corewind

D6.4
LCOE, CAPEX and OPEX reduction: Key Performance Indicators and executive summary

RAMBOLL, IREC, DEWI, UPC, COBRA, INNOSEA, EQUINOR, JDR, WindEurope

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List of Abbreviations

Abbreviation	Definition
ADP	Abiotic Depletion Potential
AHTV	Anchor handling tug vessel
AP	Acidification Potential
CAPEX	Capital expenditures
CCOB	Cantabria coastal and ocean basin
CTV	Crew transfer vessel
DECEX	Decommissioning expenditures
EoL	End of life
EP	Eutrophication Potential
EPBT	Energy pay-back time
EROI	Energy return on investment
FOW	Floating offshore wind
FOWT	Floating offshore wind turbine
GEBCO	General bathymetric chart of the ocean
GWP	Global warming potential
HLV	Heavy lift vessel
HSE	Health, safety, and environment
ICTS	Singular Techno-Scientific Facility
JUV	Jack-up vessel
KPI	Key performance indicator
LCA	Life cycle assessment
LCOE	Levelised cost of energy
MBL	Minimum breaking load
MCE	Major component exchange
OEM	Original equipment manufacturer
OPEX	Operational expenditures
OSS	Offshore substation
PBA	Production-based availability
PED	Primary energy demand
PSO	Particle swarm optimisation
RNA	Rotor nacelle assembly
ROI	Return on investment
ROV	Remotely operating vehicle
SOV	Service operation vessel
T&I	Transport and installation
TBA	Time-based availability
WP	Work package
WTG	Wind turbine generator

Executive Summary

The COREWIND project successfully achieved its primary objective of reducing the Levelized Cost of Energy (LCOE) and enhancing the Life Cycle Assessment (LCA) of floating offshore wind installations through the implementation of innovative research, modelling, and optimisation techniques. For this, various solutions have been studied that impact both the LCOE and environmental LCA across the entire value chain of a wind farm.

The structure of the document is designed to present the key performance indicators (KPIs) that are relevant to floating concrete-based wind technologies investigated within the CORWEWIND project, as they directly influence the outcomes of LCOE and LCA. Specifically, the KPIs include capital expenditures (CAPEX), operational expenditures (OPEX), decommissioning expenditures (DECEX), and annual energy production (AEP), which are essential components in the calculation of LCOE. Furthermore, the KPIs encompass global warming potential (GWP), primary energy demand (PED), energy pay-back time (EPBT), and return on investment (ROI), which are associated with the environmental aspects of LCA.

Chapter 3 outlines the methodology applied in the assessment, including a workshop, survey, and industry perspective on cost reduction potentials in the floating wind value chain. The methodological procedure for LCOE assessment is described.

Chapter 4 details the updated inputs and refinements of the baseline model developed in D6.2 [1] and used to calculate the LCOE and LCA baseline case. Chapter 5 presents the outcomes of cost reduction potentials identified through the workshop, survey, and interviews. It also describes the design improvements, innovations, and optimisations implemented to reduce costs and environmental impact.

Chapter 6 presents the conclusive results of the LCOE and LCA, emphasizing the previously mentioned key performance indicators (KPIs) and engaging in discussions. This is followed by chapter 7, which verifies the conclusions derived from experimental tests conducted during the project. Subsequently, the report concludes with overall project conclusions.

Finally, an envision of LCOE projections in standardized/industrialized cases is provided to look beyond the project and how it can boost offshore floating wind technology in the next decade. The key findings can be summarized as follows:

- The average LCOE for the reference scenarios investigated was €99.7/MWh, which was reduced to €86.6/MWh through optimisation. The costs are expressed in relation to 2022.
- The layout optimisation had a major effect on the optimised LCOE reducing it in average by 4.25% for all reference scenarios.
- The O&M strategy optimisation allowed an average reduction on the OPEX of the different wind farm scenarios of 35.04% which resulted in an average LCOE reduction of 6.84%.
- Through the optimisation of the LCOE, notable reductions in environmental impacts were achieved, resulting in all scenarios being below 20 gCO_2 eq./kWh (with an average of 11 gCO_2 eq./kWh). This outcome surpasses the initial project proposal's targets, making it an exceptional achievement.

The study aimed to reduce the LCOE for floating wind by 15% compared to the 2014 bottom-fixed LCOE of €127/MWh [2]. This required an average LCOE of maximum €108/MWh for the floating wind scenarios, which was successfully achieved across all studied cases. The Task 6.3 results demonstrate that COREWIND achieves a low-cost scenario in line with LCOE projections for 2025, highlighting the potential of enhanced research, development, and innovation. The study findings envision a €72/MWh reduction in the LCOE by 2035, establishing COREWIND as a leading project driving the progress of concrete-based floating wind technology.

1 Introduction

COREWIND project has developed innovative research and modelling for concrete-based floating substructure concepts in work packages WP1 to WP4 in order to find cost-effective solutions. Outputs from these work packages (WP) were aligned with WP6 in charge of the LCOE and LCA analysis which activities finished with task 6.3 execution. This task is dedicated to updating and reviewing the CAPEX, OPEX, and LCOE after optimisation actions for cost-reduction scenarios which were defined and evaluated preliminarily in previous tasks 6.1 and 6.2. In addition, the industrialization perspective resulting from WP5 is also considered. Moreover, the specific objectives of task 6.3 are also to provide the results of the LCOE and LCA analysis using FowApp (the Floating Offshore Wind Assessment app) after updating and optimisation. All these outcomes have been developed in the confidential deliverable D6.3, [3], to feed this final public report of WP6, *D6.4 LCOE, CAPEX and OPEX reduction: Key Performance Indicators and executive summary.*

2 Key Performance Indicators of LCOE and LCA

When aiming to decrease LCOE and minimize environmental impact, it is important to focus on the key KPI, which are the parameters or metrics that have a direct impact on LCOE and LCA. These parameters were already addressed from task 6.1 to task 6.3. For LCOE, the crucial metrics that affect the outcome are the CAPEX, OPEX, DECEX, and AEP. Similarly, for LCA, the significant environmental metrics were selected previously to report the results in FowApp as given in D6.3, such as Eutrophication Potential (EP), Acidification Potential (AP), Abiotic Depletion Potential (ADP), GWP also known as carbon footprint, PED, EPBT, and ROI.

The optimisation of the LCOE and LCA outcomes involves targeting the influencing factors of each individual metric, which can be broken down into specific components. In this vein, 8 KPIs with their respective units were chosen in this report to describe the levelised cost and environmental performance of COREWIND research results for concrete-based floating wind technology cost reduction, which are briefly described in the following subchapters.

2.1 CAPEX

CAPEX refers to the costs used by a company to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology, or equipment. CAPEX is measured in €/MWh in the floating wind power technology is influenced by factors: such as:

- Site assessment and preparation costs
- Permit and regulatory compliance costs
- Production costs:
    - Complexity of floating offshore wind turbine (FOWT) and offshore substation (OSS)
    - Type of primary materials of FOWT and OSS
    - Material masses
    - Length of mooring lines and power cables
    - Type (material, dimensions) of mooring lines and power cables
- Transport & Installation costs:
    - Location of production facility and/or fabrication harbour and distance to wind farm
    - Vessel spread, prices, availability, and weather limits
    - Fuel consumption and price
    - Duration of installation
    - Environmental conditions

2.2 OPEX

OPEX refers to all expenditure occurring from immediately after point of takeover, whether one-time or recurring, related to the wind farm. OPEX is quantified in €/MWh. The factors influencing the OPEX of a floating wind farm can include the following:

- O&M strategy:
  - Major component exchange strategy
  - Vessel fleet for scheduled and minor corrective maintenance
  - Access system
  - 12 or 24 hours shift set-up
  - Service agreement and contractual set-up
  - Spare part stock and availability
  - Berthing capacity in port

- Vessel fleet composition:
  - Wind farm size and layout (number of WTGs and OSS, cable and mooring system layout)
  - Location of O&M harbour and distance to wind farm
  - Vessel prices, availability, and weather limits
  - Fuel consumption and price
  - Inspection frequency and duration
  - Environmental conditions
  - FOWT motions

- Aspects influencing the direct costs:
  - Spot market prices of vessels
  - Spare part costs
  - Component reliability
  - Crew size
  - Personnel salary
  - Contractual set-up
  - Port fees
  - Fuel costs and consumption
  - Insurances

2.3 DECEX

DECEX is related to decommissioning costs measured in €/MWh:

- Location of dismantling port/ facility and distance to wind farm
- Location of landfill/ recycling/ incineration facilities to dismantling port
- Vessel spread, prices, availability, and weather limits
- Fuel consumption and price
- Duration of dismantling and removal procedure
- Environmental conditions
- Complexity of floating offshore wind turbine (FOWT) and offshore substation (OSS)
- Type of primary materials of FOWT and OSS

- Material masses
- Length of mooring lines and power cables
- Type (material, dimensions) of mooring lines and power cables

2.4 AEP

The following aspects were considered in the model to calculate the annual energy generated:

- Turbine rating
- Wind turbine availability/ downtime
- Wind turbine layout (wake effects)
- Electrical grid efficiency
- Wind conditions

2.5 GWP

GWP measures the CO2 eq emissions per MWh associated with the wind farm life cycle, from the raw material extraction through production, manufacturing, transportation, installation, operation, and maintenance to decommissioning and end-of-life (EoL). This also includes the recycling rates of materials and the impacts of incineration/ landfill.

2.6 PED

The parameter PED, or primary energy demand, represents the total amount of energy, measured in MJ (megajoules), needed for the production, manufacturing, operation, and decommissioning of the wind farm.

2.7 EPBT

The Energy Payback Time (EPBT) refers to the duration, measured in years, required for the energy produced by the wind farm to balance the energy expended during its manufacturing, transportation, installation, operation, and decommissioning phases.

2.8 ROI

The Return on Investment (ROI) or Energy Return on Investment (EROI) represents the ratio between the energy generated by the wind farm and the energy consumed in its manufacturing, transportation, installation, operation, and decommissioning processes.

3 Methodology

The initial LCOE and LCA evaluation of the scenarios was detailed in D6.2 [1]. After applying the optimisations and innovations developed in technical WPs, the LCOE and LCA methodologies are followed to re-evaluate the economics and the environmental impacts along the life cycle of floating wind farms. The methodological procedure is described in the next sections.

3.1 Industry insight to cost reduction opportunities

The project planned to engage with the industry to validate internal expert's views and provide insights on cost reduction opportunities within the value chain of floating offshore wind. Two workshops, a survey, and interviews were prepared in such a way that involved consortium partners would have feedback from industry experts, the Floating Offshore Wind Task Force and Offshore Wind Working Group. The results of the survey, workshop and interviews are given in chapter 5.1.

