight lift vessel for example the Rambiz), a 3-day service for installation and 3-day delay due to weather windows:

- Mobilisation: 120.000 EUR
- 6-day operation / at port: 60.000 * 6 = 360.000 EUR
- De-mobilisation: 120.000 EUR
- **Total: 600.000 EUR**

And as introduced in Section 1.3.6, the power capture unit is transported to and from site using two tug boats, with total cost of **25.000EUR.**

Total installation costs for a TLP LiftWEC amount to 1 MEUR.

Castro-Santos and Diaz-Casas (2014) estimate that the installation expenditures for a TLP configuration are about 4 times more expensive than the semi-sub and spar installation; which is aligned to the estimates of this report.

Overall, the mooring complexity of the TLP will normally require more operations than the single-point connection of the two floating configurations (spar and semi-sub). This has been reflected in the annual OPEX estimates.

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3.2 Output Values

LiftWEC LCOE Calculation Tool

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885 - The LiftWEC Project. The development of the COE Calculation Tool has been previously funded by the Danish funded projects "The COE tool for WECs – Improvement and Dissemination" (grant agreement 2013-1-12135, 2013-2014) and "Beton til Bølgeenergi" (64018-0600).

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

Project summary

Project name	TLP LiftWEC
Deployment location	France - Ifremer
Power density at the location	40 kW/m
Project lifetime	25 years

Main dimensions and characteristics

Main active dimension	30,0 m
Secondary dimension (length/width)	12,0 m
Total dry weight (excl.mooring)	180 ton
Station keeping type	Floating
PTO type	Direct drive
PTO average efficiency	98%
Generator rated power	1240 kW

Economic Assessment for TLP LiftWEC

Development stage: Phase 1 / TRL 3 — [-30 to 80%] Uncertainty

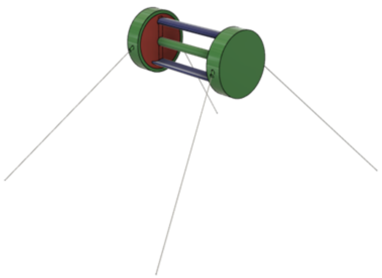
Total CAPEX	5,11 MEUR	**[CAPEX / MW]**	4,1 MEUR/MW
Annual OPEX	250 kEUR/year	**[annual OPEX / CAPEX]**	5%

Discount rate	0%	3,5%	5,0%
LCOE (25 years, in EUR/MWh)	168	207	227

Performance Assessment for TLP LiftWEC

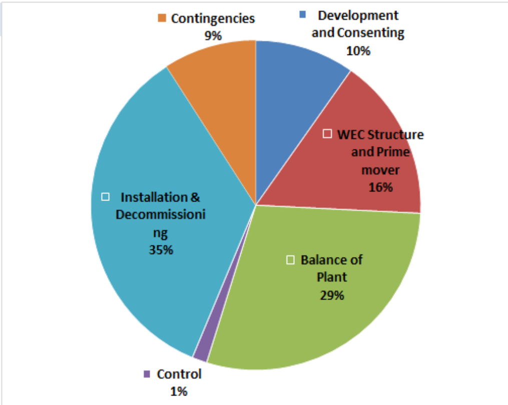
WEC rated power	1240 kW	**Average annual electricity production**	308 kW
Annual Energy Production	2700 MWh/y	**Average annual Capture width**	8,7 m
Capacity factor (C_f)	25%	**Average annual Capture width ratio**	29%

Concept picture



Breakdown of costs

Total CapEx	**5,11 MEUR**
Development and Consenting	500 kEUR
WEC Structure and Prime mover	818 kEUR
Balance of Plant	1484 kEUR
Control	75 kEUR
Installation & Decommissioning	1770 kEUR
Contingencies	465 kEUR
Annual OpEx	**250 kEUR/year**



4 SEMI-SUB LIFTWEC ECONOMIC ASSESSMENT

The floating or semi-submergible LiftWEC configuration consists of the two-hydrofoil rotor attached at both ends to a bracket substructure. This substructure is supported by a floater as shown in Figure X.

The main difference of this configuration to the two previous ones is that this is a floating concept slack moored to the seabed.

Assumption: There are 3 mooring lines attached to a turret mooring point on the front of the structure and each mooring line connected to drag-anchors on the seabed. The mooring system allows the structure to weather-vane.

