PivotBuoy

An Advanced System for Cost-effective and Reliable Mooring, Connection, Installation & Operation of Floating Wind

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D7.2 – LCoE assessment of the PivotBuoy Concept

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EXECUTIVE SUMMARY

This deliverable presents a theoretical study of the potential LCOE impact of using PivotBuoy technology for pre-commercial and commercial scenarios in different European sea basins. The study also assesses the impact of installing on different site locations and different farm capacities. The cost data has been obtained using theoretical cost functions.

The primary objective of the PivotBuoy project is to demonstrate that with its innovative technology it is possible to reduce the Levelized Cost of Energy (LCoE) from floating offshore wind by 50% when compared with a 2018 state-of-the-art floating offshore wind farm.

This deliverable describes all the steps taken for the calculation of the economic benefits that PivotBuoy technology can bring to the floating offshore wind market, with focus on the impact of the concept's innovations on the LCoE and other key metrics. To conduct such assessment, it was developed a techno-economic model which methodology, assumptions and tool functionality are described in this report.

The results of the study show that an LCoE between 80-130€/MWh can be achieved already for a small pre-commercial 30 MW array and an LCoE of 45-75€/MWh for the first commercial-scale floating wind farm (420MW), depending on the site conditions, turbine size and learning rates applied, and further cost reduction potential is expected through the full industrialization of the technology for large-scale deployment. Such values were accomplished through a CAPEX and OPEX reduction and an increase of the AEP. These are great results that prove the potential of this innovative technology and how it can be a game changer in the floating offshore wind market.

The tool developed also allows to compare the impact of different location sites, different turbines' capacity, and total installed capacities. It was concluded that the wind speed has a decisive impact on the returns of the investment as locations with a higher average wind speed result in lower LCOE due to an increase in electricity production. Looking at the installed capacity, both capital and operational costs are reduced when the installed capacity is increased, being favourable to cost reduction a low number of higher capacity turbines than the opposite.

To conclude the assessment, it is examined the risk associated with such project, market environment of the floating offshore wind and the industrialization of the PivotBuoy.

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ABBREVIATIONS AND ACRONYMS

AEP	Annual Energy Production
CAPEX	Capital Expenditures
CF	Capacity Factor
CTV	Crew Transfer Vessel
D&C	Design & Consent
D&D	Decommissioning & Disposal
EFGL	Éoliennes Flottantes du Golfe de Lion
FOW	Floating Offshore wind
GWA	Global Wind Atlas
I&C	Installation & Commissioning
IPR	Intellectual Property Rights
IRR	Internal Rate of Return
KOWL	Kincardine Offshore Windfarm Ltd
KPI	Key Performance Indicator
LCC	Life Cycle Costs
LCoE	Levelized cost of energy
LR	Learning Rate
NPV	Net Present Value
O&G	Oil and Gas
O&M	Operation & Maitenence
OPEX	Operational Expenditures
P&A	Production & Acquisition
PB	PivotBuoy
PPA	Power Purchase Agreement
SoA	State-of-the-art
SPM	Single Point Mooring
TEM	Techno-Economic Model
TLP	Tension Leg Platform
TTP	Tow-to-Port
WTG	Wind Turbine Generator

1) INTRODUCTION

1.1 Scope and Outline

This deliverable, developed under the scope of task 7.2 of the PivotBuoy project, is about the development of an LCoE model and its application to case studies using the PivotBuoy technology. A Techno-Economic Model (TEM) has been developed under the task scope and complemented by the contributions and lessons learned throughout the project. The document will describe the methodology, framework, scenario definition, results and is finalized with the main conclusions.

This section provides an introductory context to this deliverable, by giving an overview of the Floating Offshore Wind (FOW) sector and its financial perspective. Following that, a highlight is given to the PivotBuoy technology by briefly addressing its technical characteristics and financial advantages. To finalise this section, the analysed Key Performance Indicators (KPIs) are revisited as well as the reference values to which the PivotBuoy compares to and the proposed advantages.

Section 2) describes the scenarios chosen to be simulated on the TEM. Four wind farm array scenarios were defined (three pre-commercial and one commercial) and one of the pre-commercial scenarios is compared to the 2018 state-o-the-art (SoA) FOW farm. The scenarios were selected based on potential developments and to study the influence of key variables (turbine capacity and total capacity) in the LCoE calculations. The different scenarios include turbines with a power capacity of 10 MW, 12 MW and 15 MW, while the total installed capacity for the different scenarios varies from 30 MW to 420 MW.

Section 3) comprises the selected locations for the application of the scenarios. It describes the site location specificities and the reasoning behind the selection of each site. All of them are well-referenced and high-potential sites for the development and installation of FOW technologies – Gran Canaria (Spain), Golf du Lyon (France), Viana do Castelo (Portugal) and the North Sea.

Section 4) presents the cost model from which the TEM derives from, by explaining the cost structure breakdown and the cost items that compose each one of the model's sections.

After the description of the cost model, Section 5) introduces the Techno-Economic Model developed on Microsoft Excel. The methodology and assumptions behind the model are described, as well as a description of the model and its functionality.

Section 6) presents the results from the model simulations coupled with an analysis and discussion. This section also explores the impact of the different variables through a sensitivity analysis of the TEM and a brief reflection on some qualitative indicators. This section is the result of the effort applied to the development of task 7.2 and combines the content of the previous four sections, providing final numbers to the LCoE calculations.

The final part, Section 7) provides the conclusions from the performed work.

1.1 Floating Offshore Wind – Sector Overview and Financial Perspective

When compared to onshore, offshore wind offers a vast area of unexplored wind energy with the advantages of having less constraints from human activities, higher and more uniform wind speeds

with less turbulence, and a reduced visual and sound impact [1]. The further from the coast is the installation the wider is the available explorable area, offering more stable wind conditions while reducing the visual impact from the coastline and the negative effect on other economic activities such as fishing and tourism [2].

However, with bigger distances from shore comes increasing water depth, and above 40 to 60 meters water depths fixed foundations are no longer economically competitive [3]. Given that 80% of offshore wind resources are located in waters of more than 60 meters depth [3], and with the maturity from existing floating Oil & Gas (O&G) structures, floating offshore wind (FOW) comes as the evident course of action for offshore renewable energy [4] [5].

Accordingly do the Global Wind 2021 report [6], in 2020 the total offshore wind capacity exceeded 35 GW, contributing to 4.8% of the global cumulative wind capacity. Looking to Europe [2], during 2020 a total of 356 new offshore wind turbines, across a total of 9 wind farms, were connected to the grid, adding 2.9 GW of new offshore for the total of 25 GW installed capacity (Figure 1). These numbers are a clear indication of the growing investment on offshore wind and how important is to develop the technology into allowing a broader exploitation of the resources.
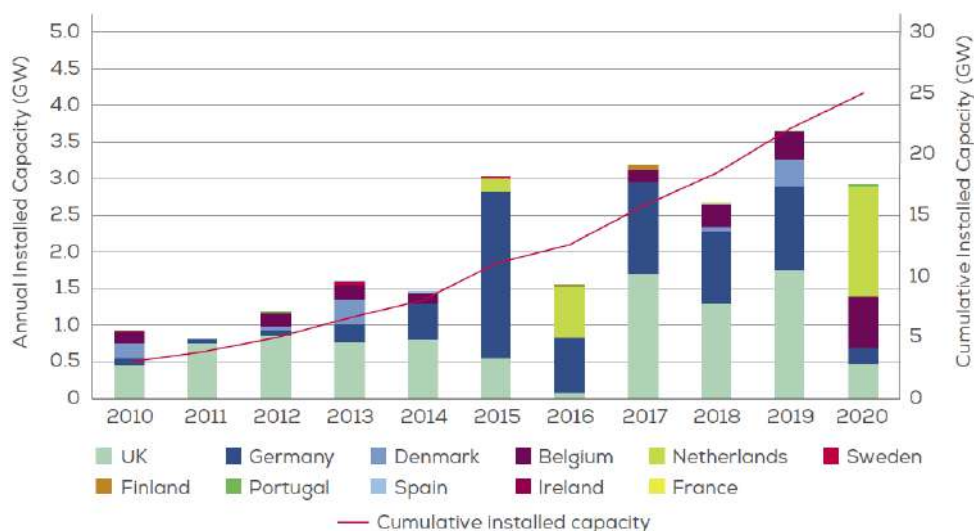
Figure 1: Annual offshore wind installations country in Europe [2]*.*

Focusing on floating wind, by the end of 2020 Europe possessed a total of 62 MW of installed capacity, contributing to 83% of the global capacity. The main contributor to the achievement of 2020 was the commissioning of WindFloat Atlantic (25 MW) in Portugal. In October 2021, the Kincardine 50 MW wind farm got fully operational, this project is composed of one 2 MW and five 9.5 MW turbines, making it the world's largest floating wind project to date [7]. On the 8th of June of 2021, China's first floating wind platform (5.5 MW) was installed for demonstration purposes at the 400 MW Yangxi Shapa III offshore wind farm [8].

Looking for the future of offshore wind, the European commission defined as target the installation of at least 60 GW offshore wind by 2030 and 300 GW by 2050 to power Europe's green transition [9]. With this in mind, it was produced the 2nd SET Plan [10] that outlines the strategy to reach the 2050

commission's target. The plan emphasises the need of a dramatic increase of the installation rate and suggested a set of measures to achieve such rate.

With the proposed strategy in the EU SET-Plan targets, and assuming a high deployment rate, the plan forecast that floating offshore wind could reach 130€/MWh by 2025 (dependent of 1.5 GW installed capacity) and 62 €/MWh in 2030 with the assumption of 6 GW of installed capacity [10]. Looking to 2050, a report by DNV GL predicts that the cost of floating wind will fall to a global average of 40 €/MWh. The main driver for such reduction is the introduction of larger turbines, larger wind farms, significant technology developments and the creation of a highly cost-competitive supply chain [11].

To maintain Europe's leadership in floating wind technology it is imperative a cooperative action between governments, policymakers, industry, financing institutions and all stakeholders. Looking forward to industrialization, the key suppliers needed for a future competitive price for offshore wind are wind turbine suppliers, installation contractors, vessel suppliers and construction ports [12].

Although the FOW industry could use between 60-70% of the existing offshore wind supply chain, an investment in ports infrastructure is essential for the future of FOW industry. WindEurope estimates a need of 6.5B€ of investment until 2030 in port infrastructures to allow the expansion of offshore wind [13].

In terms of financing, the first Power Purchase Agreement (PPA) for offshore renewables was signed in 2018 for roughly 120 MW of Kriegers Flack's output (Denmark) [3]. By 2020 eleven more corporates had signed PPAs for offshore wind, including the 30 MW Hywind Scotland FOW park and the 50 MW Kincardine Offshore Windfarm Ltd (KOWL) [14] [15]. This growing number of PPAs is a clear indication how those are a valuable option for corporates who are looking to source large volumes of renewable electricity [3]. From the developer's perspective, PPAs come as a guarantee for long-term revenue, which is of the most importance in enterprises from zero-subsidies.

1.1.1 PivotBuoy Technology

The PivotBuoy Project is developing a prototype, which includes the PivotBuoy system, with the aim reduce the levelized cost of energy (LCoE) of floating wind. The PivotBuoy (PB) is an innovative subsystem that aims to reduce the costs of mooring systems and floating platforms, allow faster and cheaper installation and a more reliable and cost-effective Operation and Maintenance [16].