3.2 The LCOE assessment

WP6 aimed at evaluating floating offshore wind farms both from the economic as well as the environmental points of view. To this end, a series of reference scenarios were defined and analysed from two perspectives. The first perspective was an initial analysis considering current procedures and technology. The second perspective was considering disruptive technologies and optimisations to reduce the overall LCOE.

3.2.1 Updated reference scenarios

Deliverable D6.1 "General frame of the analysis and description of the new FOW assessment app" [4] was submitted in November 2020, including the reference scenarios to be used along the project to define, optimise and analyse a variety of wind farms. These reference scenarios are listed in Table 3-1 and define the working framework, excluding the details subject to change or optimisation, on which all the analyses in WP6 are based.

Table 3-1. Updated reference scenarios for the LCOE and LCA assessment.

Scenario	Location	Capacity (turbines)	Grid connection
1A	W of Barra	60 MW (4 WT)	Single string to onshore substation
2A		300 MW (20 WT)	5 strings to offshore substation, plus export cable to onshore substation
3A		1200 MW (80 WT)	16 total strings to 2 offshore substations, plus export cables to onshore substation
4A & 4W	SE of Gran Canaria	60 MW (4 WT)	Single string to onshore substation
5A & 5W		300 MW (20 WT)	5 strings to onshore substation
6A & 6W*		1200 MW (80 WT)	16 total strings to 2 offshore substations, plus export cables to onshore substation
7A & 7W	Morro Bay	60 MW (4 WT)	Single string to onshore substation
8A & 8W		300 MW (20 WT)	5 strings to offshore substation, plus export cable to onshore substation
9A & 9W		1200 MW (80 WT)	16 total strings to 2 offshore substations, plus export cables to onshore substation

A: ActiveFloat, W: WindCrete, WT: wind turbine, (*): scenarios not fully analysed due to low power demand in the region and limited area with depths below 1000 m.

3.2.2 Updated baseline analysis and collection of optimisations information

The baseline analysis conducted in D6.2 [1], and submitted in 2021 was required to be updated by new project insights gained since then. All the changes (since August 2021) on the designs and procedures in all the technical work packages affecting the LCOE and/or LCA were tracked and classified in Table 3-2.

Table 3-2. Changes since D6.2 (August 2021) affecting the LCOE and/or the LCA.

Responsible partner	Change	Type
Innosea & USTUTT	Station keeping system design including fatigue analysis to reduce safety factors	Refinement
Innosea	Peak load reduction system	Optimisation
Innosea	Shared mooring lines and shared anchors	Optimisation
IREC	Consideration of site bathymetry and updated layouts	Refinement

IREC	New layouts, including new cable and mooring lengths	Optimisation
IREC	Introduction of offshore substations, updated connections and static cables	Refinement
IREC	Wind farm control for lifetime extension	Optimisation
IREC	Contingencies for net activity durations	Refinement
IREC	FowApp improvement and adaptation	Refinement
IREC	Updated decommissioning model	Refinement
JDR	Cables economies of scale	Refinement
JDR	CW003/4/6 full details	Refinement
JDR	CW005 section (materials) and losses	Refinement
JDR	Updated cable and hardware costs	Refinement
JDR	Cable design to stand up to 75 MW: CW008	Refinement
Ramboll	New offshore transport and installation procedures	Refinement
Ramboll	Updated O&M strategy	Refinement
Ramboll	Wind farm monitoring	Optimisation
Ramboll	Major component exchange optimisation	Optimisation
UL	Cost reductions due to standardisation/industrialisation	Standardisation
UPC	Liquid ballast	Optimisation
UPC	Substructure reuse	Optimisation

Through regular alignment with the consortium partners the list was completed and complemented by the survey and workshop results and provided input the calculation of the LCOE and LCA in the FowApp tool.

3.2.3 Industrialization approach for CAPEX, OPEX and LCOE estimation

Floating offshore wind is a novel technology with specific challenges. That is why it is difficult to transfer experiences from onshore wind and bottom-fixed offshore wind. Published market projections on cost reductions for floating offshore wind show that learning rates from other technologies can only be roughly estimated for a few aspects.

The analysis of the industrialised scenarios will be conducted applying learning curves to the optimised LCOE results:

- The current learning curves derived from different works and studies will be analysed and used.
- The results of the optimised analysis will serve as a reference point in time to conduct the projections.

4 Updated baseline: models and assumptions

The baseline scenario from D6.2 has been updated by new project insights which have been gained in the meantime, e.g., in OPEX the port location was updated as well as the composition of the vessel fleet which led to a reduction of the OPEX compared to the initial results from D4.2 used in D6.2. IREC has updated the wind farm layout which led to a cost reduction as well. These updates do not include innovations which are new to the market.

Deliverable D6.2 “Initial LCA and LCOE” [1] was submitted in September 2021, analysing the performance, costs and environmental impacts of the reference scenarios. Since then, for more than a year, a few refinements have been conducted in the models used, as well as on the initial assumptions. As the analysis conducted is multidisciplinary, many partners have been involved in these changes. The objective of the improvements was not only optimising the wind farms to reduce their costs and impacts, but also to provide more accurate results and allowing stronger and more solid conclusions. In the following sections, the updated models and considerations are described.

4.1 Components

4.1.1 WindCrete substructure

The solid ballast of WindCrete substructure was replaced by dense fluid with two main advantages. On the one hand, assuming the required ballast mass is the same as for solid ballast, the purchasing cost per ton of liquid ballast is lower. On the other hand, liquid ballast facilitates the installation process and particularly the decommissioning of the substructure, which was extremely complex with solid ballast.

4.1.2 Improved classical station keeping system

The mooring system was redesigned in WP2 following the classical approach and with the aim to pass the fatigue tests with minimal cost. Details on the optimised mooring system compositions which are used for the LCOE and LCA calculations are given in Appendix A.

Two additional mooring system types have been developed and are presented in chapter 5.2.3 and 5.2.4 to further reduce costs.

Usual layouts used by the industry are optimised for the two floaters and the three sites. The optimisation is performed using an optimisation tool, allowing cost savings on the design process itself. More details can be found on D2.2, [5].

4.1.3 Additional high voltage cables and updated costs

The initial LCOE assessment and LCA considered a single cable model (CW002) for all connections. To further adjust the cables to the scenarios, the following cables were introduced:

- CW005, a reinforced dynamic cable, to be used in Morro Bay to deal with the extreme tensions due to the deep waters in the site because CW002 could not resist.
- CW008 to carry up to 75 MW, as CW002 cannot be used to deliver more than 60 MW.
- A static 220 kV export cable to carry out the power between the offshore substations and the onshore substation.
- A dynamic 220 kV export cable to connect the offshore substations to the static export cable. The properties and cost of the cable were estimated as the technology does not exist yet.

All the costs were updated to 2022 € to reflect the current situation of the industry, in particular the cost of the materials. Additionally, non-linear economies of scale were contemplated for both cables and hardware.

4.1.4 Offshore substations

Floating offshore substations were introduced for some medium-size scenarios and for all large-size scenarios as already nowadays these wind farms are not directly connected to shore. The substation sizes considered were 300 MW and 600 MW. From the LCA perspective, only the impact due to the transport, installation and decommissioning was considered. From the LCOE perspective, all costs were considered except their maintenance.

4.2 Arrangement

4.2.1 Site bathymetries

The sites analysed were originally defined as a point in the map, where its depth was the reference for the whole wind farm. While the wind farm systems have been designed according to the reference depth, slight variations of these, depending on the bathymetry, have been considered to achieve more realistic results. FowApp was adapted to work with bathymetric data, and GEBCO grid [6] was used. The bathymetry of all sites is displayed in the following Figure 4-1, Figure 4-2, and Figure 4-3 where (0, 0) Easting/Nothing represent the site reference point.

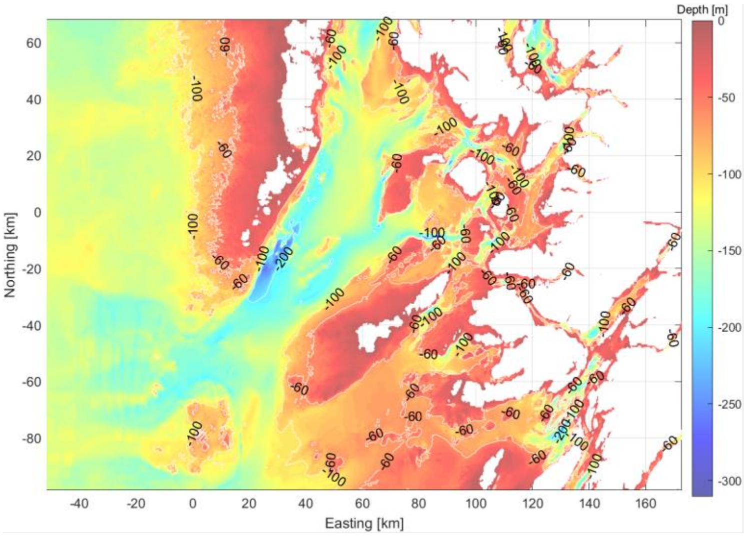

Figure 4-1. Site A - West of Barra. Bathymetry. (Source: FowApp software)

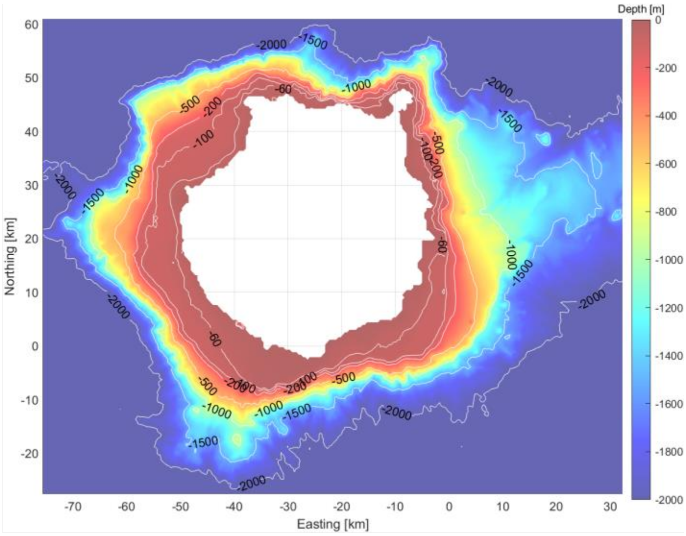

Figure 4-2. Site B – Gran Canaria. Bathymetry. (Source: FowApp software)