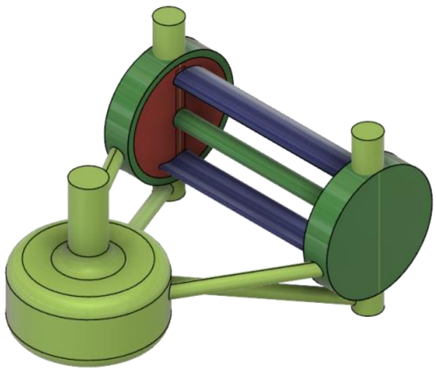


Figure 4.1: Semi-sub LiftWEC

4.1 INPUT VALUES

4.1.1 Main dimensions: dry weight and mooring costs

Arredondo-Galeana *et al*. (2021) calculates the floating support structure composed by a support bracket, with a mass of 103 tonnes, and 3 floaters with a total mass of 276 tonnes. Each floater is constructed with 3 cylinders of an outer diameter of 3 m and a height of 5 m; the connecting rods of the floater have a diameter of 1 m. Calculations assume that the floater is made of steel with thin walls inside. However, it is noted that the mass of the structure could be reduced if the cylinders are redesigned and built from a different material.

The semi-sub LiftWEC has been conceived to only have one floater. As a first approximation, it is estimated that **total weight of the semi-sub floating structure is of 200 tonnes**, corresponding to 100 tonnes for the floater, and 100 tonnes for the support bracket structure. It is also made in steel.

Thus, **total dry weight of the semi-sub LiftWEC,** excluding the mooring, is estimated at about 180 tonnes (120 tonnes for the nacelle and rotor, 36 tonnes for the hydrofoils, and 200 tonnes of buoyancy for the drums).

A similar system of single-point connection mooring as the one developed by Pelamis for its P2 and P3 devices is selected for the two floating configurations (semi-sub and spar). Total cost of the mooring, including lines, anchors and connectors are of 300.000 EUR (WES, 2016). Pelamis P2 was deployed at EMEC at 50 meter water depths.

4.1.2 Annual Energy Production

5% lower performance for the semi-sub LiftWEC is assumed compared to the TLP estimates. This is mainly due to the disturbance from the floater to the flow, even though the semi sub can weather vane. It shall also be considered that the TLP configuration will also have some blockage due to bigger shaft. Taking these elements into account, a 5% lower estimate seems reasonable at this development stage. Hence, annual energy production at deployment site at Ifremer is estimated to 2.6 GWh/y (2.59 GWh/y).

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4.1.3 Control Cost Estimates

The semi-sub LiftWEC shares the two common controls (pitch and phase control) in all four configurations:

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

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

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

4.1.4 Moorings and Installation Cost Estimates

The same mooring system used for the Pelamis P2 deployed at EMEC at 50-meter water depth is assumed, amounting to 300.000 EUR (WES, 2016).

Installation of mooring, prime mover and structure:

- Mooring Installation. **In total 70.000 EUR** assuming (Bimep, 2018):
    - Cost of an anchor handling vessel: 10.000 EUR/day
    - 4 days for installation, plus mobilization/demobilization and waiting on weather days: 3 days. Total 7 days.

Assuming similar procedure than for the tower LiftWEC, considering that the prime mover, bracket structure and floater are assembled onshore at harbour facilities and towed out to deployment site:

- Mobilisation: 50.000 EUR
- 4-day operation / at port: 25.000 * 4 = 100.000 EUR
- De-mobilisation: 50.000 EUR
- **Total P**rime mover, bracket structure and floater **tugboat: 200.000 EUR**

Once the anchors and mooring lines are in place the single point connection system should make the installation operation quicker and faster, and also possible in higher sea states than for the other two non-floating configurations (TLP and Tower). Assuming so, only extra diving work required for operations and supervision is estimated at 2500 EUR/day, 2 days; in total **5.000 EUR**.

Summing all elements up, total Installation costs for the semi-sub LiftWEC are of **275.000 EUR.**

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4.2 Output Values

LiftWEC LCOE Calculation Tool

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Output Summary. Economic and Performance Assessment. Single WEC - Semi-sub LiftWEC

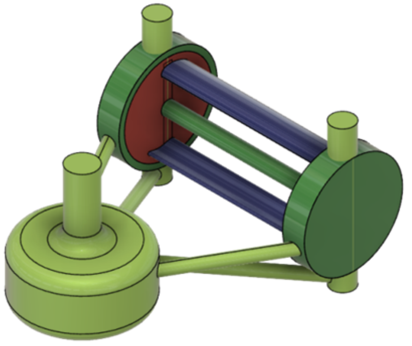
Project summary

Project name	Semi-sub LiftWEC
Deployment location	France - Ifremer
Power density at the location	40 kW/m
Project lifetime	25 years