The technology combines the advantages of Single Point Mooring systems (SPM) with the stability and low weight of Tension Leg Platform (TLP) designs. It is a 2-parts modular design composed of the lower body, permanently moored, and the upper body, that can be quickly connected or disconnected if necessary [17]. This modular feature enables a passive yaw and a Tow-to-Port (TTP) maintenance approach to the PB system where the large repairs can be carried out at port [18]. Figure 2 presents a high-level view of the final design of the PivotBuoy mooring system integrated in the X30 platform.
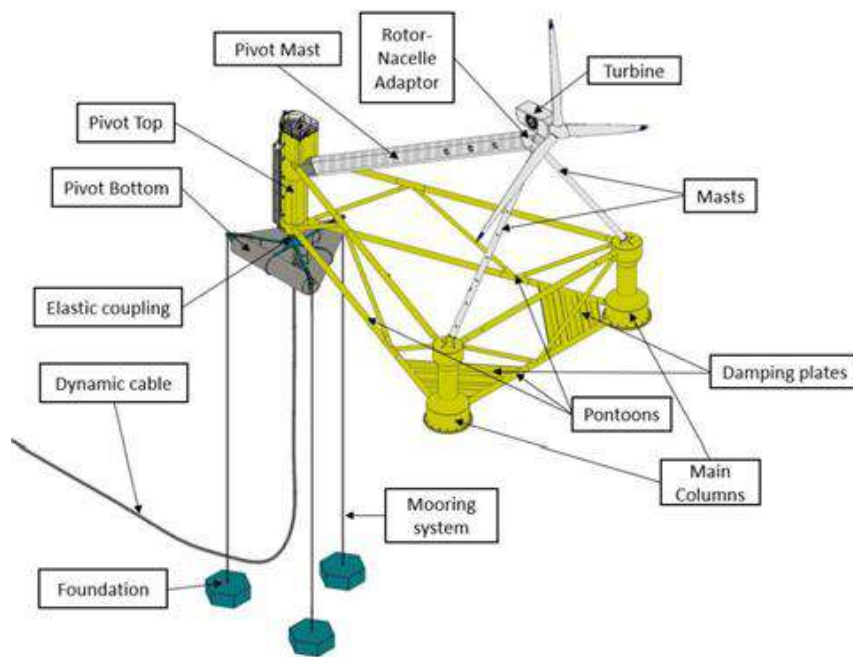
Figure 2: PivotBuoy part-scale X30 design [55].

The lower body (Pivot Bottom) is an excess buoyancy body moored to a gravity-based anchor through a tension three-legged leg system, where the umbilical cable is also connected. The upper body (Pivot Top) is the connection point of the weathervaning part where the remaining structure that is assembled at shore and dragged to the installation point and connected to lower body.

The platform and turbine are one of the most important parts of the project because they determine the loads going through the PivotBuoy mooring system. The platform is composed of three columns connected by a twin pontoon, where the turbine nacelle is supported by three upper masts that connect to each column. A downwind turbine is installed, allowing it to weathervane freely around the mooring point orientating itself with the incoming wind. Due to the weathervane feature, it is no longer necessary an active yaw system, reducing the mass located at hub height. With the downwind turbine, there is no need for pre-coning and blade pre-bending because the turbine blades deflect away from the support masts while under load [18]. PivotBuoy technology is described in more detail in deliverable D5.4 [18], where a benchmark of possible competitors' solutions is presented.

Given the potential of and the tendency for higher investment in the sector, PivotBuoy technology aims to create bigger impact on the floating offshore wind industry through the "Production and Acquisition", "Installation and Commissioning" and "Operation and Maintenance" stages [4]. In terms of cost reduction, PivotBuoy aims to reduce costs in the following fronts:

Production costs - A TLP mooring system enables a low weight design of the floater, lowering construction costs.

Installations costs - The three columns provide enough stability during transit facilitating the installation process at shore and removing the need for expensive dedicated vessels, reducing the global installation costs. The single-point mooring allows for quick connection during hook-up and therefore reduces installation time.

O&M costs - The quick-connection mechanism, allowing for fast and reliable disconnection of the floating platform enables a tow-to-port strategy for major repairs and avoiding the use of large offshore vessels. This allows a reduction of the risk and time when disconnecting and connecting, and thereby reducing downtime costs. The other significant characteristic of the PivotBuoy floater is the reduction of active systems, there is no active yaw nor active ballast, removing the cost associated with maintaining such systems.

One of the big advantages of the PivotBuoy system is the use of downwind turbines, which allows the turbine blades to be lighter, longer, and cheaper as they can bend away from the structure. This will be another key advantage in the long-term cost reduction required to make floating offshore wind competitive, as turbine grows larger.

To summarize, the PivotBuoy project combines the advantages of a TLP mooring system, such as minimization of the footprint on the seabed and low weight design for the platform with the ease of installation of a semi-submersible, and the weather vanning capacity of single point mooring systems with a downwind turbine. It enables a CAPEX (Capital Expenditures) reduction due to the significant platform weight reduction and assembly and installation simplification. The PivotBuoy technology also comes with several drivers that will reduce the OPEX (Operational Expenditures), through the reductions of active systems (no required active yaw or ballast system), reduced fatigue on the dynamic cable, quick connection/disconnection mechanism and a Tow-to-port strategy for major overhauls.

1.1.2 Sector positioning

As a distinctive technology PivotBuoy does not have yet a direct competitor. Nevertheless, there are several projects where some components and aspects can be compared to the PivotBuoy platform.

As addressed in deliverable D5.4 [18] it is possible to place PivotBuoy technology in relation to existing floating wind technologies and competitors as represented in Figure 3. PivotBuoy system is a hybrid TLP concept that should reach a 5-6 TRL level by the end of the project. Such TRL will be reached through the X30 PivotBuoy prototype in a real operational environment on PLOCAN, in Gran Canarias.
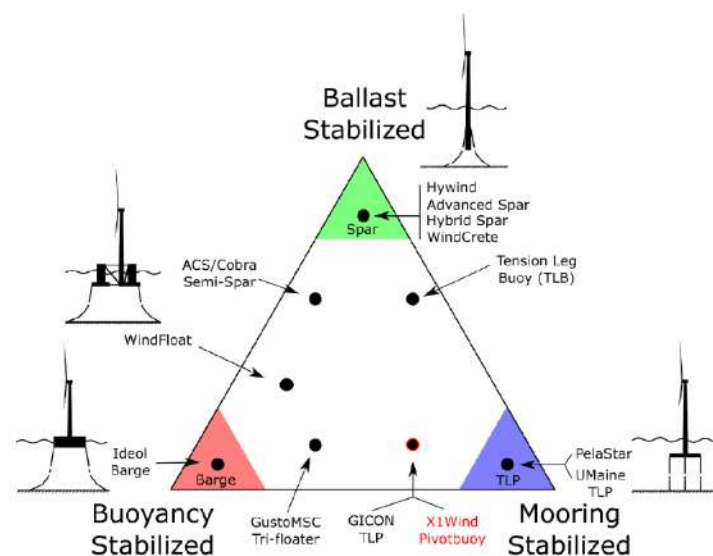
Figure 3: Positioning of X1 Wind PivotBuoy amongst other floating wind concepts as a function of their main stability drivers. Source: D5.4 [18].

1.2 Key Performance Indicators

To fully address PivotBuoy technology, five high-level Key Performance Indicators (KPI) were considered when building the Techno-economic model as a form of evaluating PivotBuoy Life Cycle Costs (LCC) and the Levelized Cost of Energy (LCoE).

For the purpose of assessing the potential reduction of LCoE, a 2018 state-of-the-art (SoA) scenario with an LCOE of 240€/MWh was defined based on research studies for existing pre-commercial projects and information on upcoming feed-in-tariffs for pre-commercial projects [19] [20].

The first KPI is the variation of the final LCoE. LCoE measures the average net present cost of electricity generating over a generation plant lifetime, is one of the most common indicators used both for investment planning and to compare different electricity generation technologies as it allows to level the cost per MWh of competitive technologies with different life spans, sizes, costs, risks, return, and capacities. For this study, besides the actual LCoE of PivotBuoy technology in different scenarios and locations, it will be calculated the position of PivotBuoy LCoE when compared to similar projects, which is the first KPI and it is identified by equation (1):

$$LCOE_\Delta = \frac{LCOE_{PivotBuoy} - LCOE_{Other\ solutions}}{LCOE_{Other\ solutions}} \times 100 \tag{1}$$

Similarly, the variation of PivotBuoy's CAPEX and OPEX will be analysed. CAPEX is commonly associated to the initial phases of the project (Design and Consent, Production and Acquisition, Installation and Commissioning) phases, while OPEX relates to the costs of operation and maintenance.

Equation (2) and (3) formulate de CAPEX and OPEX variation respectively.

$$CAPEX_\Delta = \frac{CAPEX_{PivotBuoy} - CAPEX_{Other\ Solutions}}{CAPEX_{Other\ Solutions}} \times 100 \tag{2}$$

$$OPEX_\Delta = \frac{OPEX_{PivotBuoy} - OPEX_{Other\ Solutions}}{OPEX_{Other\ Solutions}} \times 100 \tag{3}$$

The fourth KPI, equation (4), relates to the Energy Production and expresses a direct comparison between the energy produced through PivotBuoy and the reference solution.

$$EnergyProduction_\% = \frac{EnergyProduction_{PivotBuoy}}{EnergyProduction_{Other\ solutions}} \times 100 \tag{4}$$

One of the main goals of an electricity generation technology is high energy output values, however, high energy values increase the risk of balancing costs (costs associated to the difference between the contracted energy and the delivered energy) if it does not provide the expected amount. This KPI comes has essential to provide investors an insight of how PivotBuoy position itself in relation to similar

solutions in terms of energy production. The "*Other Solutions"* variable on the KPI's will be the reference values from the 2018 SoA project.

The overall objective of the PivotBuoy project is to develop and validate an advanced system to reduce the Levelized Cost of Energy of floating wind by 50% compared to the 2018 SoA.

To reach such LCoE value, the PivotBuoy technology aims to (in relation to the 2018 state-of-the-art) reduce the CAPEX by 54%, OPEX by 19% and to increase by 4%, in order to reach a LCOE reduction of 50%.

To complement the LCoE high-level assessment, the following three qualitative indicators will be analysed: Risk, Market Environment, and Industrialization. The Risk KPI compiles the most relevant risks associated with such technology while identifying its impact and corresponding mitigation measures. In Market Environment, it will be analysed the factors that could affect PivotBuoy technology ability to grow after this project conclusion. Lastly, it will be examined how industrialization will impact LCoE and PivotBuoy future value.

2) ASSESSMENT SCENARIOS

To better interpret the LCoE model outcome, three pre-commercial and one commercial scenario will be assessed, see Table 1. For each scenario a set of parameters was defined based on its needs and specific location.

The first scenario (30MW) will be used for a direct comparison with the 2018 state-of-the art FOW project. Scenario 2 and scenario 3 (≈45 MW) were set to compare the impact on the LCoE of pre-commercial scenarios with 12 MW and 15 MW turbines, which are the highest capacities turbines produced that are currently in prototyping phase. The final scenario is a future possible commercial one with a total capacity of 420 MW. Table 1 summarizes the evaluated scenarios.

Table 1: Scenarios evaluated on the TEM.

#	Scenario	Configuration	Total Capacity
1	Pre-commercial Baseline	3 X 10 MW	30 MW
2	Pre-commercial 2	4 X 12 MW	48 MW
3	Pre-commercial 3	3 X 15 MW	45 MW
4	Commercial	28 X 15 MW	420 MW

For the purpose of this report and the analysis conducted, a set of inputs of the techno-economic model will be fixed for all the scenarios. The inputs to the TEM is presented in Table 2.

Table 2: TEM fixed inputs.

Wind farm

Electrical losses	2.5 %
Wake losses	**2 % // 5%**
Downwind rotor losses	0 %
Availability	92% // 94.5% // 97 %
Generator type	Direct drive
Onshore substation	AC-AC MW
Grid connection	New
Turbine substructure	PivotBuoy
Wind profile equation	Power law

Financial

Manual FIT (default 0)	0 €/MWh
Project lifetime	**20 yr // 25 yr**
Electricity pricing	FIT
Discount rate	**10 % // 8 %**
Learning rate	**5.9 % // 9.5%**

Install / O&M

Install quarter	Any
Preventative repair quarter	Any
O&M method	Detailed
Installation method	Detailed
Number WTs per minor repair	2
Shift pattern	12 h
Significant wave height	1.5 Hs
Number of install vessels	2

For electrical losses it was considered a value of 2.5% based on the range of values obtained on the optimized layouts studies [21] and [22]. Regarding wake losses, a parameter that changes with the size

and layout of the farm, was set to 2% for the pre-commercial scenarios and 5% for the commercial one. The reference values for the wake losses were chosen based on [23] and by considering the impact of a downwind rotor.

To use a downwind rotor could in theory add additional losses when compared to more conventional turbines. However, the literature is conflicting regarding this matter as some indicate that downwind turbines could reduce the losses [24], while others state the opposite [25]. X1 wind performed an internal assessment of this matter that showed that a downwind configured turbine on the PivotBuoy platform can achieve similar AEP levels as for an upwind turbine, for this reason the assumed losses for the downwind rotor was set to 0%.