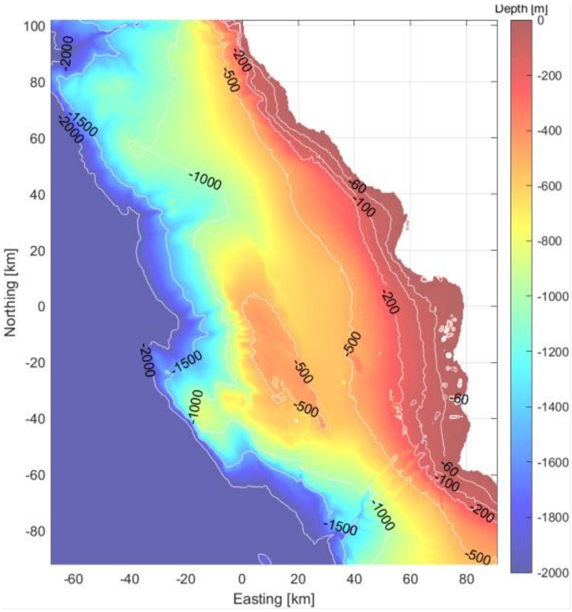

Figure 4-3. Site C – Morro Bay. Bathymetry. (Source: FowApp software)

4.2.2 Layout

The onshore substation of Site A was moved from Barra to South Uist to benefit from the existing network and larger size of the island. Similarly, the onshore substation of Site B was slightly displaced to be in a more suitable area. The initial baseline layouts considered a 7Dx7D spacing for all reference scenarios, except for 7W-9W, where the spacing was set to 9Dx9D to avoid mooring footprints overlapping. With the new mooring system designs, the turbine spacing of scenarios 7-9 was increased to 10Dx10D in the updated baselines for the same reason. The rectangular turbines arrangement was maintained as 1x4, 4x5 and 5x16 for 60, 300 and 1200 MW respectively.

Regarding the turbine rotation, the initial layouts considered the prevailing wind direction, placing the short side of the rectangles parallel to it to minimise the wake effect. Moreover, the turbines were centred on the site coordinates and moved, if needed, to ensure a minimum distance of 8 km to shore. The rotation and displacement of the offshore assets in the updated baseline scenarios was defined simultaneously: ensuring the same distance to shore is kept, locating the offshore substations in the perimeter of the turbines array and rotating the offshore assets to minimise the length of the export cables. Furthermore, the bathymetry was considered to avoid turbines in very shallow/deep waters.

Again, the layout of the updated baseline scenarios was arbitrarily defined, ensuring the feasibility, to serve as starting point of the layout optimisation.

4.2.3 Electrical connections

The topology of the updated electrical grids of the scenarios without offshore substations was maintained. In addition, all the strings of the 300 MW scenarios were connected to the offshore substation in a radial configuration, except in Gran Canaria where the onshore substation is only around 10 km from the site. The turbines in the largest scenarios were clustered in 2 groups and connected to an offshore substation each.

The sites bathymetry was considered to determine precise lengths, with tethered wave configurations in site A and lazy waves in sites B and C for the dynamic cables. The array connections were maintained at 66 kV, while export cables between substations were set to work at 220 kV.

4.3 Life cycle model updates

4.3.1 Transport and Installation model

The transport and installation (T&I) phase of the two floater types at the three reference sites was investigated in parallel to this deliverable in Task 4.5 of the COREWIND project. To model the installation of the ActiveFloat and the WindCrete floaters in the LCOE model the work breakdown structures of the required marine operations were shared by Ramboll and can be found in the deliverable D4.5, [7].

The marine operations are divided into separate main steps which include each 5 to 6 tasks. For each task the involved vessel and equipment, as well as the estimated net duration of the task are given. The installation process includes the following main steps in the performed study of D4.5, [7]:

- FOWT Anchor installation
- FOWT Mooring lines deployment
- FOWT Hook-up
- OSS Anchor installation
- OSS Mooring line deployment
- OSS hook-up
- Inter array cable laying
- Export cable-laying

4.3.2 O&M model

For the execution of Task 6.3, the O&M model developed in Task 4.2 was reused to examine the effect of certain innovations on the relevant KPIs of the operation and maintenance phase. For this purpose, certain simplifications made in the initial model had to be revised to reflect the impact of these innovations. These include a precise definition of the O&M ports for daily maintenance with crew transfer vessels (CTV) and service operation vessels (SOV) and a definition of the port in which heavy lift vessels (HLV) could be chartered and tow-in operations could be carried out. Further, the composition of the vessel fleet was slightly adjusted, since the definition of the ports had changed the distances of transit. This then also resulted in an optimisation of the number of personnel, adjusted to the new vessel fleet.

The input parameters and assumptions taken for the baseline model are given in D4.2 [8]. Table 4-1 to Table 4-3 list the updated assumptions which differentiate from the former model.

Table 4-1: Updated port assumptions for the three reference sites including approximate distances to site.

	Site A - West of Barra	Site B – Gran Canaria	Site C – Morro Bay
Port Type	**Port Name**	**Port Name**	**Port Name**
CTV/SOV port	Stornoway; 195 km	Port of Las Palmas; 45 km	Hueneme; 250 km
Tow-in port	Orkney (Scapa Flow); 400 km	Port of Las Palmas; 45 km	-
Tow-in Bay	-	-	St. Luis Bay; 90 km
HLV charter port	Orkney (Scapa Flow); 400 km	Port of Las Palmas; 45 km	Long Beach; 355 km

Figure 4-4. Assumed port locations for site A - West of Barra (Source: Bing maps).

Figure 4-5. Assumed port locations for site B – Gran Canaria (Source: Bing maps).

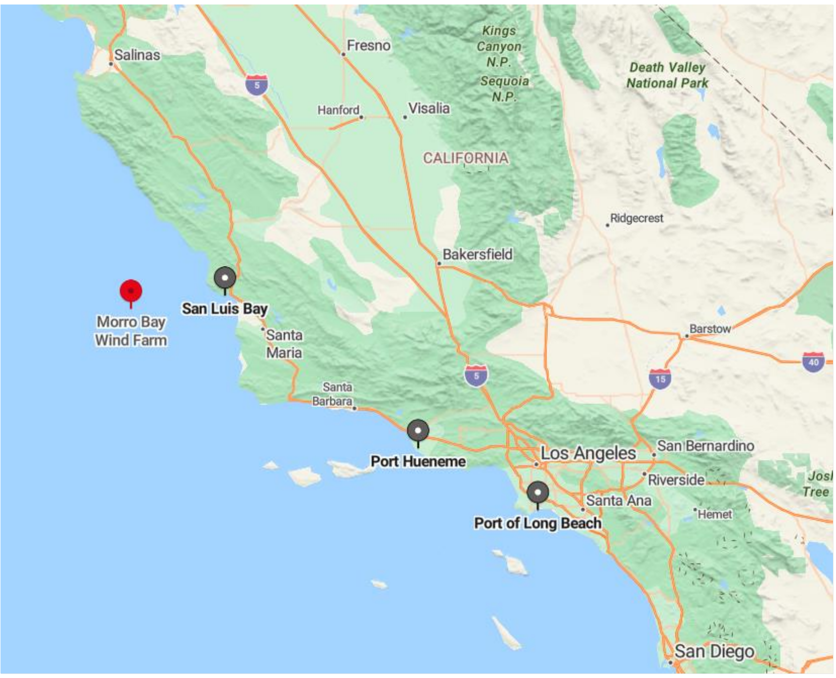

Figure 4-6. Assumed port locations for site C – Morro Bay (Source: Bing maps).

The maintenance strategy for **West of Barra** foresees an O&M port in Stornoway for day-to-day maintenance activities conducted by two SOVs. The SOVs return to port in 2 weekly cycles, operate throughout the year and are also used for the periodic subsea inspections. The port of Scapa Flow in Orkney for major component exchange (MCE) of the ActiveFloat wind turbine. It is to be noted that a reference case with the spar-type WindCrete floater is not foreseen for this site due to the low water depth of approximately 100m.

For **Gran Canaria** all maintenance activities are assumed to happen in the main port of the island, Las Palmas, which lies in close proximity to the wind farm. The day-to-day maintenance and above water inspections are performed by crew transfer vessel (CTV). For the periodic subsea inspections, a remotely operating vehicle (ROV) is chartered which is supported by a service operation vessel (SOV). For MCE the wind turbines are towed into the harbour of Las Palmas where an onshore crane performs the component exchange. The water depth of tow-in port has been neglected for this study and the tow-in process of the spar type floater shall be seen as theoretical study.

For **Morro Bay** it is assumed that the daily maintenance activities are organized from the port of Hueneme which is closest to the wind farm location. The maintenance activities are conducted by two SOVs. The SOVs return to port in 2 weekly cycles, operate throughout the year and are also used for the periodic subsea inspections. It is further assumed that the wind turbines are towed into the St. Luis Bay for MCE instead of a bigger port like Long beach, as this would reduce the transit time significantly and will result in a higher availability of weather windows for the operation. The exchange would be performed by a jack-up vessel positioned in the shallow water of the bay. Same as for the port of Gran Canaria, the water depth of the bay has been neglected for this study and the tow-in process of the spar type floater shall be seen as theoretical study.

The work breakdown structure of the different operation steps for the tow-to-port operation for MCE are summarized in Table 4-2 indicating the required offshore tug vessels and anchor handling tug vessels (AHTV), as well as the net durations of the working steps. The transit time is calculated by the simulation tool and depends on the distance to port and the prevailing weather of the three reference sites.

Table 4-2: Work break-down structure of the tow-to-port operation for major component exchange.

Task	Key marine spread/equipment	Net duration [h]
Mobilisation from harbour	AHTV + 2 Offshore tugs	168
Sail to site	AHTV + 2 Offshore tugs	Site dependent
Remove cables and wet store	AHTV	36
Release tension in mooring arrangement	AHTV	12
Connect tug lines to foundations	2 Offshore tugs	8
Disconnect mooring lines and wet store them	AHTV + 2 Offshore tugs	20
Tow of WTG floater from wind farm to port/ bay	AHTV + 2 Offshore tugs	Site dependent
Component replacement & WTG commissioning	Onshore crawler crane at port or JUV in bay	Component specific (see D4.2, [8])
Leave port/ bay and sail to site	AHTV + 2 Offshore tugs	Site dependent
Recover wet stored mooring lines and reconnect	AHTV + 2 Offshore tugs	20
Tensioning of mooring arrangement	AHTV	12
Recover and connect cable	AHTV	30
Final WTG commissioning	-	24
Sail back to harbour	AHTV + 2 Offshore tugs	Site dependent
Total (excl. transits & replacement)		**330**

The jack-up vessel is the only addition to the vessel fleet composition compared to D4.2, [8] and only applies to the reference site of Morro Bay. Further, the costs for the subsea inspections were adapted to more competitive values. Table 4-3 shows the assumed costs for the JUV and the updated subsea inspections costs. The costs for the other vessels and equipment are given in Table 4-10 of D4.2, [8].