Main dimensions and characteristics

Main active dimension	30,0 m
Secondary dimension (length/width)	12,0 m
Total dry weight	350 ton
Station keeping type	Floating
PTO type	Direct drive
PTO average efficiency	98%
Generator rated power	1240 kW

Concept picture



Economic Assessment for Semi-sub LiftWEC

Development stage: Phase 1 / TRL 3 — [-30 to 80%] Uncertainty

Total CAPEX	3,99 MEUR	**[CAPEX / MW]**	3,2 MEUR/MW
Annual OPEX	125 kEUR/year	**[annual OPEX / CAPEX]**	3%

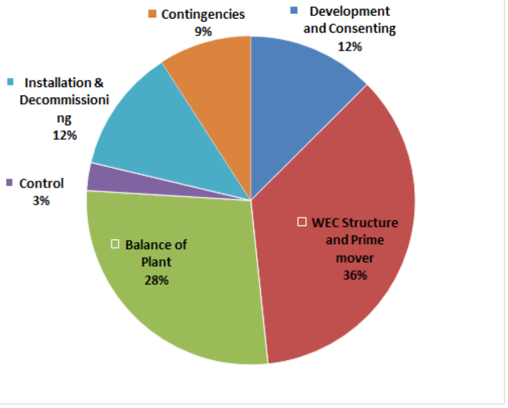
Discount rate	0%	3,5%	5,0%
LCOE (25 years, in EUR/MWh)	110	142	158

Performance Assessment for Semi-sub LiftWEC

WEC rated power	1240 kW	**Average annual electricity production**	295 kW
Annual Energy Production	2590 MWh/y	**Average annual Capture width**	8,4 m
Capacity factor (C_f)	24%	**Average annual Capture width ratio**	28%

Breakdown of costs

Total CapEx	**3,99 MEUR**
Development and Consenting	500 kEUR
WEC Structure and Prime mover	1430 kEUR
Balance of Plant	1104 kEUR
Control	110 kEUR
Installation & Decommissioning	487 kEUR
Contingencies	363 kEUR
Annual OpEx	**125 kEUR/year**



5 Spar buoy LiftWEC Economic Assessment

The spar buoy LiftWEC configuration consists of the two-hydrofoil rotor attached at both ends to a spar buoy structure.

The mooring allows the structure to weather vane. The same mooring configuration as the semi-sub LiftWEC is assumed.

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

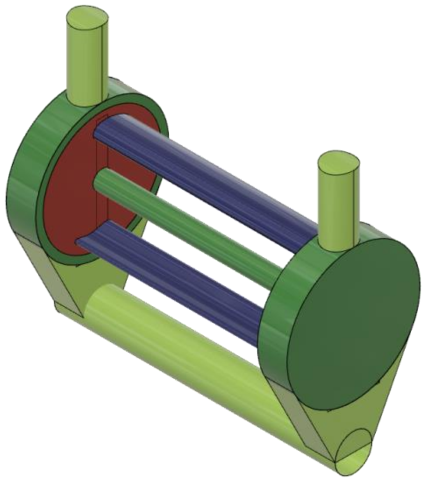


Figure 5.1: Spar buoy LiftWEC

5.1 Input Values

5.1.1 Main dimensions: dry weight and mooring costs

The spar buoy LiftWEC is estimated at a **total weight of 85 tonnes of steel** (about 85% the weight of a floater). This might be a conservative estimate.

Total cost of the mooring, including lines, anchors and connectors are estimated to be 300.000 EUR (WES, 2016), as done for Pelamis P2.

5.1.2 Annual Energy Production

The same performance for the TLP is assumed for the spar buoy. It is estimated at 2.7 GWh/y at the Ifremer site.

5.1.3 Control Cost Estimates

The spar LiftWEC shares the two controls (pitch and phase control) common to the four configurations:

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

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

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

5.1.4 Moorings and Installation Cost Estimates

The same type of mooring and a similar installation procedure is assumed for the spar buoy and the semi-sub. Similarly as before, the single point connection system should make the operation quicker and faster compared to the tower and the spar solution, and possible in

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higher sea states. The system would however require an additional turret in front of the device, and a tether from each nacelle to the turret. A 10% cost increase (30.000 EUR) compared to the semi-sub mooring cost is foreseen, hence 330.000 EUR in total.