The availability is set to change with the total installed capacity, as it considers that as the project gets bigger and mature there is less uncertainties and therefore higher availability factors [26]. The values on the TEM are based on ranges from different reports and defines an availability of 94.5% for pre-commercial scenarios [27] and 97% for commercial ones. The value for the commercial case comes from the prediction that on the long-term the PivotBuoy floating wind system will have similar availability as onshore wind, the use of a more passive system will make it less prone to O&M activities that reduces the availability.

Project lifetime and Discount rate inputs are automatically set based on the project total capacity, but with the possibility of specifying the value for both variables. In the case of a pre-commercial scenario the model will set a 20-year lifetime and a 10% discount rate, if the input scenario is a commercial one, it will set a 25 years lifetime and an 8% discount rate. The discount rate values were set based on the "Levelized cost of energy for offshore floating wind turbines in a life cycle perspective" study [28]. 25 years of lifetime is a common project duration for a commercial project defined by [29], and the limits associated with the project life are a current grey area, as few relatable projects fixed-bottom offshore wind have reached this important milestone. Pre-commercial scenarios were given 20-year lifetimes, to account for reduced operation offshore but to recognise the potential for project extensions and repowering opportunities.

The impact of applying a 5.9% or a 9.5% learning rate will be analysed for all scenarios. The rates were obtained from the latest Floating Offshore Wind: Cost Reduction Pathways to Subsidy Free [30].

2.1 Baseline Scenario 1 (3 x 10 MW)

The Baseline Scenario was constructed to compare to a 2018 state-of-the-art commercial floating wind farm of 30 MW.

The Baseline scenario assess a 30 MW array consisting of three 10 MW NREL wind turbines for each of the site locations mentioned in section 2).

The following technical parameters (Table 3) will be set as input on the LCoE tool. The parameters were chosen based on the scenario characteristics and on the cost-effective commercially available cables that matched the minimum necessities of the scenario. Being a 30 MW farm, one 66kV export cable is sufficient for the installation.

Table 3: Technical parameters set for Baseline scenario.

Wind Farm	
Array cable type	66 kV
Export cable type	66 kV
Number of export cables	1
Wind turbine capacity	10 MW
Number turbines	3

2.2 Pre-commercial Scenario 2 (4 x 12 MW)

Scenario 2 is composed of four 12 MW GE Haliade X turbines, with a total of 48 MW capacity. It was chosen a 12 MW turbine because it is the current highest capacity on an installed offshore wind turbine.

Table 4 presents the parameters set for Scenario 2. As on the previous scenario, the parameters were chosen based on the scenario characteristics, with a 48 MW farm, it will be necessary one 132kV export cable for the installation.

Table 4: Technical parameters set for pre-commercial Scenario 2.

Wind Farm	
Array cable type	66 kV
Export cable type	132 kV
Number of export cables	1
Wind turbine capacity	12 MW
Number turbines	4

2.3 Pre-commercial Scenario 3 (3 x 15 MW)

Similar to the previous scenario, Scenario 3 will assess the impact on the LCoE of high-capacity wind turbines considering a setting of three 15 MW IEA Wind turbines (3 x 15 MW).

For this scenario it is simulated 15 MW turbines for being the capacity of the turbine developed withing IEA Wind Task 37 [31].

The parameters set for this scenario are represented on Table 5. Because scenarios 3 and 4 have a total capacity of around 45 MW, the same parameters were adequate for both scenarios.

Table 5: Technical parameters set for pre-commercial Scenario 3.

Wind Farm	
Array cable type	66 kV
Export cable type	132 kV
Number of export cables	1
Wind turbine capacity	15 MW
Number turbines	3

2.4 Commercial Scenario (28 x 15 MW)

The final scenario is a commercial one composed of twenty-eight 15 MW turbines (28 x 15 MW) making a total of 420 MW. The market is moving to 15 MW turbines by 2026-2030 and at this point there are already granted development rights and approved licencing for floating wind projects of about 500 MW [32] [33].

The commercial scenario, with a total capacity of 420 MW, will require two export cables, each with a 220kV capacity. The parameters set for this scenario for each location are represented in Table 6.

Table 6: Technical parameters set for the commercial scenario.

Wind Farm	
Array cable type	66 kV
Export cable type	220 kV
Number of export cables	2
Wind turbine capacity	15 MW
Number turbines	28

3) SITE LOCATION

The deployment of floating offshore wind is very much constrained by the conditions of the chosen location, such as wind speed, water depth, distance to shore, etc. Around the globe there are many locations that might be utilised for offshore wind power generation, but several aspects need to be considered. Looking solely for wind speed, Figure 4 illustrates the global offshore wind potential in coastal areas around the globe [34].
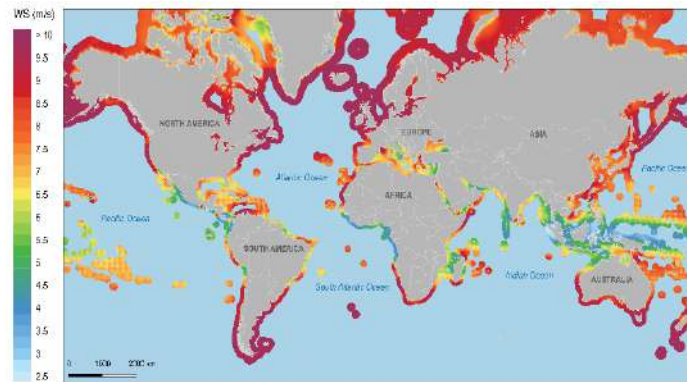
Figure 4: Global Offshore Wind Potential by WBG/ESMAP

High wind speed in a considerable amount is the first aspect to be considered when assessing installation sites to guarantee that power production is made in an efficient and bankable way. Considering locations where this is ensured, the next crucial aspect is the distance to shore. In a purely economic perspective, the nearest to shore the lower the installation and O&M costs, but environmental aspects and the so-called "not in my backyard" narrative hinder this distance. Other aspects that must be considered are the marine fauna, fishery activities, sea transportation routes and minimization of the visual impact.

Inherently, increasing distances from shore results in a higher depth in many ideal locations which is an impediment of fixed foundations. The water depth obstacle was already solved, by the Oil & Gas sector several years ago, by using floating structures that enabled cost reduction and an escape from the engineering limitations of fixed foundation. This alternative solves the visual impact aspect of offshore wind.

Currently, the most common and easy solution for site assessment is to go for locations where most constraining aspects were already settled such as: locations defined in public tenders, existing tests sites and reutilisation of Oil & Gas structures for wind power generation purposes.

Following this, four sites were selected for this LCoE assessment, one in the North Sea and three in Southern Europe: Canary Islands, Golf du Lion and Viana do Castelo. The coast of north-east of Scotland in the North Sea was chosen because there are a few pre-commercial farms that have been developed there. The Southern Europe locations are sites where floating technologies will have a more relevant role on the offshore wind market due to higher water depths. Northern locations (surrounding the North Sea) have its wind resources available at lower depth, which is proper for fixed foundations, reason why such locations were not assessed for the future installation of PivotBuoy structures.

The data used to classify each location was obtained from multiple sources. Water depth data was retrieved from EMODnet platform [35]. The geographic coordinates and distance to ports was acquired through google maps tools [36]. Soil type is not considered in detail for the LCoE model, for all scenarios it was assumed Suction/Gravity Based Anchors.

The simulations carried on this project used the power law, described in 5.1, to calculate the wind data at hub height section. The distances to shore and substation for each location takes into consideration a margin to include the irregular path taken by the vessels and by the export cable as described in section 5.1.

3.1 Canary Islands – Spain

The selection of this site location for the LCoE assessment of PivotBuoy technology became essential since it is the site where the 1:3 scale will be deployed. Furthermore, wind availability is quite considerable, and the depth and the type of soil are suitable for TLP concepts.

Considering commercial and pre-commercial scenarios, this location holds high potential for its high wind resources and for being mentioned as one of the key areas identified in Spain's Roadmap for Offshore Wind and Marine Energy. The roadmap was approved in December of 2021 and will lead the country to research, develop, and build 1 to 3 GW of floating offshore wind power by 2030 [37], with several projects announced and/or under development in the region, and in particular in the South East cost of Gran Canarias [38] [39] .

The site location characteristics are presented in Table 7 and its graphical location is showed in Figure 5. The presented location is not the test site of PLOCAN because this LCoE assessment was done considering pre-commercial and commercial scenarios (described in section 2), whose possible installations are the same as existing future projects from the Spanish roadmap.

Table 7: Southeast of Gran Canaria site characteristics.

Southeast of Gran Canaria (Spain)	
Coordinates (Lat, Long) [°]	(27.77, -15.36)
Max. significantWave height [m]	5,50
Water depth [m]	100
Average wind speed at 10 m [m/s]	8.76
Cable distance to substation [km]	9.62
Distance to closest port [km]	9.70

Figure 5: Southeast of Gran Canaria geographic location at (27.77, -15.36)

3.2 Viana do Castelo – Portugal

Viana do Castelo was among the sites chosen due to its favorable characteristics and because it is where is currently installed an operational 25MW floating wind farm (WindFloat Atlantic).

The positive outcome from WindFloat Atlantic project boosted the investment in offshore renewable technologies in the region, with already new projects such as ATLANTIS [40] and EU-SCORES [41] being developed.

The geographic location is presented in Figure 6 and the site characteristic are summarized in Table 8.

Table 8: Viana do Castelo site characteristics.

Viana do Castelo (Portugal)	
Coordinates (Lat, Long)	(41.72, -8.96)
Max. significantWave height [m]	8.38
Water depth [m]	100
Average wind speed at 10m [m/s]	6.24
Cable distance to substation [km]	21.25
Distance to closest port [km]	17.00
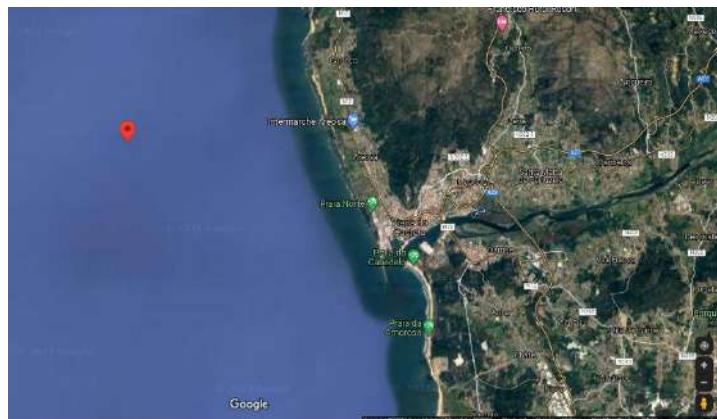
Figure 6: Viana do Castelo geographic location at (41.72º, -8.96º)

3.3 Golf du Lion – France

To add diversity to the chosen site locations, the third site is Golf du Lion on the Mediterranean Sea, a high energy site with favourable conditions for floating offshore wind, in addition, there is the ongoing Éoliennes Flottantes du Golfe de Lion (EFGL) project by a joint venture between CDC Investment Works and Ocean Winds that will install three 10 MW floating wind turbines by the year of 2023 [42].

The site characteristics are summarized in Table 9 and the geographical location is represented in Figure 7.

Table 9: Golf du Lion site characteristics.

Golf du Lion (France)	
Coordinates (Lat, Long)	(42.84, 3.24)
Max. significantWave height [m]	6.87
Water depth [m]	75
Average wind speed [m/s]	8.29
Cable distance to substation [km]	21.87
Distance to closest port [km]	17
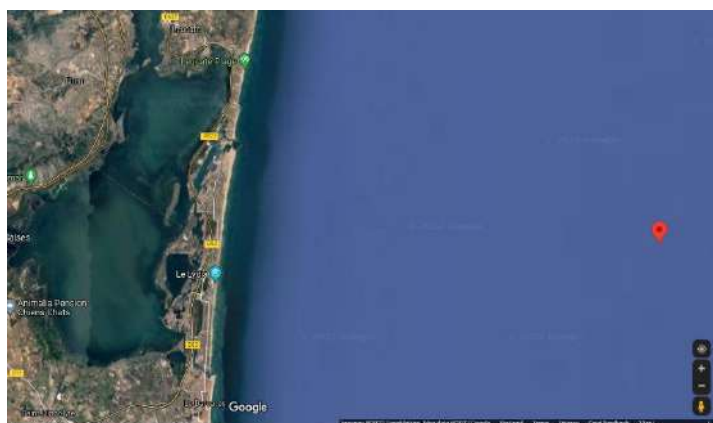
Figure 7: Golf du Lion geographic location at (42.84º, 3.24º)

3.4 North Sea

One of PivotBuoy project objectives is cost reduction and production increase when compared with the state-of-the-art project during 2018, a floating wind 30 MW array. Given than, one of the site locations to be simulated in the TEM model is in the North Sea which characteristics are presented in Table 10. The site location is represented on Figure 8.