Table 4-3: Updated vessel costs for JUV and subsea inspections.

Vessel	Purpose	Day rate [€/day]	Mob. and Demob. cost [€]	Hs Limit	Wind Speed Limit [m/s]	Fuel consumption [mt/24h]	Vessel speed [km/h]
SOV + ROV garage with ROV	Subsea inspections and repairs	35,000	1,085,000	Hs/Tp matrices provided in D4.2, section 5.4.2, [8]	-	10	29.6
Jack-up vessel (JUV)	Major component exchange in bay	200,000	4,200,000	1.80 m	15	11	18.5

The wind farm layouts 9A and 9W (see Table 3-1) at all three sites and both floater types have been modelled for the baseline scenarios. Shoreline Design, a time-based simulation engine described in D4.2, [8], was used for modelling. The results are presented in Table 4-4, indicating a trend of higher costs with greater distance to port and harsher weather conditions for Morro Bay and West of Barra. West of Barra has an exceptionally high yearly OPEX of 98,000 €/MW/year due to high vessel standby costs caused by non-available weather windows.

Table 4-4: OPEX and Availability results of the updated baseline scenarios.

Reference site	Floater type	TBA [%]	PBA [%]	Lifetime OPEX rounded [€]	OPEX/MW/year rounded [€]
Morro Bay	ActiveFloat	97.85	98.35	1,876,000,000	62,500
Morro Bay	WindCrete	98.17	98.69	1,896,000,000	63,200
Gran Canaria	ActiveFloat	98.09	98.69	1,466,000,000	48,900
Gran Canaria	WindCrete	98.09	98.69	1,464,000,000	48,800
West of Barra	ActiveFloat	95.19	95.56	2,939,000,000	98,000

4.3.3 Updated decommissioning model

The decommissioning of the wind farms was updated to avoid inconsistencies with the detailed transport and installation study, with activities ranging the site preparation to the site clearance, including all the disconnections, disassembly, towing and other transport of the components to the authorised ports for dismantling in the region.

5 Improvements, innovations, and optimisations for cost and impact reduction

This section is dedicated to describing the main remarks and outcomes from the industry survey, the public workshop and the interview, as well as the innovations that were identified and applied for cost reduction to the optimised scenarios.

5.1 Survey, workshop and interview

5.1.1 Industry survey and workshop results

Two workshops were planned to receive feedback from industry experts, the Offshore Wind Floating Task Force and Offshore wind Working Group.

The primary objective of the **internal workshop** held in April 2022 was to identify the key life cycle contributions that offer potential cost reduction opportunities, considering the CAPEX, OPEX, and AEP parameters involved in the LCOE. Additionally, the aim was to create guidelines for preparing the initial strategy surveys based on the identified cost reduction opportunities. The categories for discussion were classified into five categories:

- Floating substructure technology
- Cables
- Mooring system
- Layout
- O&M

A questionnaire was drafted based on the identified cost reduction opportunities from the internal workshop with the intention to distribute it as **survey** among experts in the offshore wind sector and other interested stakeholders. The survey included 24 multiple-choice questions and was completed by 25 companies, mainly project developers, consultancies, certification bodies, suppliers for specialized equipment, and marine contractors (June-August 2022).

The survey was followed by an **online workshop** that gathered 79 participants and addressed specific non-clear topics, with a focus on validating the survey results in open discussions. The expertise of people was foundations (24%), moorings (12%), electrical (0%), installation (8%), O&M (8%), and other (48%). Other included mostly researchers, consultants and certification bodies.

A summary of the main conclusions of the survey and external workshop outputs is given in Table 5-1, which feed into the LCOE and LCA assessments of the COREWIND tasks 6.3.1 and 6.3.3.

Results from surveys and workshops allow highlighting the main areas having more influence in the cost-reduction of floating offshore wind in the context of the COREWIND project. The following characteristics and aspects are taken into account to help accomplish the objectives of task 6.3:

- Floating-specific components (moorings, anchors, etc.) lifetime should be kept as 25 years regardless of its possibility to endure longer. A longer lifetime would impact the design requirements and as a result possibly become more expensive.
- As there is no specific data, a multiplication cost factor should be used for the anchors drilled piles applicable for rocky seabed (Canary Islands study case). For example, 20% higher.
- Assumptions for tower material should remain on steel as it is the most widely used (design wise) and certified in the offshore environment. Concrete would result in a stiff-stiff design which could lead to higher costs.
- Installation and O&M of inter array cables should have more detailed assumptions where possible as they can have higher failure rates than export cables. Installation rates for onshore is too small.
- Shared mooring lines and AUVs don't have conclusive evidence of lower cost.

Table 5-1: Main conclusions from surveys and workshop.

Main remarks from survey	Main remarks from workshop
Foundations	
• The size and weight seem to not be a limitation for upscaling foundation designs. Experts suggest that concrete foundations are more easily scalable compared to steel ones. • It is possible to manufacture one foundation in less than 30 days (for semi-sub and spar). One of the main manufacturers of foundations today in Europe would be able to deliver up to 10 floaters a year (so approximately 36 days). • The lifetime of concrete foundations is 40-50 years. It is mainly developers and suppliers who think that concrete foundations have a longer lifetime. The consultancies and certification bodies consider it 25 years.	• There is not much knowledge about energy consumption for manufacturing foundations. The only comment is that is the energy used is more than 100 kWh/ton and 10 litres/ton for a concrete semi-submersible. • In terms of the design, there are different factors that affect the final choice including the cost of commodities, taxes and availability of manufacturing/assembly facilities. • It is difficult to say which are the cost advantages (quantitative) of concrete foundations over steel. Qualitatively, concrete foundations require less increase for a large turbine compared to steel. And they can have a longer lifetime.
Mooring and Anchor System	
• Deepwater mooring systems pose different technical challenges, but the most influential for the LCOE are the installation and O&M strategy. Experts think the manufacturing capabilities could be a bottleneck	• The experts agreed on the 25-year assumption. • The selection of anchors largely depends on the seabed.

	• For shared mooring lines the design is not so straightforward as the maximum load works in a main direction. This means some lines need to be able to carry more load and fatigue over their lifetime.
Dynamic Cables (Electrical System and Installation)	
• Deepwater dynamic cables pose different technical challenges, but the most impactful for the LCOE is designed at wind farm level. Experts are most concerned about the lack of dynamic export cables.	• 66 kV is a good rating for inter-array but for export, a voltage higher than 132 kV might be a requirement. • Considering areas under development, it seems that in the next 10 years floating projects will not go into very deep waters (>200m). • In terms of failure, participants agree that inter-array is more likely to fail than export cable. • There is an even opinion about the lifetime of dynamic cables. Half of the experts think it can be longer than 25 years, and the rest think it is less than 25 years. So, 25 years (median) could be a reasonable assumption. • There is an even opinion about the time it takes to install offshore cables. Site conditions (like water depth) have a direct impact.

5.1.2 Interviews

Questions, which could not be addressed within the questionnaire nor in the workshop, were planned to be asked in one-on-one interviews. The organisation of the interviews was to be divided among the partners. However, only a single point was open after the questionnaire and workshop, and to this end RAMBOLL organised two interviews with mobile crane providers to resolve it. Both interviews took place in August 2022 and aimed at gaining more insights to the working procedure of a lifting operation on site using turbine mounted, temporary crane solution. The following information taken from the interviews was incorporated into the O&M cost model for the MCE operation:

- To transport the equipment of the wind turbine mounted crane offshore a JUV (jack-up vessel), barges, or floating vessels can be used. For stable positioning the barge needs to be anchored and the floating crane vessel needs to be equipped with a dynamic positioning (DP) system.
- The steps of the MCE using a turbine mounted crane are the following:
    - The temporary crane system is brought to the turbine (by a vessel with DP system or a barge with anchors)
    - Different solutions exist in the market for fixing the temporary crane on the wind turbine. For the two systems from the conducted interviews, one foresees the installation of a work deck on the external platform, while the other installs a base plate on the top of the nacelle.
    - The temporary crane is either installed in segments on the work deck of the turbine or lifted to the tower top where it is fixed on the previously installed base plate.
    - The broken components from the rotor nacelle assembly (RNA) are deinstalled and lifted down by the temporary crane.
    - The spare parts are lifted by the crane and installed on the RNA.

- The peak wind limit for the crane installation and the lifting operations is 18 m/s.
- A CTV brings the personnel on/off the wind turbine.
- Approximately four people from the crane equipment provider (50% at the bottom and 50% at the top) are required to overlook the operation. Additional personnel from the wind turbine supplier should be present, as well as further stakeholders checking the installation quality, and HSE representatives.

5.2 Innovations and optimisations

In this section, multiple innovations, optimisations and disruptive technologies are described to reduce the LCOE as well as the environmental impact of floating offshore wind farms.

5.2.1 Wind farm layout optimisation

The micro-siting of floating offshore wind farms is the process of locating the offshore assets (turbines, cable joints and offshore substations, if applicable). In COREWIND, the criteria followed when doing this process was minimising the LCOE of the reference scenarios, which depends on the selected layout because the energy yield and the costs of the wind farm depend on it, including:

- Wake losses and cable losses.
- Area leasing costs.
- Cable costs and station keeping system costs.
- Installation costs and decommissioning costs.
- End of life costs.

The layout was optimised applying the Particle Swarm Optimisation (PSO) to the LCOE as objective function, with the turbine and offshore substation positions as decision variables. For more information on the approach, the formulation, the constraints, the objective function and the algorithm, please refer to D3.4 [9].

Considering the refinements and model improvements described in chapter 3.2, the LCOE reduction of the reference scenarios due to the layout optimisation is significant, as it can be observed in Table 5-2.

Table 5-2. LCOE reduction due to layout optimisation.

Reference scenario	Initial LCOE [€/MWh]	Optimised LCOE [€/MWh]	LCOE reduction [%]
1A	99.5	97.5	1.9
2A	93.5	92.0	1.6
3A	95.3	94.4	1.0
4A	79.6	69.1	13.2
4W	61.1	58.6	4.2
5A	80.2	68.6	14.5
5W	60.8	57.9	4.8
7A	133.0	130.1	2.2
7W	124.8	121.5	2.7
8A	119.0	116.5	2.1
8W	112.2	109.8	2.1
9A	122.1	119.2	2.3
9W	115.1	112.0	2.7

Notes regarding the results:

- As in the initial optimisation in D3.4 [9], the bumpy area of site A leaded to low performance of the algorithm.
- Site B includes areas with deep waters; therefore, the layout optimisation becomes critical, especially for scenarios with expensive station keeping systems such as 4A and 5A.
- The station keeping system footprint continues to be a major constraint usually active.