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5.2 Output Values

LiftWEC LCOE Calculation Tool

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

Project summary

Project name	Spar LiftWEC
Deployment location	France - Ifremer
Power density at the location	40 kW/m
Project lifetime	25 years

Main dimensions and characteristics

Main active dimension	30,0 m
Secondary dimension (length/width)	12,0 m
Total dry weight	235 ton
Station keeping type	Floating
PTO type	Direct drive
PTO average efficiency	98%
Generator rated power	1240 kW

Economic Assessment for Spar LiftWEC

Development stage: Phase 1 / TRL 3 — [-30 to 80%] Uncertainty

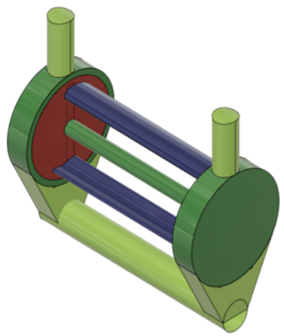
Total CAPEX	3,60 MEUR	**[CAPEX / MW]**	2,9 MEUR/MW
Annual OPEX	125 kEUR/year	**[annual OPEX / CAPEX]**	3%

Discount rate	0%	3,5%	5,0%
LCOE (25 years, in EUR/MWh)	100	127	141

Performance Assessment for Spar LiftWEC

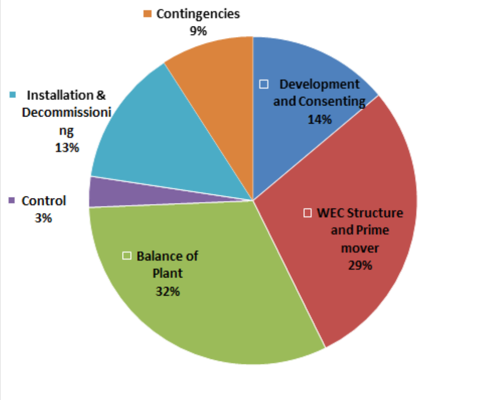
WEC rated power	1240 kW	**Average annual electricity production**	308 kW
Annual Energy Production	2700 MWh/y	**Average annual Capture width**	8,7 m
Capacity factor (C_f)	25%	**Average annual Capture width ratio**	29%

Concept picture



Breakdown of costs

Total CapEx	**3,60 MEUR**
Development and Consenting	500 kEUR
WEC Structure and Prime mover	1039 kEUR
Balance of Plant	1140 kEUR
Control	110 kEUR
Installation & Decommissioning	487 kEUR
Contingencies	328 kEUR
Annual OpEx	**125 kEUR/year**



6 SUMMARY TABLE OF COMPARISON

	Tower	TLP	Semi-Sub	Spar Buoy
Main dimension (width of the WEC) [m]	30 m	30 m	30 m	30 m
Secondary dimension (Rotor diameter) [m]	12 m	12 m	12 m	12 m
Water depth [m]	50 m	50 m	50 m	50 m
Prime mover: Rotor (in steel) [ton]	120	120	120	120
Prime mover: Hydrofoils (glass fiber) [ton]	36	36	36	36
Support structure weight (in steel) [ton]	260	20	200	85
Foundation / mooring [ton]	260	200	140	140
Rated Power (P_r) [MW]	1.5 MW	1.5 MW	1.5 MW	1.5 MW
Annual Energy Production (AEP) MWh/y	3000	2700	2600	2700
Capacity factor	28%	25%	24%	25%
Average annual Capture width ratio	32%	29%	28%	29%

	Tower	Tension-leg	Semi-Sub	Spar Buoy
CAPEX [EUR]				
Development costs	500.000	500.000	500.000	500.000
Structural cost: nacelle & rotor	400.000	400.000	400.000	400.000
Hydrofoils	340.000	340.000	340.000	340.000
PTO and housing	750.000	750.000	750.000	750.000
Mooring cost (lines + anchors)		680.000	300.000	330.000
Support structure	900.000	68.000	680.000	290.000
Foundation cost (monopile)	520.000			
Control cost	250.000	75.000	110.000	110.000
Installation + Mooring installation cost	2.200.000	1.000.000	275.000	275.000
Total CAPEX [MEUR]	**8.3 M€**	**5.1 M€**	**4 M€**	**3.6 M€**
Annual OPEX [kEUR/y]	500 k€/y	250 k€/y	125 k€/y	125 k€/y
LCOE (25 years, r=5%) [EUR/MWh]	**360 €/MWh**	**230 €/MWh**	**160 €/MWh**	**140 €/MWh**
CAPEX per MW [MEUR/MW]	**6.7 M€/MW**	**4.1 M€/MW**	**3.2 M€/MW**	**2.9 M€/MW**