Table 10: North Sea site characteristics.

North Sea site	
Coordinates (Lat, Long)	(57.50, -1.20)
Max. significantWave height [m]	8.12
Water depth [m]	112
Average wind speed [m/s]	8.01
Cable distance to substation [km]	30
Distance to closest port [km]	25

Figure 8: North Sea site geographic location at (57.50º, -1.20º)

4) COST MODEL

The cost model for the techno-economic analysis of the Pivot Buoy technology was built on five modules: 1) Design & Consent (D&C), 2) Production & Acquisition (P&A), 2) Installation & Commissioning (I&C), 4) Operations & Maintenance (O&M) and 5) Decommissioning & Disposal (D&D).

Throughout the project, adjustments were made to the life-cycle costs, initially described on deliverable 7.1, ending-up with the framework presented in Figure 9. These changes were necessary to align the cost model with the real development process that was conducted for the 1:3 scale prototype.

C1 – Design and Consent	C2 – Production and Acquisition	C3 – Installation and Commissioning	C4 – Operation and Maintennance	C5 - Decommissioning and disposal
C1.1 – Project management	C2.1 – Turbine	C3.1 – Turbine	C4.1 – Equipment & vessels	C5.1 – Removal
C1.2 - Legal	C2.2 – Pivot Buoy mooring system	C3.2 – Pivot Buoy mooring system	C4.2 - Rent	C5.2 – Site Clearance
C1.3 – Engineering	C2.3 – Floater structure	C3.3 – Floater structure	C4.3 – Insurance	C5.3 – Transportation of parts
C1.4 –Surveys	C2.4 – Electric system	C3.4 – Electric system	C4.4 – Personnel cost	C5.4 – Port preparation
C1.5 - Contigency	C2.5 - Control system	C3.5 - Personnel cost	C4.5 – Loss of revenue	C5.5 – Disposal of parts
C1.6 - Insunrance		C5.6 – Insurance		

Figure 9: PivotBuoy Life-Cycle costs

It is important to state that all the cost items concern a single unit full-scale of PivotBuoy technology. All the increments related with pre-commercial and commercial scenarios have in their root the application of learning rates that allow cost estimation of future Floating Offshore Wind parks.

The following sub-sections describe the considered cost items in each of the five modules. The cost items referred below were provided either by the partners involved in this task (mainly, X1 Wind) or by literature review. Since this is a public delivery and considering the Intellectual Property Rights (IPR), concrete values for each one of the cost items related with PivotBuoy technology will not be provided in this report.

4.1 Design and Consent

Design and Consent encompasses all the cost items related with a project early-stage, which includes research and development to design the optimal solution and the necessary to secure consent and manage the development process up to financial close. This module also includes the environmental surveys and assessment of legal requirements. The surveys are one of the first tasks to be undertaken for the development of a potential wind farm, for the PB project it includes: environmental impact assessments, bathymetry survey, geotechnical survey, environmental survey, meta-ocean characterization, traffic and navigation assessment and real meta-ocean measurements.

Table 11 summarizes the main items present in this cost module.

Table 11: Main cost items in Design & Consent.

Project Management	Development
Project Management	Engineering
Licensing	Environmental Survey
Certification	Bathymetry survey
Financing & legal	Geophysical survey
Insurance	Metocean characterization
Contingency	Traffic and navigation
	Real metocean mesurements

4.2 Production and Acquisition

Production and Acquisition accounts all the costs associated materials and equipment purchasing, production and assembly of the components to later be installed at site.

Table 12 gathers the main costs considered for this category that include: the floater structure, PivotBuoy mooring system and anchoring, wind turbine, electrical connection, control and auxiliaries (switchboards, switchgear, sensors, automation, etc…) and cabling.

Table 12: Main cost items in Production & Acquisition.

PivotBuoy	Electrical
PivotBuoy mooring system	Offshore substation
Wind turbine	Onshore connection
Floater structure	Control and auxiliaries
	Array and export cables

Beyond LCoE calculation, the Production and Acquisition costs will allow to find the most cost-effective materials and solutions for a better decision making in the design phase.

4.3 Installation and Commissioning

This section is related with all the Installation and Commissioning costs until the installation is fully operational. It comprises the costs associated with the transport, storage and installation of the wind turbine, the floater, the PivotBuoy mooring system and anchoring, and the electrical installation.

In a general form, these costs will go through the necessary vessels, barges, fuel, cranes, tools, etc. for the installation. Costs associated with labour, insurance (material and personal) and the equipment necessary for the installation and commissioning are considered as well. The main actions considered for this cost category are indicated in Table 13.

Table 13: Main actions/stages considered in Installation & Commissioning.

Installations and Comissioning stages
Transport
Storage
Installation

Inspection	
Towing	
Comissionning	

4.4 Operation & Maintenance

This section deals with all the expenses associated with the Operation and Maintenance of the FOW farm. For operation costs, it is considered continuous costs such as logistics, rent, insurance, personnel, and equipment (tools, software, licenses, etc…). It also includes the training for the operators and health and safety inspections.

Regarding maintenance, it accounts for both personnel and material costs for the preventive actions and corrective repairs necessary to guarantee the long term operationality of the whole installation. The model considers the equipment failure rate and the type of action needed (on site or tow-to-port), as well as the loss of revenue from the amount of time that the installation was non-operational. Table 14 condenses the main cost items for O&M.

Table 14: Main cost items for Operation & Maintenance.

Operations	Maintenance
Training & personnel	Personnel
Logistics	Logistics
Equipment	Equipment
Rent	Downtime losses
Health and Safety	

4.5 Decommissioning and Disposal

The final cost stage of any installation comes from the decommissioning and disposal at the end of its life. For PivotBuoy, these expenses will be associated to the disconnection of the system, disassembly and removal from site, transportation to land, preparation of port, disposal, and sites clearance. Table 15 summarizes the main cost items for D&D.

Table 15: Main cost items on Decommissioning & Disposal.

Decommissioning and Disposal
Disconnection
Disassembly
Removal & transportation
Port preparation & logistics
Disposal
Site clearance

5) TECHNO-ECONOMIC MODEL

The model takes user inputs and provides results in a graphical dashboard format (Figure 10). All project variables are listed and can be adjusted on the left, with results and charts shown on the right. This allows the user to adjust project settings and instantly view the resulting changes to the financial indicators. All following sheets were designed to operate in the background, providing all the data and mathematical equations required without direct input and adjustment from the user. A full list of the TEM sections is shown below:

- Home – Tool description, instructions, nomenclature, updates, and scenario definitions.
- Input and Results – Dashboard to display graphical project information and LCoE results, taking into account a set of user inputs. Also, simple alerts and suggestions for components based on the user selection, to optimise results. Project's targets and the achievement percentage are also shown to check progress against key project objectives.
- Locations – Hourly wind speed and significant wave height data for the entire project timeline. Key site characteristics include distance to shore, distance to port, seabed type and water depth. Multiple satellite sources are included and compared to the quality check of the wind data.
- Wind Turbine – Wind equations for hub height wind speed, power curve data for five wind turbines, energy generation, energy loss calculations and Weibull distribution analysis.
- Power System – Market pricing based on local feed-in tariffs, total wind farm energy production and revenue.
- Installation – All the time and expense related to the Installation and Commissioning (I&C) phase. Logistics and transportation data, waiting on weather complexity factors, individual component installation costs and associated labour and vessel requirements.
- CAPEX – All other project costs that relate to the main project phases, excluding the installation or operations phase of the project: Development and Consenting; Production and Acquisition; Decommissioning and Disposal. CAPEX costs are split into per turbine values, which are then increased to full farm-scale by applying variable economy of scale and learning rates.
- Vessels – Survey, installation, and operations and maintenance vessels and associated costs and key statistics, including installation rate, towing speed and mobilisation costs.
- Detailed OPEX – A bespoke O&M costing module, specific to the PivotBuoy system and its processes, especially the quick disconnection/connection of the platform and the tow-to-port repair strategy.
- Quick OPEX – High level, per kilowatt total project operations and maintenance expenditures, from widely used and reported values. Initially used in the model for simulation and results, but then replaced by the detailed O&M module and kept for calibration purposes.
- Energy – Annualised energy totals collated from individual hourly time steps.

- <u>Financial</u> – Annualised projects costs and revenues, with discounted costs applied to each year based on the initial selected discount rate of the project. All financial indicators including Net Present Value (NPV), Internal Rate of Return (IRR) and LCoE.
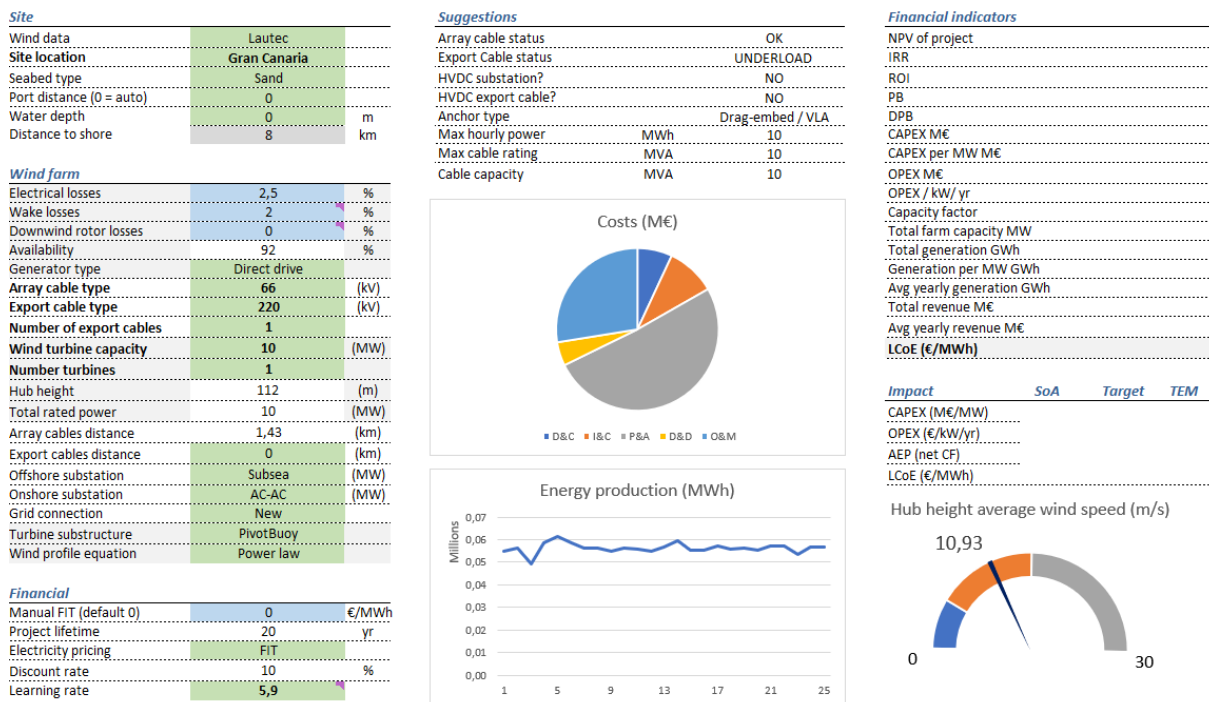
Site		
Wind data	Lautec	
Site location	**Gran Canaria**	
Seabed type	Sand	
Port distance (0 = auto)	0	
Water depth	0	m
Distance to shore	8	km

Wind farm		
Electrical losses	2,5	%
Wake losses	2	%
Downwind rotor losses	0	%
Availability	92	%
Generator type	Direct drive	
Array cable type	**66**	(kV)
Export cable type	**220**	(kV)
Number of export cables	**1**	
Wind turbine capacity	**10**	(MW)
Number turbines	**1**	
Hub height	112	(m)
Total rated power	10	(MW)
Array cables distance	1,43	(km)
Export cables distance	0	(km)
Offshore substation	Subsea	(MW)
Onshore substation	AC-AC	(MW)
Grid connection	New	
Turbine substructure	PivotBuoy	
Wind profile equation	Power law	

Financial		
Manual FIT (default 0)	0	€/MWh
Project lifetime	20	yr
Electricity pricing	FIT	
Discount rate	10	%
Learning rate	5,9	

Suggestions		
Array cable status		OK
Export Cable status		UNDERLOAD
HVDC substation?		NO
HVDC export cable?		NO
Anchor type		Drag-embed / VLA
Max hourly power	MWh	10
Max cable rating	MVA	10
Cable capacity	MVA	10

Costs (M€)

D&C I&C P&A D&D O&M

Energy production (MWh)

Financial indicators	
NPV of project	
IRR	
ROI	
PB	
DPB	
CAPEX M€	
CAPEX per MW M€	
OPEX M€	
OPEX / kW/ yr	
Capacity factor	
Total farm capacity MW	
Total generation GWh	
Generation per MW GWh	
Avg yearly generation GWh	
Total revenue M€	
Avg yearly revenue M€	
LCoE (€/MWh)	

Impact	SoA	Target	TEM
CAPEX (M€/MW)			
OPEX (€/kW/yr)			
AEP (net CF)			
LCoE (€/MWh)			

Hub height average wind speed (m/s)

10,93

0   30

Figure 10: PivotBuoy TEM input screen showing the dashboard setup.