The following figures illustrate the optimised layouts of two reference scenarios.

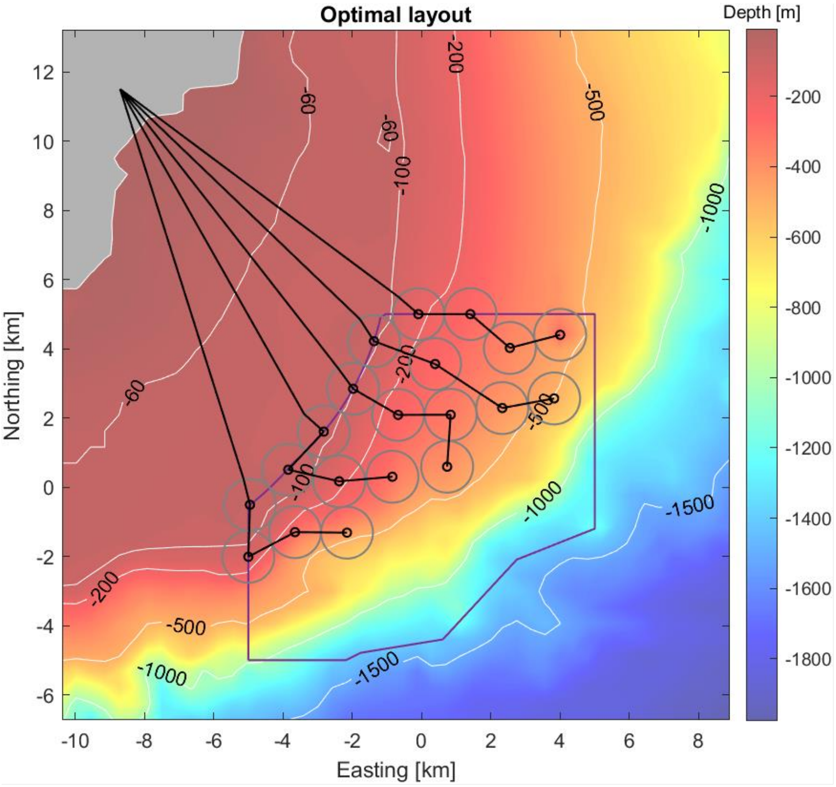

Figure 5-1. Optimal layout of reference scenario 5W. The purple polygon represents site boundaries, while the grey circles represent the station keeping system footprint. (Source: inhouse tool from IREC)

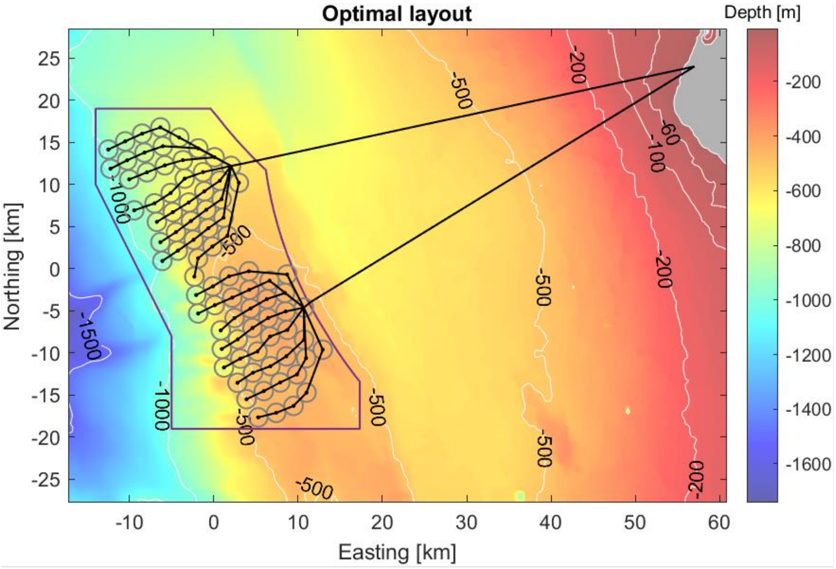

Figure 5-2. Optimal layout of reference scenario 9A. The purple polygon represents site boundaries, while the grey circles represent the station keeping system footprint. (Source: inhouse tool from IREC)

5.2.2 WindCrete reuse

WindCrete substructure has been designed with a lifespan of 60 years, but the wind farms are designed for a lifetime of 25 to 30 years. Instead of dismantling the substructure when de wind farm is decommissioned, disposing the materials (recycle, landfill or incineration), it can be used again in a new project with similar or less adverse environmental conditions. Applying this concept implies that at the end of the project, the substructure can be reused/sold, partially recovering the initial investment. Even though the sell price may be around 50% of the purchase price, the fact that it is recovered at the end of the project means that the effect on the LCOE is lower due to the value of the money. Additionally, the relative environmental impact of the substructure is also reduced, as it will be used to generate more energy. In this analysis, it is considered that the substructure is sold at the end of the project for half of its acquisition cost and that it will be used in a similar project with the same duration and generation before it is finally disposed.

5.2.3 Cost-optimised station keeping system: peak load reduction

To further reduce dimensions following previous optimisations, the use of peak load reduction system was investigated. Conclusion about this analysis is available in D2.3. Optimised configurations are listed here. System 1 and System 2 in ANNEXE B refers to two different peak load reduction technologies.

5.2.4 Cost-optimised station keeping system: shared mooring lines and shared anchors

Eventually the WP2 focused on innovative configurations such as shared anchor system and shared mooring lines. Details on the hypothesis, analysis and results can be found on D2.3, [10]. Tables in ANNEXE C described optimised mooring system obtained.

Several other aspects were studied in WP2 aiming at reducing overall costs, though not directly related to mooring system material costs. Further information can be found on D2.2, D2.3 and D2.4, ([5], [10], [11]). Those topics include:

- Reducing loads on the structure by tunning the controller.

- Developing new methodologies or tools: optimisation tool, use of surrogate model for optimisation, innovative methodology to reduce second order loads calculation time.
- Innovative designs for fairleads or reducing the mooring system footprint.
- Improve design strategies thanks to tank tests.

During the project, different types of mooring systems have been optimised including classical layouts, layouts using peak load reduction systems and layouts sharing anchors or mooring lines. Some cost savings were achieved thanks to innovative design processes or new technologies. However further cost savings could be expected. Table 5-3 below summarizes some perspectives. Further details can be found on D2.4, [11].

Table 5-3: Further cost saving perspectives for mooring systems.

Issue encountered	Consequence	Perspectives of optimisation
Lack of stiffness in some configurations	Add expensive buoys to provide stiffness	Shared layout tends to increase naturally the stiffness allowing to remove buoys
Fatigue criteria not respected	Increase number of lines and lines diameters	Use of synthetic lines or tunning of the controller might help to reduce loads allowing cost savings
Distance between 2 turbines in shared mooring configuration	Increase of line lengths to respect criteria. This increase tends to counterbalance cost saving thanks to anchors number reduction	Design at farm level including wake consideration should allow layout optimisation reducing system costs.
Peak load reduction systems costs	System costs high, counterbalancing cost savings thanks to mooring size reduction	Industrialization of those devices should allow an overall cost savings
Installation costs not accounted during optimisation	Benefits obtained using shared anchors, shared mooring lines or peak load reduction system could be underestimated	Include installation costs estimations

5.2.5 Operation and Maintenance phase outcomes

The O&M strategy for all three sites and both floater types has been updated by the implementation of two innovations which have an impact on cost and availability. The following sections provide a description of these innovations.

Innovation 1: Predictive maintenance using monitoring of the station keeping system

Within deliverable D4.3, [12], an evaluation has been conducted to determine the potential benefits associated with the use of monitoring technologies for floating wind turbine systems, compared to a traditional maintenance strategy. The assessment focuses on the reduction of OPEX as well as the increase in production-based availability.

To achieve this objective, a pre-analysis of the most promising monitoring technologies has been carried out, and a model has been developed to simulate the cost and availability outcomes of various O&M scenarios. The results of this analysis indicate that the implementation of a monitoring system for the station-keeping system would have the most significant impact on the O&M strategy. Consequently, a predictive maintenance approach using this monitoring system has been incorporated into the cost and availability model.

Finally, a cost reduction of 15.2 % and a relative reduction of the loss of PBA 24.6 % could be identified in D4.3 and have been accounted for as Innovation 1 in the optimised scenarios described in this chapter, which will serve as input to the LCOE calculations.

Innovation 2: On-site major component exchange with a turbine mounted crane solution

The results of deliverable D4.2, [8], showed that for the investigated cases the exchange of major components by towing the floater into harbour where economically more attractive than to use large floating crane vessels. In this deliverable the tow-to-port solution will be compared to an innovative in-situ methodology of using a turbine mounted crane on site.

For this purpose, a work breakdown structure is developed for the in-situ operation, estimating the durations of individual work steps. These durations can differ between different temporary crane solutions available on the market and are to be understood as a best estimate for this study. Time-based simulations of the O&M phase over the wind farm's lifetime are performed for the three reference sites and two floater types. The study shall identify the potential the innovative technology has to reduce cost and risk of the MCE operation. The work breakdown structure of the different operation steps for the MCE are summarized in Table 5-4 indicating the required vessels and net durations of the working steps. The transit time is calculated by the simulation tool and depends on the distance to port and the prevailing weather of the three sites.

Table 5-4: Work break-down structure of the on-site major component exchange using a turbine mounted crane.

Process activities	Vessel	Net Duration [h]
Mobilisation	Barge + 2 tug boats	168
Loading of toolbox on Barge	Barge + 2 tug boats	12
Transit to wind farm	Barge + 2 tug boats	Site dependent
Positioning & anchoring of Barge	Barge + 2 tug boats	12
Preparations: release sea fastening, transfer personnel, install crane	Barge + CTV	36
Lowering of old and lifting of new component	Barge + CTV	Component specific (see D4.2, [8])
Deinstallation of the temporary crane system & commissioning of WTG	Barge + CTV	24
Preparation of barge for transit back: anchor removal, sea fastening	Barge + 2 tug boats	12
Transit to port	Barge + 2 tug boats	Site dependent
Deloading of toolbox from Barge	Barge + 2 tug boats	24
Demobilisation	Barge + 2 tug boats	72
Total (excl. transits & replacement)		**360**

The purchase costs of a 15 MW wind turbine crane assumed for this study are 10m€. The dayrate including a barge and two tug boats to tow the barge to site was assumed to be 86,800€ with a total mobilisation and demobilisation cost of 406,000€.