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7 COMPARISON OF THE FOUR BASELINE CONFIGURATIONS

Comparing the LCOE calculated for the four baseline configurations, taking into account the estimated annual energy production and accumulated costs of construction, installation and operating over the lifetime of the projects, **the two floating LiftWEC configurations (the semi-sub and the spar) have the lowest Cost of Energy of 140 €/MWh. This is about half compared to the LCOE of the Tower LiftWEC. The TLP configuration is in between.**

Table 7.1: LCOE for the four LiftWEC Baseline Configurations.

	Tower	TLP	Semi-Sub	Spar Buoy
LCOE (25 years, r=5%) [EUR/MWh]	360 €/MWh	230 €/MWh	160 €/MWh	140 €/MWh

This conclusion comes as a result of several considerations.

The **high LCOE of the Tower LiftWEC** is due to the high installation costs (a heavy lift vessel is needed to embed the monopile a third of its length into the sea bottom) and higher OPEX, approximately twice or three times more, than in the other configurations. The latter is driven by the fact that the attachment / de-attachment of the prime mover to the jack-up tower / transition piece requires a weather window with no waves and must be carried out using a lift vessel, which generally is twice or three times more expensive than vessels used for the other configurations.

The TLP configuration has a medium LCOE. This is mainly driven by an OPEX twice as high as that of the floating configurations. The TLP has more complex mechanism under loads (mooring drums), and connection/de-connection operations are always going to be more time consuming than those of the single point connection (spar and semi-sub). The only positive thing when looking into OPEX is that a smaller tug is expected (although this has a minor cost influence). The TLP CAPEX are mainly driven by the high costs of mooring and the Installation.

The **low LCOE value of the Spar LiftWEC** is mainly driven by low structural costs; as the support structure only adds 85 tonnes of steel on top of the mass of the prime mover. Installation costs are not high, and are in the similar range as those for the semi-sub; which makes the Spar LiftWEC to have the lowest CAPEX of the four, estimated at a total of 3.6 MEUR or 2.9 MEUR/MW. As a reference, Table 7.2 compares modelling values of CAPEX per MW as presented in a recent ETIP report addressed to the European Commission (Cochrane *et al.*, 2021). OPEX for the Spar LiftWEC are also on the lowest level, as the single connection point is expected to allow for a quick and easy connection, and also possible in higher sea states than for the other two non-floating configurations (TLP and Tower).

The **LCOE of the semi-sub configuration is also in the low range**, and in the same order of magnitude as the LCOE of the spar buoy. Both the spar and the semi-sub are based on a single point connection (thus OPEX and Installation cost are the same). The difference between the two is on higher CAPEX for the semi-sub due to a higher support structure; and a slightly lower energy production (estimated at 5%, and even though it can weather-vane) for the semi-sub compared to the spar, mainly to account for the disturbance from the floater to the flow. Total CAPEX are in the lower range, at 4 MEUR or 3.2 MEUR/MW.

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Table 7.2: CAPEX inputs for European and Global SET Plan scenario modelling for wave deployments (MEUR/MW), (Tsiropoulos et al., 2018).

Year	2020	2025	2030	2035	2040	2045	2050
CAPEX (EUR/MW)	5.6	3.3	2.5	1.6	1.5	1.4	1.3

Based on the above, it could be concluded that at this stage of development and analysis, **installation costs** and **OPEX** are the cost centres that lead to a higher or lower LCOE.

To finalise the conclusions, it is noted that the Joint Research Centre (JRC, 2019) estimated that wave energy technologies are expected to reach an LCOE of 150 EUR/MWh in 2030. Aligned to this target, the LiftWEC project set up an end-of-project LCOE target of 120 EUR/MWh. The analysis and results shown in this deliverable indicate that the four LiftWEC Configurations are aligned to both 2030 JRC targets and the project targets.

It is also acknowledged that at this stage of development (Stage 1, TRL 3), the uncertainty in the LCOE is in the order of -30% to 80%.

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8 Discussion

To cover the purpose of the economic feasibility analysis of WP8 some generic assumptions have been made. These allow drawing the above conclusions for each device, and also to compare configurations. However, the authors acknowledge that there are some elements that would significantly change the economic results presented here.