5.1 Method

Based on the *site* location and turbine rating, the wind speed data is then chosen from a 25-year, hourly dataset for each of the four locations. This would be disadvantageous for a TEM with more than three sites, due to around 270,000 rows of wind data for each location and would negatively impact processing speed in Excel. For four locations however, the model performed adequately with the wind data kept within the model. Initial wind data was provided at 10m reference height, which was then transferred to higher wind speeds at hub height depending on the selected wind turbine capacity. Both the power law and log law can be used in the model for extrapolating hub height speeds, with the power law preferred due to faster speeds in closer agreement to a reference wind speed resource. Further details on this decision can be found in the assumptions section below.

Hub height wind speeds were then filtered to exclude wind speeds that would result in the turbines being non-operational. Generally, this is wind speed below the cut in 3m/s, and above the cut out 25m/s. At this stage, a fitted curve equation of the selected wind turbine power curve was then applied to the data, to translate hub height wind speed into generated energy in kWh. A well established and accurate method of doing this, especially to avoid broad Weibull estimations that only take the mean wind speed and a distribution shape factor, is to use the in-built Excel solver to fit a generated power curve line based on the following equation:

$$Y_{fit} = A \cdot (1 - e^{(-k \cdot t^n)}) \tag{5}$$

With t equalling wind speed at hub height, and all other parameters dimensionless. Excel solver is used to minimise the sum of the squared errors between the measured power curve data (Figure 11 in blue) and the power curve in red, the result of adjusting the remaining parameters above in equation (6) gives an optimised solution, with the equation applied to each hour of wind speed to provide generation in kWh, that is then transferred to MWh. Electrical and wake losses can then be applied to the generation data, preceded by multiplying the generation of the one wind turbine into the entire farm. The initial power curve data was provided by [43] with power curve data for wind turbines ranging from 6MW to 18MW. A single source of data for the three chosen wind turbines in this analysis (10MW, 12MW, 15MW) was chosen for consistency. They are all also reference power curves to aid scientific research, which is useful to avoid the potential bias associated with manufacturer data.
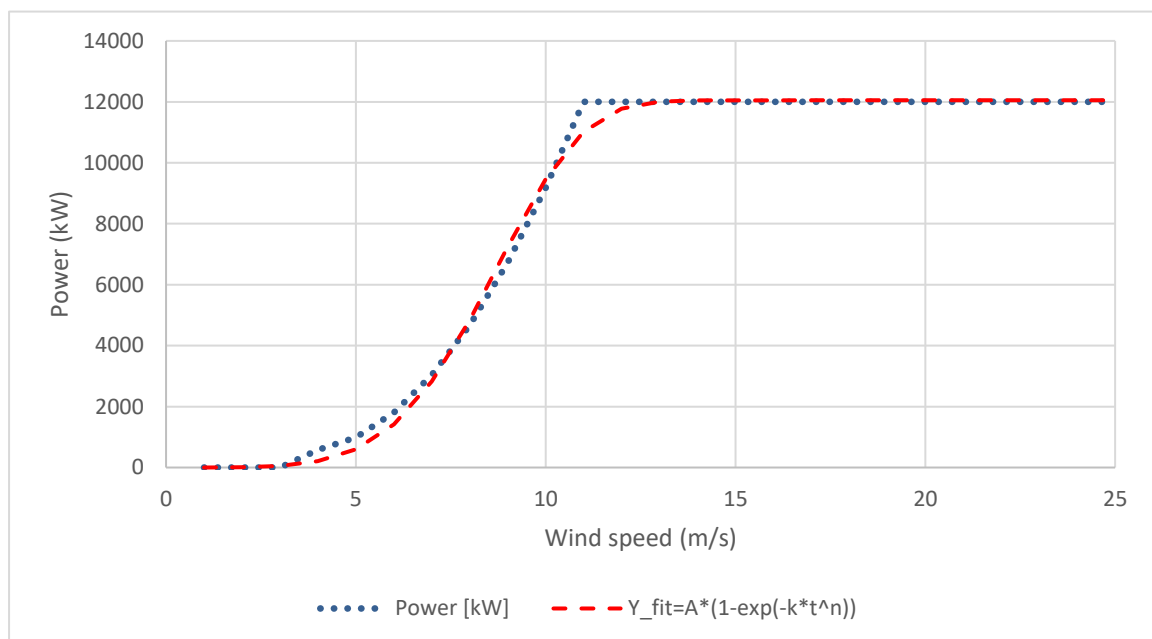

Figure 11: Measured power curve and Excel Solver power curve for the DTU 12MW wind turbine.

After energy production, costs can be calculated and are mainly influenced by the size and number of turbines, plus the learning rate which governs the improvements made for each doubling of capacity through "learning by doing". For simplicity and to follow the conventions used in offshore wind, costs are computed in order of the project phase (D&C, I&C, P&A, O&M, D&D). Due to lack of operational and cost data associated with the project, the costs used in the LCoE assessment were a combination of high-level costs data from well-known reports such as [44], cost functions developed at WavEC and equipment expenses as detailed from X1 Wind.

I&C CAPEX was created in a standalone module, as ease of installation away from expensive heavy lift vessels is one of the main drivers of LCoE minimisation in the PivotBuoy project. For accuracy, each aspect of the I&C process was split into separate installation groups: turbine; platform; moorings and anchoring; and finally electrical.

Preceding the installation process, a logistical calculator assigns distances and costs based on an initial manufacturing location, and then adjusts for each of the four chosen locations. Then, the total time for each process is computed, mainly as function of distance and the number of turbines. Personnel and vessel costs are then added. For example, the installation of an array cable will be a function of distance to shore, the length of the array cable, the installation speed of the vessel, and the daily rate. The equation for the installation of the cable is given below:

$$cost_{install} = \frac{daily\ rate}{install\ speed \cdot 1440} \cdot comp \tag{6}$$

Being $daily\ rate$ the total cost to hire a vessel for 24 hours, $install\ speed$ in m/s, which is then multiplied to m/day. This cost is then in €/m, which can then be multiplied into total values depending on the site conditions. The $comp$ factor accounts for the fraction of hours in a quarter that the wave height is above the maximum admissible by the vessel. The cost of vessel transit to and from the site can also be calculated, for example the towing of a PivotBuoy generator to site:

$$cost_{towing} = \left[\frac{distance\ to\ port \cdot daily\ rate}{wet\ tow\ speed \cdot 24} + \frac{distance\ to\ port \cdot daily\ rate}{transit\ speed \cdot 24}\right] \cdot comp \tag{7}$$

With $distance\ to\ port$ in km, $wet\ tow\ speed\ and\ transit\ speed$ in km/h, multiplied out into km/day. These cost functions allow the PivotBuoy installation to be accurately modelled for the three scenarios. The only broad costs that were applied from widely used reports were for installation insurance and contingency that was provided by [29].

After the I&C phase, P&C combined most of the cost functions provided by X1 Wind with high level report expenses used for environmental surveys, project management and insurance. With the initial project phases up to operation costs complete, and entire energy generation also calculated, the next step involved calculating the O&M costs. As previously mentioned, the TEM allowed a "Quick" and "Detailed" computation method. The former was an initial simple estimation which served to check that the detailed O&M module was in an acceptable range. The high-level O&M costs were provided by [29] and these were expected to be improved upon, considering these costs are based on a fixed-bottom offshore wind farm using jack-up vessels.

The O&M detailed module can be described similarly to the installation, with most costs calculated as a function of time, distance, number of turbines and the number of vessels and personnel. The module is grouped by preventative and corrective maintenance, with the corrective maintenance further divided into subgroups such as moorings and anchoring system and then by component. Unlike the installation phase, O&M is governed by component or system failures, and this was integrated into the model using three sources of failure rates, with the average value taken. They were then multiplied into total annual failures by the number of turbines or components, or cable length for the array and export type. To consider transit times, repairs were then assigned "on-site" for smaller repairs, usually at lower cost and duration, and "TTP" which account for tow to port repairs. The latter accounting for longer duration and higher expense costs, which would then require a towing vessel instead of a regular crew transfer vessel (CTV).

Total repair time could then be calculated, considering the costs of parts, personnel, and vessels. Weather windows were assigned based on user input, as the TEM allowed for seasonal adjustment for repairs to gauge the impact on LCoE. Turbine downtime was also determined, which was then subtracted away from the generation in the Energy module. This module summed hourly generation and revenue values into separate years.

Finally, the financial module creates a projection for all costs, revenues and generation across the project lifetime, discounting generation and OPEX to account for the time-value of money. This provides final cashflows, NPV and LCoE values that feed back into the input screen, with an entire simulation only requiring a few seconds to run.

5.2 Assumptions and Tool description

There will always be certain assumptions to strike a balance between accuracy and processing speed in any modelling process. The key assumptions that were present in the CAPEX, wind resource, O&M and installation modules are discussed in this section.

As mentioned, distances to shore have a significant impact on CAPEX, OPEX and therefore LCoE, and so assumptions made for components and processes that depend on distances are critical. An exemplar installation lists a 25km distance from shore (straight line) but an export cable of around 30km. In that sense, a 25% addition to the straight-line distance to shore for the four locations is added, to allow for cable route complexities such as rocks or gravel. Distance to port has a similar addition to allowing ships to progress out of port through a deeper channel, before navigating directly to the site.

As previously discussed, the CAPEX module took high-level report costs and detailed functions provided by the developer. Such high-level costs are mature and well understood, and it was of higher importance to obtain accurate developer costs for the PivotBuoy structure and components. Nacelle cost data were retrieved from [45] with the economy of scale effects applied with increasing turbine ratings. The high-level costs data not supplied by X1 Wind was mainly in a £/kW or €/kW format which was then increased to farm size, with the former converted from Pounds to Euros at an exchange rate of 1.16, or Dollars to Euros at 0.85. Anyhow, this conversion was only required for the nacelle costs. Electrical costs for dynamic array and static export cables, were provided by WavEC in the form of cost functions, applied to the apparent power flowing from the farm, and increased to the total cable lengths.

Actual site-based measurements are extremely hard and expensive to acquire for any new site, especially in deeper waters where no previous wind projects have been deployed or met masts have been installed. As such, satellite-based data is often the preferred method for inputs into a TEM, but this method often uses a grid measurement method that can provide inaccuracies, especially close to land, as most satellite-based wind speeds use the ocean's surface. As the LCoE equation is highly sensitive to energy generation, great care was taken to ensure a quality wind resource was used in the simulations for all three locations.