Innovation impact on OPEX and Availability

The baseline scenarios for all three sites and both floater types have been modelled in the time-based simulation engine Shoreline Design, which is further described in D4.2, [8]. The results are summarized in Table 5-5.

Table 5-5: Results of the optimised scenario including the effect of the innovations on OPEX and availability.

Reference site	Floater type	TBA [%]	PBA [%]	Lifetime OPEX rounded incl. innovation impact [€]	OPEX/MW/year rounded [€]	ΔOPEX (baseline vs. optimised scenario) [%]
Morro Bay	ActiveFloat	98.32	98.66	1,116,170,000	37,200	40.48
Morro Bay	WindCrete	98.32	98.66	1,116,250,000	37,200	41.14
Gran Canaria	ActiveFloat*	98.57	98.01	1,242,430,000	41,400	15.34
Gran Canaria	WindCrete*	98.57	98.01	1,241,360,000	41,400	15.16
West of Barra	ActiveFloat	97.76	98.10	1,086,260,000	36,200	63.06
					Average	**35.04**

**Innovation of turbine mounted crane is slightly disadvantageous for the site of GC and was therefore not assumed in the optimised scenario.*

The waterfall diagrams shown in Figure 5-3 to Figure 5-8 illustrate the impact of innovation 1, an implemented monitoring system of the station keeping system, described in D4.3, [12], and of innovation 2, the use of a turbine mounted crane for MCE as alternative to towing the wind turbines into harbour. These two innovations show both positive and negative effects on the operational costs depending on the reference site.

Site A - West of Barra

In West of Barra, harsh weather conditions have a significant impact on both minor scheduled and corrective maintenance activities, but especially on the MCE operations. In the baseline scenario, the floating offshore wind turbines (FOWTs) are towed to the harbour of Orkney for the replacement, which is located 400 km away from the site. In combination with the difficult weather conditions, the wind farm's availability reaches only 95.56% (see Figure 5-4). This further leads to long downtimes for the vessels and high OPEX costs in the baseline scenario.

The implementation of the monitoring system allows for a reduction in OPEX and an increase in PBA, illustrated in Figure 5-3 and Figure 5-4. However, the turbine mounted crane has the highest impact, showing enormous potential for reducing downtime during the O&M phase. This results in a significant increase in PBA and a reduction in operational costs.

Maintenance activities in such conditions are particularly costly, as restricted weather windows and long distances to the port lead to significant losses. Therefore, any measure that reduces the number of inspections or the time spend offshore positively influences OPEX.

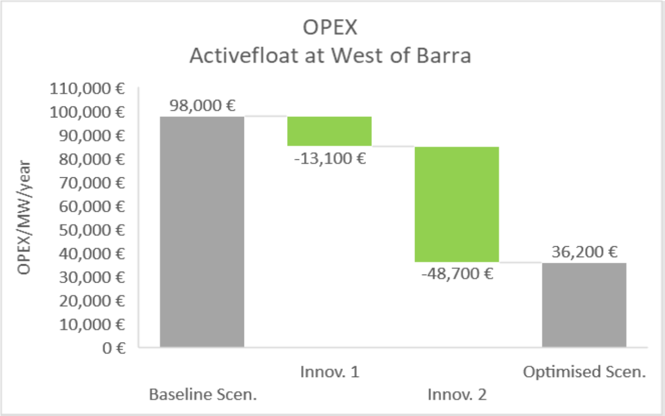

Figure 5-3: ActiveFloat at site A: Individual impact of the two innovations (Innov. 1: monitoring system; Innov. 2: mobile crane for MCE) on OPEX of the optimised scenario.

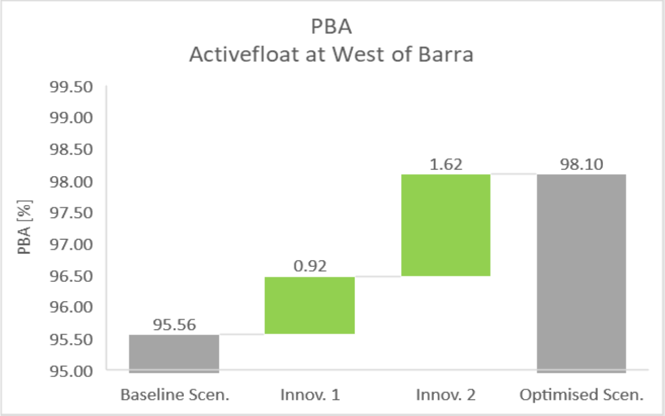

Figure 5-4: ActiveFloat at site A: Individual impact of the two innovations (Innov. 1: monitoring system; Innov. 2: mobile crane for MCE) on PBA of the optimised scenario.

Site B - Gran Canaria

The wind farm reference site in Gran Canaria is situated in close proximity of 45 km to the Las Palmas port, while the sea conditions in the region are very calm. As a result of these favourable conditions, the tow-to-port operation is extremely easy to execute, making it the most cost-effective solution for MCE. The in-situ replacement is slightly more expensive for both floater types and causes a slight loss in availability compared to the baseline scenarios. It was therefore decided to only include the favourable effects of innovation 1 to the optimised scenario of Gran Canaria and to assume a tow-in strategy for MCE. This then results in an OPEX of 41,400 €/MW/year and a PBA of 99.01% for both floaters (see Figure 5-5 and Figure 5-6).

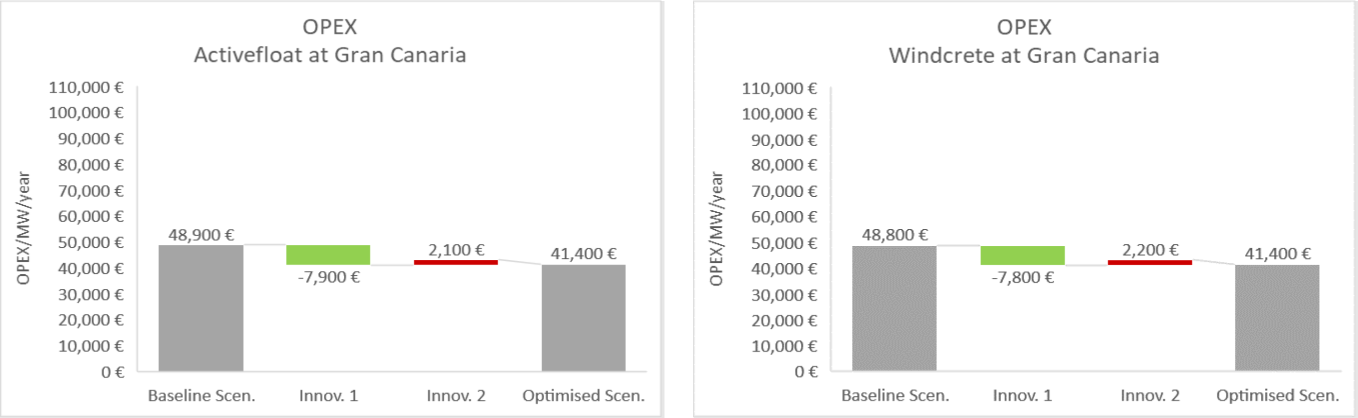

Figure 5-5: ActiveFloat and WindCrete at site B: Individual impact of the two innovations (Innov. 1: monitoring system; Innov. 2: mobile crane for MCE) on OPEX of the optimised scenario.

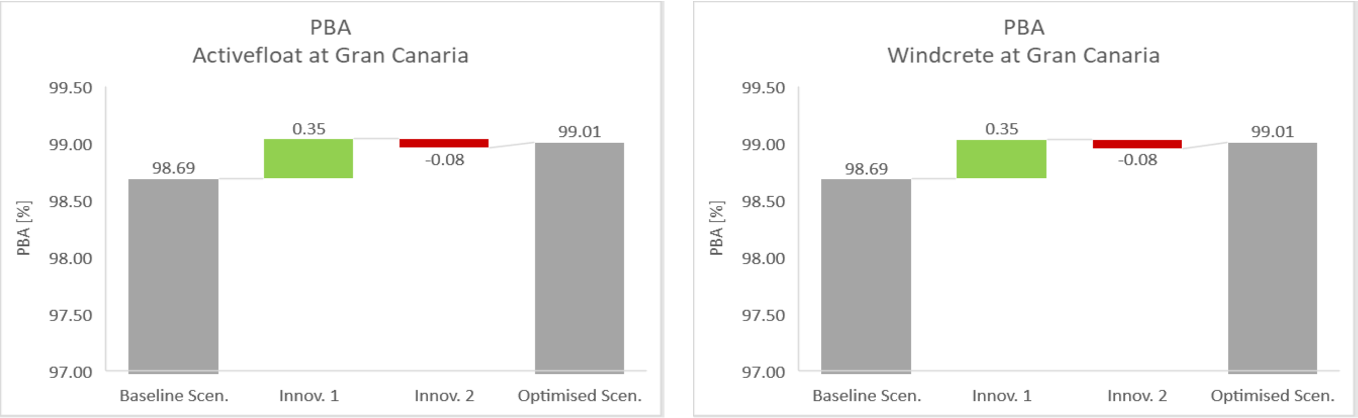

Figure 5-6: ActiveFloat and WindCrete at site B: Individual impact of the two innovations (Innov. 1: monitoring system; Innov. 2: mobile crane for MCE) on PBA of the optimised scenario.

Site C - Morro Bay

The Morro Bay area experiences moderate weather conditions, and it is located at 250 kilometers from its designated O&M port in Hueneme. However, the bay is only 90 kilometers away for towing operations, which minimizes the downtime during such operations. This contributes to the great impact the use of the turbine mounted crane has on OPEX (see Figure 5-7), which is double the gain achieved by the predictive maintenance approach through the monitoring system. However, the PBA experiences a slight reduction due to the use of the turbine mounted crane (see Figure 5-8). This is because the longer duration of the on-site operation leads to slightly higher wind turbine downtime than for the tow-to-port operation. Nevertheless, the economic benefits counterbalance this effect.