Some of these elements are the following:

A significant fraction of total project costs can be attributed to vessel chartering. Improved knowledge on installation procedures and maintenance activities for each configuration, including dedicated vessels for each activity, would allow more concise calculations and perhaps lead to different results.

It should be noted that single point mooring connection for the floating configuration should increase that limit as demonstrated during the Pelamis deployment, but this is yet be demonstrated for the LiftWEC concepts. In absence of specific data, a 2 meter Hs is assumed the maximum operational limit for offshore operations (like personnel transfer from vessels or jacking up/down activities. Analyzing deployment location weather windows for a specific wave height would allow improving the economic feasibility analysis for each configuration.

The Tower LiftWEC configuration seems solid both from a structural as well as from a power absorption and conversion point of view. However, and according to the feedback received from WP7 dealing with Installation and O&M, the type of vessels it requires for its installation (a heavy lift vessel of Svanen type) and requires almost no waves, which in the deployment site selected in the analysis, named Ifremer, occurs very few times a year. This can in worst case mean that you can be waiting for half a year before the right weather window appears.

This seems to also be the case for the maintenance strategy. A return-to-base strategy requires also low Hs conditions, which rarely happens for a 10-hour window. This means that there will be long waiting times to recover the device and also to install it after it has been maintained in harbour. Waiting time imply no electricity production, and hence no revenue; and increased expenditures on vessels (same daily rates in port as offshore usually apply), harbour facilities and personnel.

This remark might indicate that perhaps another location or innovations concerning the installation concept could lead to a more competitive Tower LiftWEC configuration and maintenance strategy.

Also, as an established technology, there are some benefits using a monopile (depth dependent). A major benefit is that it allows for a fixed cable connection between the Tower and the seabed. Also the submergence control is a benefit; i.e. lowering the device in the water column in survivability conditions, as well as raising the device out of the water for maintenance.

OPEX Estimates: OPEX data is found to be limited at this stage. Further work on detailed O&M procedures and methods, specific requirements, and also vessels requirements and operational limits, would allow improved final estimates. Some questions for further work on O&M are detailed below:

- Glass fibre hydrofoils have a 15-year lifetime. What is the expected exchange method and associated costs to it?

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- Draw estimates on how different control types induce more failures in the system, and the trade-off between increased Annual Energy Production due to improved power absorption capabilities, and increased maintenance expenditures due to more mechanical parts. Estimates on control associated lifetime (i.e. max. number of cycles).

LCOE estimates have been drawn based on a discount rate of 5%. It has been recently recommended to use a 3.5% discount rate (Cochrane *et al.* (2021), which references (HM Treasury, 2018)), which would give a lower LCOE for the four configurations, as shown in Table 8:

Table 8.1: LCOE for the four LiftWEC Baseline Configurations calculated for a discount rate of 3.5%

	Tower	TLP	Semi-Sub	Spar Buoy
LCOE (25 years, r=3.5%) [EUR/MWh]	335 €/MWh	205 €/MWh	140 €/MWh	125 €/MWh

Annual Energy Production: The AEP affects the LCOE directly and Work Package 5, looks into the control strategies, and which configurations would allow better control than others. The gain of increase energy absorption of such control needs to be fully quantified. As a first attempt, a comparison is provided below maximizing the possible annual energy production and seeing the effect on the final LCOE, maintaining all the other parameters constant.

Calculations below assume AEP of Tower LiftWEC is 25% higher than for the TLP, and that the Spar and the semi-sub have 25% lower AEP than the TLP. The AEP of the TLP configuration is maintained as the reference.

Table 8.2: LCOE for the four LiftWEC Baseline Configurations changing the Annual Energy Production.

	Tower	TLP	Semi-Sub	Spar Buoy
Reference Annual Energy Production [MWh/y]	3000	2700	2600	2700
LCOE (25 years, r=5%) [EUR/MWh]	360 €/MWh	230 €/MWh	160 €/MWh	140 €/MWh
Extremes in Annual Energy Production [MWh/y]	3400	2700	2000	2000
LCOE (25 years, r=5%) [EUR/MWh]	320 €/MWh	230 €/MWh	200 €/MWh	190 €/MWh

LCOE estimates assuming extreme AEP values turn the Tower Configuration more competitive and the two floating configurations less competitive. Further knowledge on the real implications of control (higher energy capture, but also more O&M) would allow a better quantification of control.

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