Two forms of reanalysis data were used, [46] and [47], to provide hourly estimates of metocean conditions (wind and wave). Both use ERA5 [48] reanalysis which provides a spatial resolution of around 10 to 30km, depending on the latitude of the site. The main benefits include being a free access resource, with accurate and hourly data resolution and the largest available dataset, ranging from

(1979 to present). It was observed, in the majority of the cases, that the second wind data source (Lautec [49]) provided higher wind values, and therefore chosen especially as it had a closer match to a third reference wind speed measurement developed by [50]. This can be seen below in Figure 12 with the Lautec datapoint (blue) showing noticeably higher wind speeds across both locations, compared to the green curve that shows a secondary source of wind data.
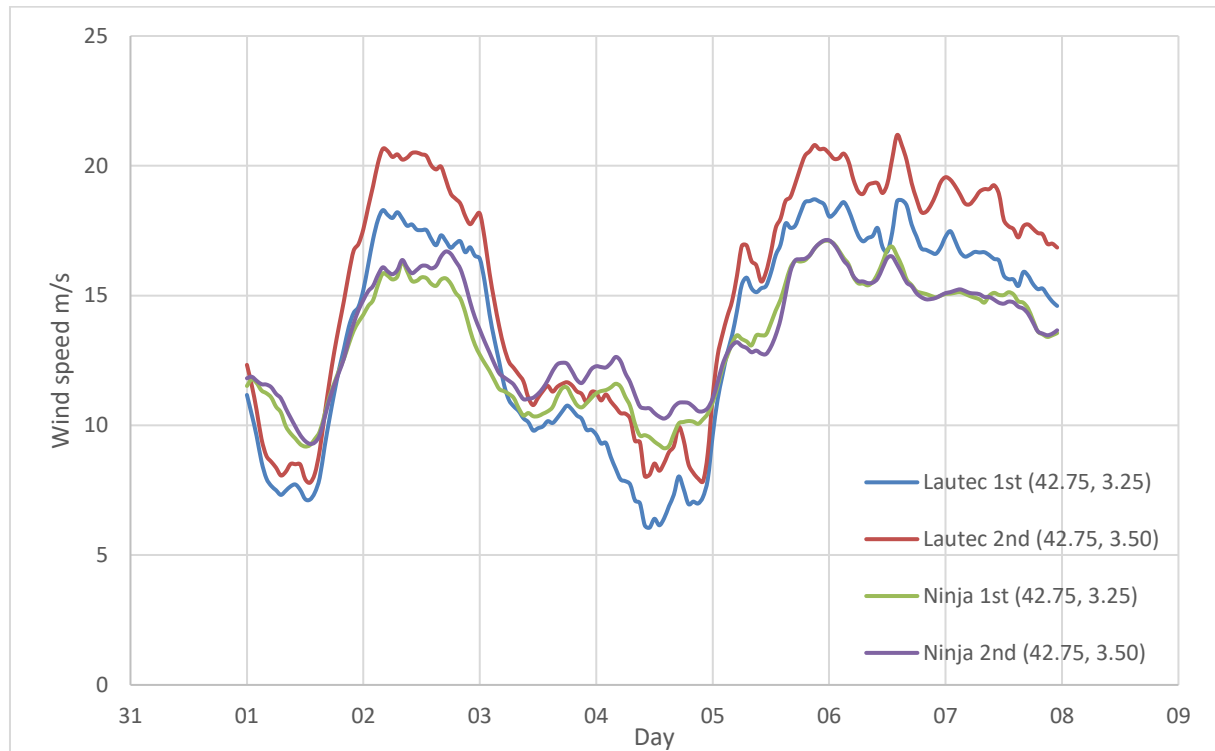

Figure 12: Variations in wind speed using the reanalysis data at Golf du Lion

The initial site locations were provided in the early planning stages of the LCoE assessment. Still, the Lautec wind data operates by selecting a datapoint at a spatial grid resolution of 0.25° x 0.25°. The closest point was chosen to the initial site coordinates, across all three locations. The added benefit of using this dataset was an automatic 40-year package of hourly data, with significant wave height and period also included at an hourly resolution. However, inaccuracies were found with sites close to shore, due to part of the grid occupying land which affects the wind speed calculations, when compared to Global Wind Atlas (GWA) wind resource. To solve this issue, the datapoint was moved 0.25° away from the coastline. This correction can be observed in Figure 12, with the 1st (initial) sites clearly showing lower wind speed than the 2nd (relocated away from the coast) points. It can be seen from the above graph however, that the wind resource across the four data sets show good agreement and capture the hourly differences in wind speed well. In the case of this project the wind data time frame goes from 01-01-2010 to 25-12-2034.

As can be seen below, in Table 16, the second data point still didn't give a close agreement with the GWA resource. This resource was chosen as it combines mesoscale and microscale modelling, which occupies a much higher resolution and accuracy. The reason for not using this resource for the entire dataset is because the GWA only provides a mean value either annually or monthly, which does not match the hourly timesteps used in the simulations. It can be seen in Table 16 that the wind speed has a large impact on LCoE, and so the initial site data was used, which was then adjusted to match the

overall GWA values. This allows for an hourly dataset which matches the accuracy of the GWA microscale data at the exact location.

Table 16: The second Lautec data, and differences with the Global Wind Atlas data at the same location

	Lautec 2nd	GWA 2nd	Δ m/s	LCoE difference
Golf du Lion	9.23	10.52	1.29	14%
Viana do Castelo	8.06	8.48	0.42	8%
Gran Canaria	9.15	8.98	-0.17	-2%

With the wind speed now correctly correlated to the GWA at 10m height, wind speed needs to be adjusted to hub height. There are two conventional methods to achieve an extrapolation to hub height, where a reference height and wind speed are known. First implemented into the model is the log law:

$$u(z_2) = u(z_1) \cdot \frac{ln(z_2 - d)/z_0}{ln(z_1 - d)/z_0} \tag{8}$$

Where $u(z_2)$ is the new wind speed at hub height, $u(z_1)$ is the reference wind speed, z_1 is the reference height in m, z_2 is the hub height, z_0 is the surface roughness length, which tends to be 0.0002 for open sea with at least 5 km fetch. This calculation is widely used for heights up to 100m, and inaccuracies were found when comparing the hub height wind speed with the GWA equivalent. The power law equation was found to give higher accuracies, and was installed into the TEM to give the user the option of using either equation for simulations:

$$u = u(r) \cdot \left(\frac{z}{z_r}\right)^\alpha \tag{9}$$

With z the hub height in m, z_r the reference height, and $u(r)$ the reference wind speed in m/s, α is a constant that is usually 0.143 but was adjusted to 0.1 to provide the best match to the GWA wind speeds.

A key financial assumption that has a large effect on LCoE was assigning a discount rate that reflects the financing costs to raise project capital. This value was automatically adjusted in the TEM depending on the project size, with demonstrator and pre-commercial arrays assigned a higher value than commercial arrays. With large, fixed bottom offshore wind farms set as a base value of 6%, pre-commercial arrays and demonstrators were given a 10% rate, with commercial floating offshore scenarios assigned 8%.

Project lifetime was set at 25 years of active production for a commercial array, occurring immediately after the time accrued for installation and commissioning phases. Pre-commercial and prototype scenarios were both given 20-year lifetimes.

5.3 Tool Functionality

There were multiple key input variables that were changed during the LCoE simulations for all four sites, with those remaining kept constant throughout the simulations. Key variables that were changed between simulations are as follows:

- Site location – This had the largest effect on LCoE results, wind data, closest port, logistical distances, and local market pricing all change depending on the chosen location. As such, this is the first step in the model.

- Array cable type – As mentioned, the TEM provides some feedback alerts to the choice of equipment, and whether the choices are sensible. Alerts such as "OK", "underload" and "overload" advise whether the array and export cables are correctly suited. All array cables were chosen as dynamic, due to the floating array. 33kV – 220kV cables can be selected, but all scenarios required 33kV or 66kV.

- Export cable type – Alongside the array cables, incorrect and mismatched equipment leads to cables being either too thick or undersized. This can increase costs either through oversized equipment or causing the cable cost functions to be out of range. 33kV to 220kV cables can be chosen, with HVDC 150kV and 300kV, however all scenarios tested involved HVAC cables.

- Number of export cables – Only a factor for the commercial size wind farm. Export cables from 0 – 5 can be selected, although rarely should a project require more than 2.

- Wind turbine capacity – Three turbine sizes (10MW, 12MW and 15MW) were used in the scenarios. Adjusting the output power of each generator has knock-on effects to hub height wind speeds, array cable lengths, annual inspection costs and most importantly, power production, which automatically change depending on the selected turbine.

- Number of turbines – A key characteristic impacting farm energy production, cable numbers, vessel distances around the farm for O&M activities, and installation times and costs.

- Discount rate – Adjusted for project development and associated risk factor. Discussed further in the assumptions and earlier in the report.

Improvements to the model, and for future work, involve a further developed O&M module with an hourly scheduling system for O&M processes. The current version only assigns a complexity factor based on the fraction of hours that the wave height is above the maximum safe limit of an O&M vessel. For example, if 10% of the hours in a quarter are above the vessels maximum acceptable wave height, then a 10% increase to the duration in transit and operations will be added. The same could also be said for the installation phase, a Boolean "yes" or "no" based on wave heights, wind speeds, and vessel availability would be a next step for accurate offshore operations modelling.

Even though the power curve optimisation provides a very close fit, and much more exact than approximating generation based on a Weibull distribution with one mean value of wind speed, improved optimisation could be possible using a separate programming language. Also, the model was nearly at the limit with regards to the level of wind data and may have functioned better with the wind resource data kept in a separate file. For three locations however, the model performed well.

6) RESULTS AND ANALYSIS

Having the techno-economic model operational, the scenarios and locations described on the previous sections were simulated. The results will be described and analysed on the following sections.

6.1 Baseline Scenario Results

As indicated in section 1.2, the main goal of the PivotBuoy project is to reduce the Levelized Cost of Energy of Floating Offshore Wind by 50% when compared to the 2018 SoA.

Based on the four different sites presented in section 3), the techno-economic-model estimates the LCOE for a 3 x 10 MW array with the PivotBuoy technology to be between 80-130€/MWh. These LCOE values represent a reduction of 46-67% compared to the 2018 SoA. Such results shows that the PivotBuoy technology has the potential to reach one of its main goals to reduce the LCOE by at least 50%.

The range of LCOE values for the same array comes from two main varying aspects. The first is the site location, each location presents different wind resources availability resulting in higher LCoE values for sites with higher average wind speed. The second aspect is the Learning Rate (LR), the LCoE reduces when it is applied a higher LR (9.5%), that considers significant innovations on the sector, in opposition to a limited innovations Learning Rate (5.9%) that result in a higher LCoE.

Such LCoE values were achieved through a CAPEX and OPEX reduction and an increase of the AEP (represented by the Capacity Factor). From these three indicators, the OPEX was the one with the most significant improvement when compared to the 2018 SoA.

With such high reductions in CAPEX and OPEX, the PivotBuoy technology shows great potential to fulfil the main premises to achieve the lower LCoE, cost reductions on the floating wind technology and its installation (CAPEX) and cost reduction of its Operation & Maintenance (OPEX). The CAPEX reduction is primarily justified by the platform weigh reduction; the use of a TLP mooring and anchoring system and a quicker installation process using local infrastructures. Regarding the OPEX, the costs were reduced by more than half mainly as a result of reducing active systems and a lower downtime due to the quick disconnection/connection of the platform.