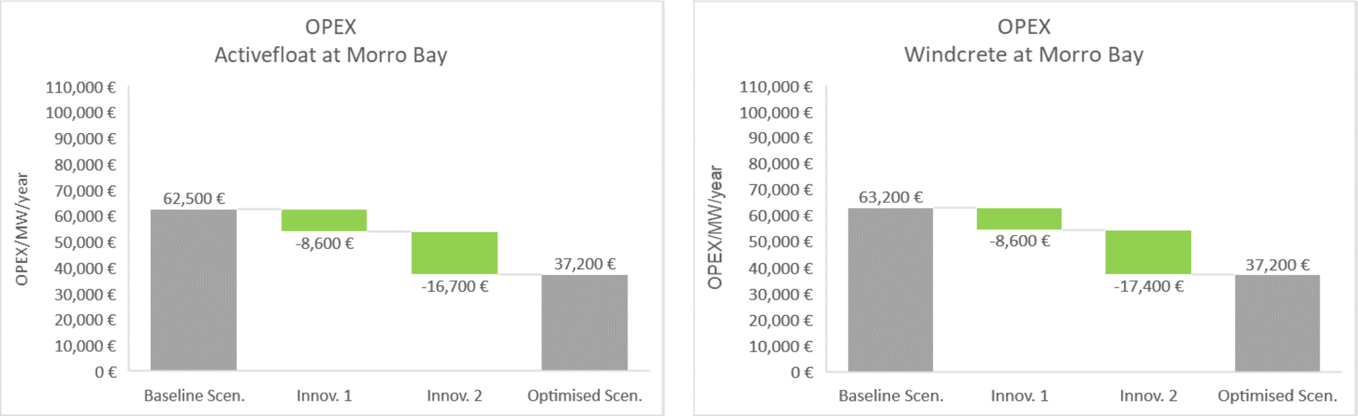

Figure 5-7: ActiveFloat and WindCrete at site C: Individual impact of the two innovations (Innov. 1: monitoring system; Innov. 2: mobile crane for MCE) on OPEX of the optimised scenario.

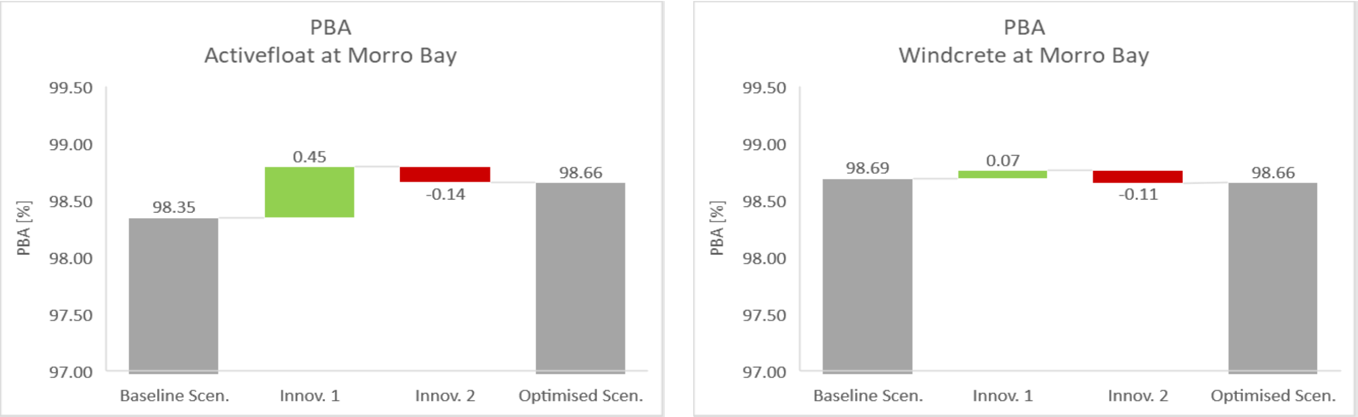

Figure 5-8: ActiveFloat and WindCrete at site C: Individual impact of the two innovations (Innov. 1: monitoring system; Innov. 2: mobile crane for MCE) on PBA of the optimised scenario.

Overall, it can be stated that for West of Barra, the baseline model indicated notably elevated operational expenditures because of the challenging environmental conditions and the extensive distances to the port. For the medium condition of Morro Bay, the effects start to shift, showing availability losses for the turbine mounted crane solution in combination with an economic gain on the maintenance costs. In the mild conditions the tow-to port solutions proves to be the most cost-effective with the on-site replacement option showing losses in both costs and availability.

The trend that can be observed originates in the fact that both solutions are very similar in the net task durations of their work breakdown structures, with the on-site operation taking slightly longer. The effectiveness of the tow-to port solution depends highly on the distance to port and the weather conditions throughout the hoof-off, transit, and hook-on procedures. This causes the differences between the harsh and mild reference site. The turbine mounted crane might have similar task durations but the tasks with severe weather limitations are shorter making this solution less prone to delays through severe weather conditions.

It should be noted that the estimated task durations may vary depending on several factors such as the type of floater, the specific site, the chosen mobile crane solution, the available harbour facilities, and equipment. These factors may significantly impact the outcomes of the study. Therefore, it is imperative to exercise caution when selecting the vessel routing and weather data for the simulation, as their quality plays a crucial role in determining the study's results.

5.2.6 Wind farm control for life extension

Fatigue loads cause the weakening of a material subjected to stress, especially when it occurs cyclically. These cyclic loads and the induced fatigue can lead to the generation of cracks or even the fracture of the structure, increasing the costs of operation and maintenance of the turbines. At the floating wind farm level, fatigue control is important to obtain a load balance in the farm, extending the life of upstream turbines. A correct active power dispatch control can distribute the power setpoints, so that the fatigue of the turbines with higher load can be alleviated.

The turbine that will suffer the highest loads in the farm will be the one placed upstream of the prevailing wind. Therefore, investigating the useful life of a floating wind turbine, it is possible to make an estimation of the equivalent fatigue load during its lifespan. More specifically, as shown in the load spectra (Figure 5-9), the useful life of an offshore generator at 25 years can withstand up to 10^7 load cycles, calculated with an average load under normal operating conditions of 100 kN·m.

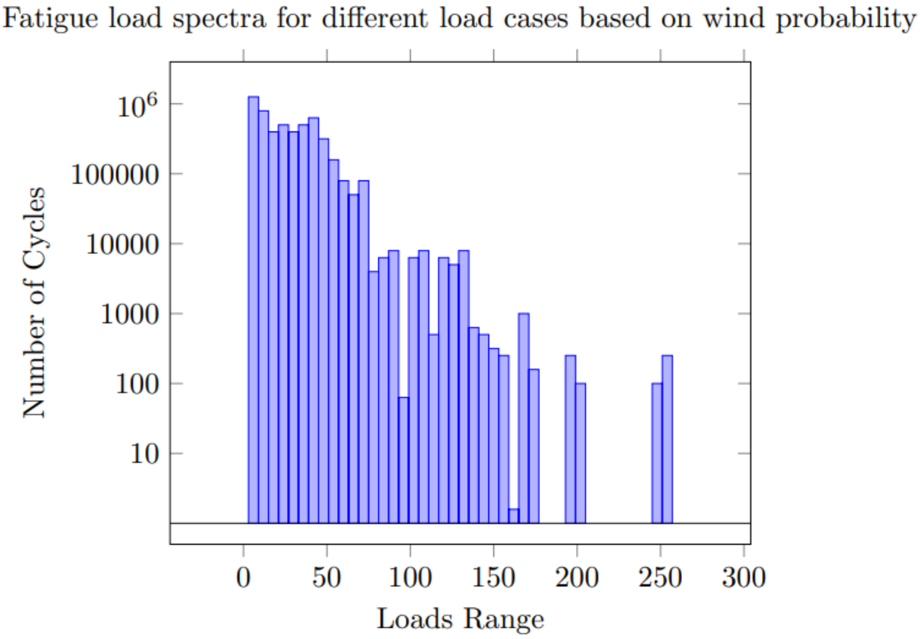

Figure 5-9. Cyclic loads in offshore wind turbines (illustration based on [13]).

As shown in the results graph (Figure 5-10), the proposed controls manage to balance the loads within the farm, which means that the turbines placed upstream will be able to lengthen their life. Although the study is carried out for 11.5 minutes (approx. 700s) the results can be amplified to a larger scale. A reduction of the variability obtained with the control of 25% of loads of the first turbine, allows to obtain an approximation regarding the lengthening of the useful life. If the control is applied every time instant until reach 10^7 load cycles, it is possible to obtain an increment of

$$\Delta t = \frac{25[years] \cdot 100\ [kN.m]}{(1-0.25)100\ [kN.m]} - 25 = \frac{2500[years \cdot kN.m]}{75\ [kN.m]} - 25 = 8.33\ years$$

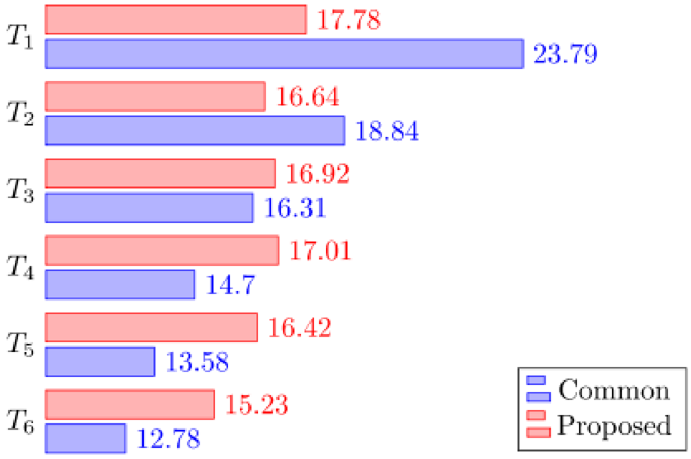

Figure 5-10. Comparison between common and proposed controls [14].

However, it results more realistic to consider the possibility of implementing the control strategy or not, due to aspects as wind availability, generation shutdowns, high peak power demands, etc. Therefore, if we consider a control a monthly possibility ratio δ, its possible to adapt the control benefits to a certain location, mainly depending on the wind conditions and demands, as:

$$\Delta t_{real} = \Delta t \cdot \delta$$

The design of δ, can be according to the annual probability of available wind speed. For example, taking the conditions of West of Barra (Table 5-6), it is possible to observe that a wind average speed equal or higher than the turbines' rated, will occur 8 out of 12 months (Note that the speeds in the table are expressed to z=10m). Therefore:

$$\Delta t_{real} = 5.5 \; years$$

Table 5-6. Annual average wind speed in West of Barra, [15].

Month	Average [m/s]
Jan	11.85
Feb	11.36
March	11.35
Apr	8.86
May	7.20
Jun	7.26
Jul	7.48
Aug	7.65
Sept	9.14
Oct	9.85
Nov	10.76
Dec	11.24
Global average	**9.50**

In any case, the controller can increase the life extension of the farm, caring the upstream wind turbines by decreasing the loads and the fatigue, meaning cost savings and maintenance reduction. This effect has been applied to the analysed cases the by increasing the lifetime of the medium-sized and large-sized projects as well as the lifespan of the components to 30 years. The small-sized scenarios, which only include 4 wind turbines, cannot benefit from this innovation because the wake effect is minimal.