6.2 LCoE

The LCoE is the first indicator to be looked upon when evaluating the feasibility and profitability of any power production installation, for that reason it is also the preferred one to compare different site locations and possible scenarios. Figure 13 graph represents the behaviour of the LCoE with changing scenario, location and learning rates. The scenarios are represented on the x-axis of the graphic without relation between graph scale and capacity, the first on the left is the base scenario and the last on the right the commercial scenario.
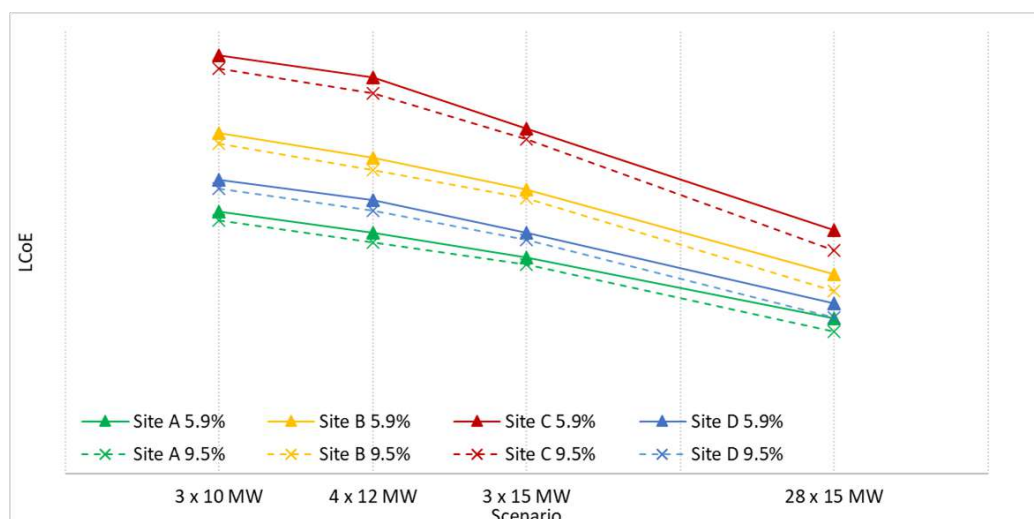
Figure 13: LCoE variation with different scenarios and locations, for a 5.9% and 9.5% learning rates.

The graph in Figure 13 shows how the LCoE is significantly affected by the site location of the floating offshore wind farm. The main driver for the difference of the LCoE between the sites is the wind speed, followed by other factors such as distance to shore and water depth. The difference in power capacity between the scenarios also highlight the reduction of the LCoE, where a major reduction occurs when shifting from a 30 MW pre-commercial to a 420 MW commercial scenario, as expected due to the impact of economy of scale.

Looking at the results for the different learning rates, it is possible to see the range of values LCoE takes between assuming a limited innovation evolution (LR=5.9%), which results in higher LCoE values, and an evolution with the innovations from published roadmaps [51] [52], that result in lower LCoE.

To analyse if the distance from shore has a major impact on the LCoE, Figure 14 presents the LCoE values for Site A and for two sites with the same characteristics but from 20 km and 40 km from shore (Site E and Site F). From such graph it is possible to verify that the distance from shore is not the main contributor to the LCoE increase when comparing site locations, a shift in distance from 10 km to 20 km and 40 km have a very a small impact on the increase of LCoE.
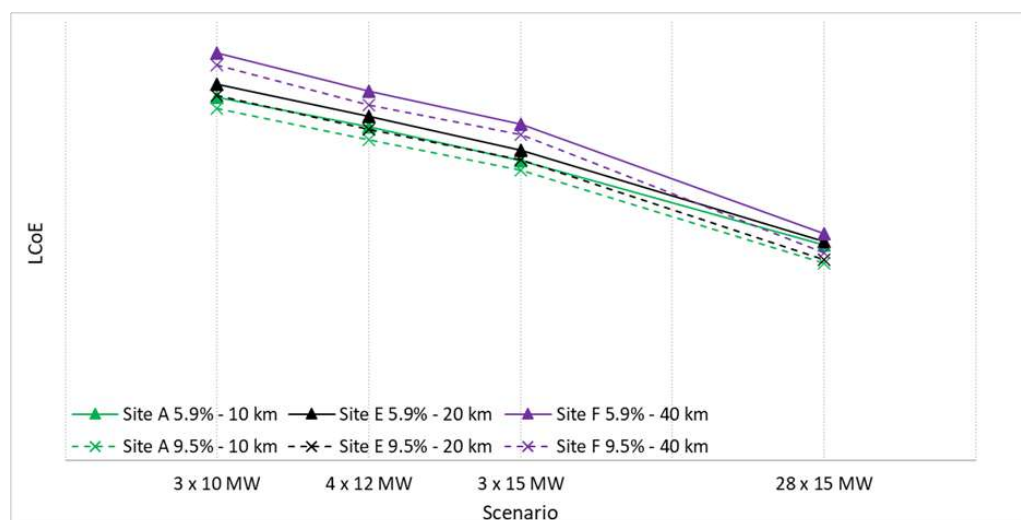

Figure 14: LCoE variation with distance from shore.

6.3 Scenario comparison

The following graphics represent how the LCoE, CAPEX, OPEX and AEP vary with each scenario for all site locations through a normalization to the baseline scenario. Because both learning rates represent a similar behaviour when changing scenarios, it is only represented values for a 5.9% learning rate.
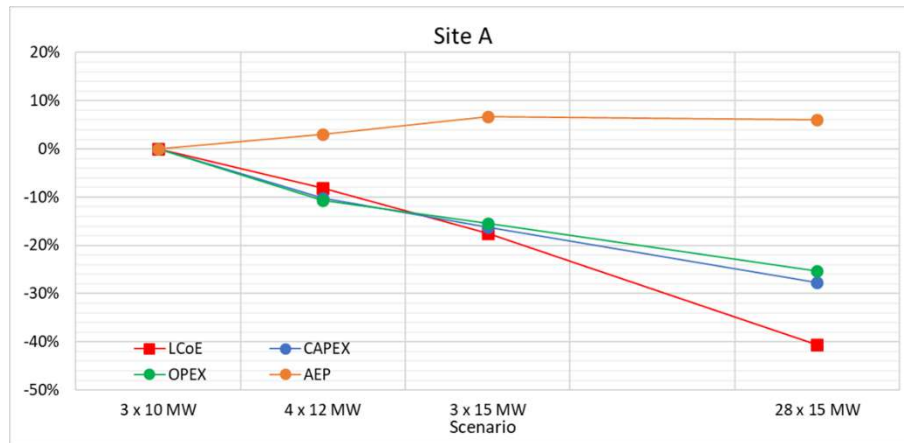

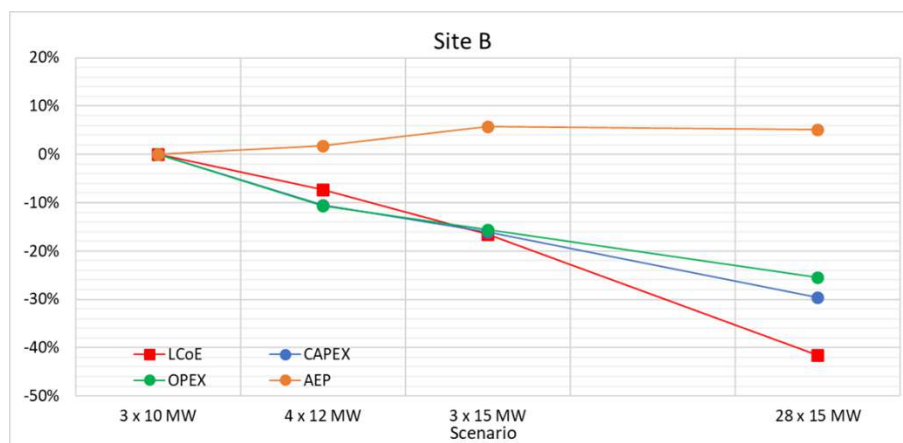*Figure 15: KPI's variation with each scenario for Site A.*

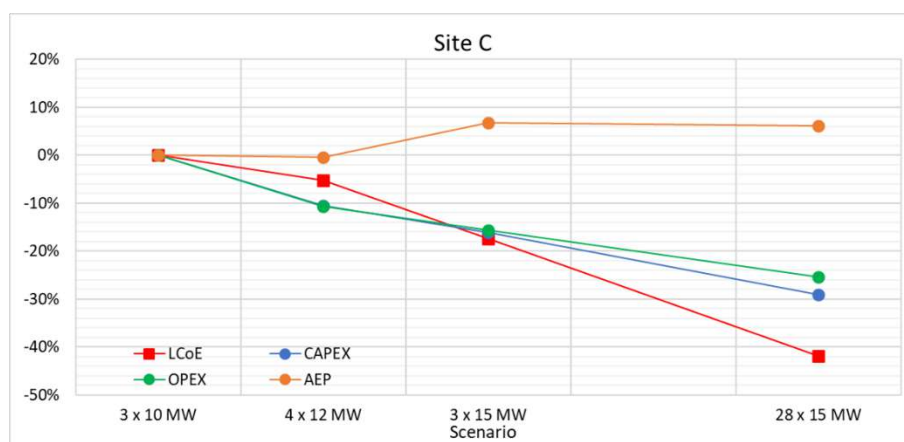*Figure 16: KPI's variation with each scenario for Site B.*

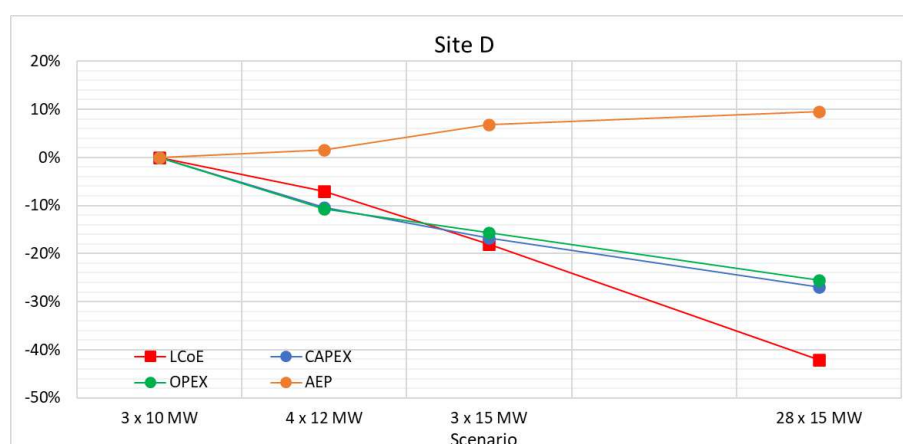*Figure 17: KPI's variation with each scenario for Site C.*

Figure 18: KPI's variation with each scenario for Site D.

The graphs show that for all locations the four indicators present a similar behaviour of improving with increasing installed capacity. However, it stands out that the results are better for the 45 MW scenario of 3 X 15 MW turbines than the 48 MW one of 4 x 12MW turbines, despite the latter having a higher total installed capacity. The reasoning for such difference is the costs savings by having a smaller number of installed turbines, as it is demonstrated by the lower CAPEX and OPEX for the 45 MW scenario.

6.4 KPI's heatmap

In order to obtain a high-level view of how the CAPEX, OPEX, AEP and LCoE varies with respect to site location, installed capacity and learning rate, a heatmap is presented in Table 17. The heatmap shows that LCOE improves with larger installed capacity, higher learning rates and sites with higher wind speeds. For the commercial scenarios the techno-economic model estimates the LCOE to be between 45-75€/MWh. This implies that the PivotBuoy technology, in the long term, could reduce the LCOE by 70-80% when compared to the 2018 SoA, which is in line with the EU SET-Plan targets for 2030.

Table 17: Heat map of the analysed parameters for the different scenarios and locations.

Location	Scenario	LR	CAPEX	OPEX	AEP	LCoE
Site A	3 x 10	5,9				
		9,5				
	4 x 12	5,9				
		9,5				
	3 x 15	5,9				
		9,5				
	28 x 15	5,9				
		9,5				
Site B	3 x 10	5,9				
		9,5				
	4 x 12	5,9				
		9,5				
	3 x 15	5,9				
		9,5				
	28 x 15	5,9				
		9,5				
Site C	3 x 10	5,9				
		9,5				
	4 x 12	5,9				
		9,5				
	3 x 15	5,9				
		9,5				
	28 x 15	5,9				
		9,5				
Site D	3 x 10	5,9				
		9,5				
	4 x 12	5,9				
		9,5				
	3 x 15	5,9				
		9,5				
	28 x 15	5,9				
		9,5				

6.5 Sensitivity analysis

On this subsection a sensitivity analysis is done to the TEM model by evaluating the impact of some key factors on the LCoE. The analysis is done for the commercial-scale scenario with wind farm capacity of 420MW.

Figure 19 demonstrates CAPEX and wind speed as the main dependencies for the LCoE. Such result was expected because CAPEX has a high contribution to the total life cycle cost and wind speed has a direct impact on the power production. The other two factors to have a significant impact and to be considered when assessing such project are the discount rate and the lifetime of the project, an increase of 4 year at the project lifetime results in an approximate 5% reduction of the LCoE.
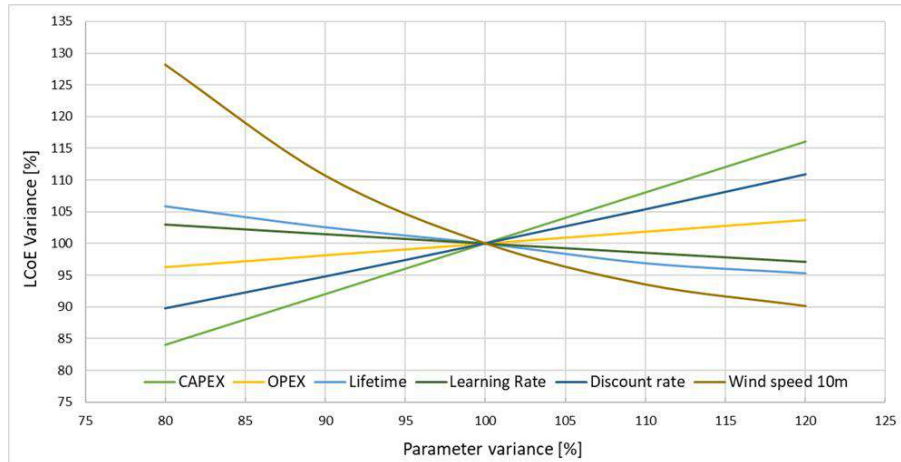

Figure 19: LCoE sensitivity analysis for a 28x15MW scenario in North Sea site.

The impact of each different cost groups on the LCoE is presented in Figure 20, where the cost group Production & Acquisition is dominating the influence on the LCoE variation. This cost group is highly influenced by the magnitude of production, which means that large-scale production would significantly reduce the cost of the PivotBuoy floating wind technology.
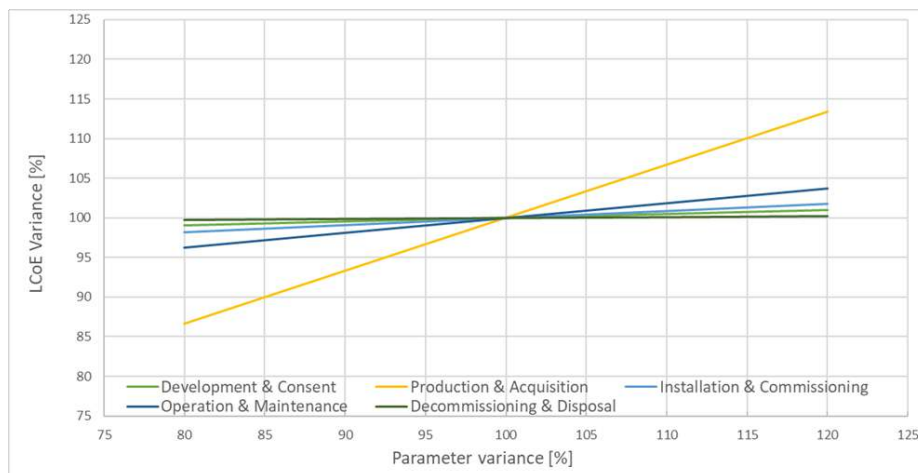

Figure 20: LCoE sensitivity analysis of costs group for a 28x15MW scenario in North Sea site.

6.6 Qualitative Analysis

In this sub-section some qualitive indicators will be addressed in a perspective of how they can influence the LCOE and the development of PivotBuoy technology. The risk associated to a deployment of an FOW disruptive technology is something that may harm the investors' engagement. To reduce this, a risk monitoring is being conducted since the beginning of the project and the main lessons learnt

during the process will be addressed. Also, a crucial factor to consider is the market environment and how PivotBuoy can position itself in the FOW sector to ensure technology development continuity within a widely competitive and emerging sector where only the most robust, resilient, and cost-efficient solutions will make the way to a competitive commercial solution. Aligned with this path to commercialisation, the industrialisation is a relevant factor considering manufacturing and installation procedures. Those can influence decision-making processes in specific locations, given the suitability of the technology, its production and deployment processes.

6.6.1 Risk

There were several constrains felt along the development process of the PivotBuoy project. In the scope of T1.4 Project implementation Risk Management, the risks were identified, quantified, and monitored.

Among all the risks identified, only a few could be associated with a general installation of a PivotBuoy platform and not the specific case of installing the prototype model at PLOCAN platform.

Grid Connection

Considering that grid connections are responsible for the Distribution System Operator or Transmission System Operator, it can be a bottleneck in the development of commercial projects and could harm the project schedule and increase the costs for the project developer and technology provider.

Weather windows and vessel availability

The weather windows suitability and vessel's availability to perform the required installation operations are of high importance when to install a FOW technology. During the installation stage of the project, several constraints were experienced on these aspects. About the weather windows, there is no clear mitigation action that can be taken since the project developer must be quite reactive. On the vessel's availability, there's a need of clear alignment and commitment between the vessel operator and the project developer taking leverage of the weather windows suitability for certain operations to ensure delivery in due time. If those aren't ensured, some over costs will happen in terms of components quay storage and personnel that will increase the overall cost of the project.

Technology validation in relevant environment

At this stage, the main risk associated to PivotBuoy technology is its validation in relevant environment. All the engineering efforts taken in the early stage of the project are pointing out to a successful validation of the concept, nevertheless this is something that needs to be considered. At the moment, the technology validation is the crucial factor for the development continuity of PivotBuoy concept, that will be achieved with the conclusion of this project through the installation and testing of the PivotBuoy platform at PLOCAN test site.

6.6.2 Market Environment [17]

In the scope of PivotBuoy project, a benchmark of the full-scale X140 platform using the PivotBuoy technology against other large FOW systems was made as an outlook for commercial projects in the 15 MW range per floating structure.

This benchmark concluded that the PivotBuoy system is placed in the hybrid category since it's combining SPM, TLP, weathervane capacity, downwind turbine, and semi-submersible floater. This concepts' combination shows the disruptive and innovative face of PivotBuoy with high potential benefits but also, as mentioned in the previous sub-section, brings the risks associated to an unproven combination of technologies. Apart from this, PivotBuoy is well positioned within its category considering its TRL developments.

Regarding competitors, there are several other technologies that bring innovation into the FOW sector. The PivotBuoy system can help floating wind platforms to achieve a lightweight platform (advantage of TLPs) with limited hydrodynamic response while keeping a low draft and stability for wet tow (advantage semi-submersibles), while allowing the platform to passively weathervane and quickly connect or disconnect for installation and O&M purposes. Th<sere are other floating wind concepts that uses the combination of TLP and a semi-sub structure or a floating structure with a SPM to allow the platform to weathervane. This opens up the possibility for the PivotBuoy technology to be integrated into the floating foundations of other floating wind concepts that uses a SPM.

The main consideration regarding LCOE of FOW is that even the most advanced designs are not in commercial stage which brings high uncertainty in the estimation of this parameter. An important takeaway is the need of reducing the overall LCOE of FOW in order to be competitive with other renewable technologies. To bring down the LCOE three main areas need to be targeted: CAPEX reduction, OPEX reduction and AEP increase. PivotBuoy technology is addressing them all since: the CAPEX is being reduced with a significant platform weight reduction and simplification of assembly and installation processes when compared with traditional TLP systems; the OPEX is being reduced through use of passive systems, the quick connection/disconnection system that reduces downtime and allows a tow-to-port maintenance strategy; the PivotBuoy favours larger wind turbines, promoting an increase in the power produced per weight ratio.

6.6.3 Industrialization [53]

The industrialisation plan is key when considering a FOW technology under development. It's paving the way to shift from a 'one of a kind' structure development process to a well-structured plan that enables a massification and a swift methodology to deliver several units for commercial projects. The main goal of the industrialisation plan is to reduce the time of receiving raw materials until the commissioning of the structures from around 1-3 months.

In this process some critical factors were identified related with the components of PivotBuoy system, fabrication and assembly sequence and launch and installation sequence. Due to the high modularity of the system, the components can be fabricated by a broad range of secondary fabrication sites with relative ease, mitigating the problems associated to it. With this in mind, the industrial plan for this technology mainly deals with an optimisation of the logistic process and the fabrication of 5 sub-

components (Wind Turbine Generator (WTG), floater, mooring system, pivot bottom and foundation) of PivotBuoy technology in independent production processes.

Following that, some considerations need to be taken into account: the fabrication of the WTG, the mooring system and the foundation are readily industrialized production lines and will therefore require little optimization; the pivot bottom is a compact component comprising relatively simple steel subcomponents, which are easily transported and stored so this production line will not be critical to the lead times; the optimization of the floater production line is ultimately governing for the overall lead times; the primary assembly yard for the floater is critical to the production line of the floater subunit and it is desirable to establish as many assembly lines as possible to minimize the lead times; to increase flexibility of logistics, temporary anchorage can be included in the assembly line, both prior to outfitting with the WTG (assembly anchorage) and installation (marshalling anchorage); since the suitable installation windows are limited, it is key to build a buffer of PivotBuoy ready for installation at the marshalling anchorage.

All these considerations for the industrialisation are key to reduce costs and increase the delivery time of PivotBuoy structures. The influence on the LCOE is clear considering that the modularity, decentralised production, and eased installation procedures of PivotBuoy will enable a competitive full-scale technology for future commercial scenarios.

7) CONCLUSIONS

This report performs a techno-economic analysis about the PivotBuoy technology by applying it into different floating wind farm scenarios. The analysis was done through the results from the techno-economic model developed within the project scope and other inputs from tasks conducted throughout the project.

The assessment in this report shows that compared to the baseline scenario at the project start (SoA of floating wind in 2018), the PivotBuoy technology has the potential to bring down the LCOE to 80-130€/MWh (46-67% reduction) for a small pre-commercial array (30MW) and 45-75€/MWh (70-80% reduction) for a commercial-scale array (420MW). This means that PivotBuoy technology achieves its main objectives within the PivotBuoy Project, to reduce the LCoE by at least 50%.

Such LCoE result was achieved by reduction of the CAPEX and OPEX and an increase in the AEP. As expected, the LCoE, CAPEX and OPEX improve when a learning rate (5.9 – 9.5%) is applied, as it accounts for learnings, economies of scale and improvements of key supply chain dynamics that result in lower costs for larger projects.

Regarding the different site locations simulated on the TEM, it is found that wind speed is the main factor influencing the LCoE values, as was demonstrated when Site A, with a higher average wind speed, presented significantly lower LCoE values than an installation in Site C where the average wind speed is much lower.

By simulating the different scenarios for all locations, results in a similar evolution of improvement of all KPI's when going from a pre-commercial to a commercial scenario. Another important take from these simulations is that the 3x15 MW scenario presented better results than the 4x12MW despite having less 3 MW of total capacity, this happens both due to the lower capacity factor of the 12 MW turbine and due to the higher number of turbines that imply higher costs (materials, installation, O&M, etc.) that are not balanced by the excess in electricity production.

A sensitivity analysis was performed to some of the key factors influencing the LCoE variation. The analysis concluded that the CAPEX and wind speed are the variables with higher impact on the LCoE.

Apart from the previously mentioned indicators, this assessment looks into the qualitative indicators of Risk, Market Environment, and Industrialization. Throughout the project it was conducted a monitorization of the possible risks as well as establishing the necessary mitigation actions. From all the addressed risk, the ones with a bigger impact on the project critical line where: windows and vessel availability and technology validation in relevant environment. These situations were overcome with exemption of the latter that will be concluded in the end of the project.

Regarding market environment, the PivotBuoy platform is enabling the reduction of the LCoE of FOW by: CAPEX reduction from a significant platform weight reduction and simplification of assembly and installation; OPEX reduction by reducing active systems and a lower downtime due to the quick disconnection/connection of the platform; and AEP increase by allowing larger and lighter downwind turbines.

Lastly, industrialization will allow PivotBuoy's to shift from a "one of a kind" technology to a well-established and commercially available one. The main consideration that will be taken to turn the technology into an industrialized one is the optimization of the floater production line. Such could be achieved by establishing multiple assembly lines for the floater subunit to minimize the lead times; temporary anchorage; and building a buffer of PivotBuoy ready for installation at the marshalling anchorage.

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