6 LCOE Results

The model that allowed the initial results calculated in D6.2 [1] have been updated to include the refinements described in chapter 4. These modifications influence the wind farms energy output, their cost and their associated environmental impact, defining a new baseline.

Moreover, the innovations and optimisations described in section 5.2 were applied to the baseline scenarios to evaluate their impact. The exception is the shared moorings/anchors innovation that was discarded as it cannot be applied to the optimised layouts because these are irregular. Instead, the peak-load reduction innovation was applied, selecting the best option between two systems in terms of cost.

The following sections analyse in detail the changes in energy production, costs and environmental impacts of the reference scenarios because of the optimisations.

6.1 Energy yield

The main outcomes related to the energy yield in the updated baseline can be observed in Table 6-1. The capacity factor of the scenarios located in Gran Canaria is the highest, followed by West of Barra and Morro Bay. After the optimisations, the energy yield increased in West of Barra and Morro Bay, while Gran Canaria experienced worsening or little improvement. In this regard, it must be noted that the innovations and other improvements did not aim at increasing the energy output of the windfarms but reducing their LCOE. Therefore, an energy output reduction means the costs were highly reduced, as it can be seen in next section.

Table 6-1. Variation of the energy yield after the optimisations.

Reference scenario	Capacity factor		AEP [GWh/year]		
	Baseline	Optimised	Baseline	Optimised	Variation
1A	66.5%	68.3%	350	359	+2.7%
2A	66.6%	68.8%	1751	1808	+3.2%
3A	64.8%	67.0%	6817	7044	+3.3%
4A	73.3%	72.4%	386	381	-1.3%
4W	73.3%	73.2%	386	385	-0.1%
5A	71.1%	71.0%	1871	1868	-0.1%
5W	71.1%	71.5%	1871	1881	+0.5%
7A	44.3%	45.1%	233	237	+1.8%
7W	44.5%	45.2%	234	238	+1.7%
8A	46.8%	47.7%	1230	1254	+1.9%
8W	46.9%	47.6%	1235	1251	+1.4%
9A	44.5%	45.6%	4684	4802	+2.5%
9W	44.7%	45.6%	4701	4799	+2.1%

Table 6-2 shows the breakdown of the energy losses in the updated baseline scenarios. Grid losses have the greatest impact, especially in Morro Bay where both the longest array cables (due to water depth and turbine spacing) and the longest export cables (due to the distance to shore) are found. The downtime losses are high in West of Barra due to the typically adverse weather that delays the repairs. Finally, it can be observed, as expected, that higher number of turbines lead to increased wake losses, especially in sites with medium and low winds.

Table 6-2. Energy loss analysis of the updated baseline.

Reference scenario	Wakes	Turbines	Grid	Downtime
1A	0.7%	3.5%	5.8%	4.4%
2A	2.9%	3.5%	3.4%	4.4%
3A	4.2%	3.5%	4.7%	4.4%
4A	0.1%	3.5%	2.1%	1.3%
4W	0.1%	3.5%	2.1%	1.3%
5A	3.1%	3.5%	2.1%	1.3%
5W	3.1%	3.5%	2.1%	1.3%
7A	0.2%	3.5%	18.6%	1.7%
7W	0.2%	3.5%	18.6%	1.3%
8A	3.8%	3.5%	10.8%	1.7%
8W	3.8%	3.5%	10.8%	1.3%
9A	5.8%	3.5%	13.3%	1.7%
9W	5.8%	3.5%	13.3%	1.3%

Table 6-3 shows the losses after the layout and maintenance optimisation. On the one hand, layout optimisation increased wake losses, as turbines ended closer to reduce cable costs and losses. In the same process, the grid efficiency was increased due to shorter cables. On the other hand, maintenance optimisation leaded to a reduction of the downtime losses, particularly relevant for site A.

Table 6-3. Energy loss analysis of the optimised scenarios.

Reference scenario	Wakes	Turbines	Grid	Downtime
1A	1.3%	3.5%	5.1%	1.9%
2A	2.5%	3.5%	3.3%	1.9%
3A	3.7%	3.5%	4.7%	1.9%
4A	1.8%	3.5%	2.0%	1.0%
4W	0.7%	3.5%	2.0%	1.0%
5A	3.7%	3.5%	1.9%	1.0%
5W	3.0%	3.5%	2.0%	1.0%
7A	0.2%	3.5%	17.3%	1.3%
7W	0.2%	3.5%	17.1%	1.3%
8A	3.0%	3.5%	10.1%	1.3%
8W	3.4%	3.5%	10.0%	1.3%
9A	4.9%	3.5%	12.2%	1.3%
9W	5.2%	3.5%	12.0%	1.3%

6.2 Levelised cost of energy

This chapter includes the LCOE results of the studied scenarios and their analysis.

6.2.1 Highlights

First commercial-scale floating wind farms will have an intermediate size, matching the 300 MW scenarios studied. Figure 6-1 shows the overall LCOE reduction achieved in such scenarios for each site, emphasizing the relevancy of the site selection, where the water depth, the wind, the seas and the closest infrastructure play a relevant role. An LCOE reduction between 11% and 18% was reached considering the mean value of both substructures.

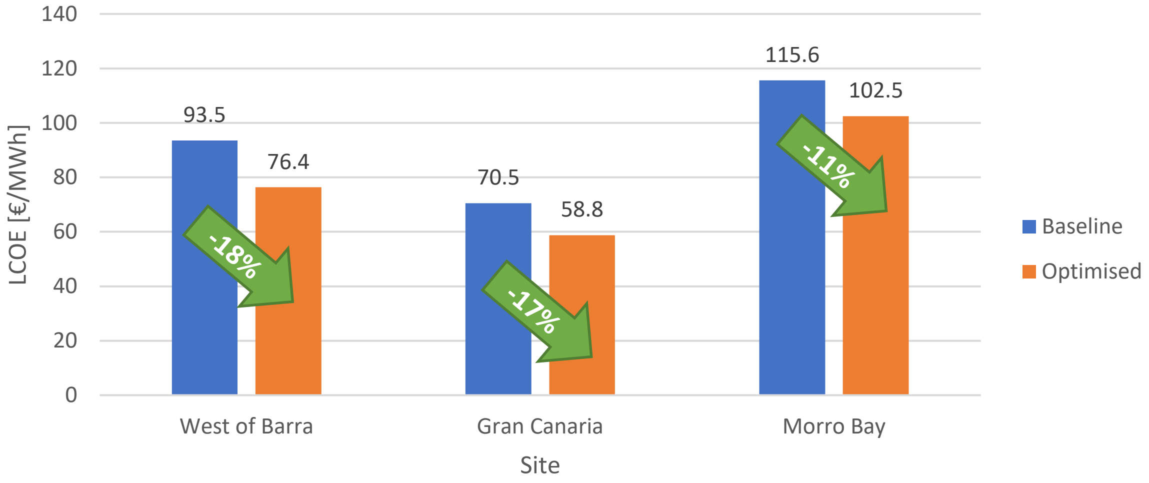

Figure 6-1. Average LCOE reduction achieved in COREWIND.

Figure 6-2 shows the average effect of the innovations on both substructures for the 300 MW scenarios, bringing to light what can be expected in the short term. Layout and maintenance improvements stand out.

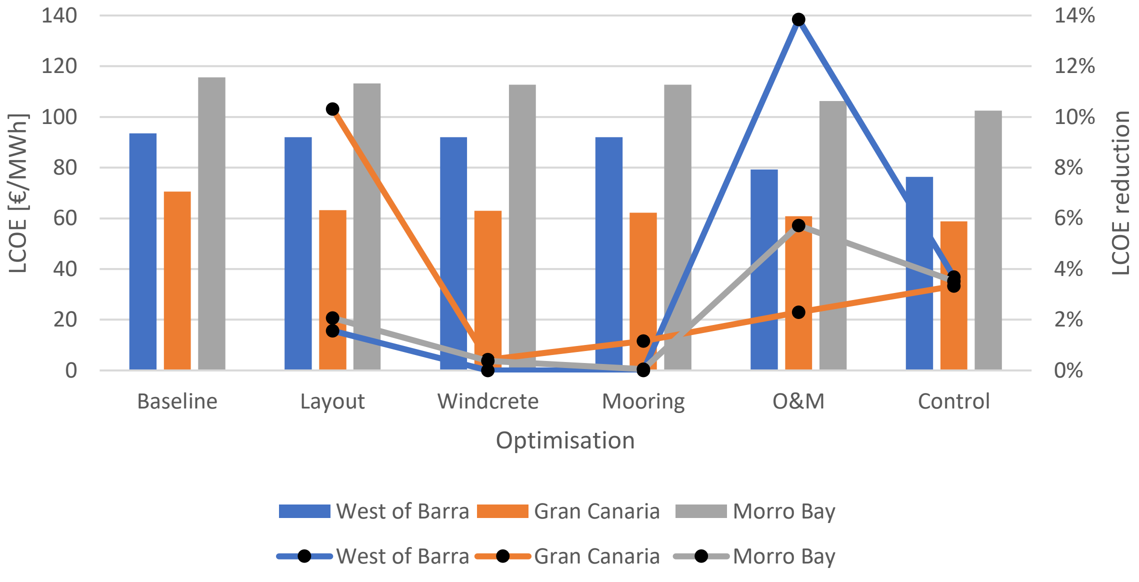

Figure 6-2. Cumulative average LCOE reduction of 300 MW wind farms by optimisation.

6.2.2 In-depth analysis

The main economic outcomes after the models refinement are shown in the following table.

Table 6-4: Economic parameters of the updated baseline.

Reference scenario	CAPEX		OPEX		DECEX		LCOE
	M€	M€/MW	M€	M€/MW	M€	M€/MW	[€/MWh]
1A	236	3.93	213	3.55	48	0.80	99.5
2A	1145	3.82	900	3.00	196	0.65	93.5
3A	4554	3.80	3534	2.95	766	0.64	95.3
4A	232	3.87	121	2.01	47	0.79	79.6
4W	169	2.81	121	2.01	36	0.60	61.1
5A	1157	3.86	524	1.75	193	0.64	80.2
5W	831	2.77	524	1.75	149	0.50	60.8
7A	226	3.76	147	2.45	47	0.79	133.0
7W	209	3.48	148	2.47	45	0.76	124.8
8A	1085	3.62	629	2.10	198	0.66	119.0
8W	1012	3.37	634	2.11	192	0.64	112.2
9A	4236	3.53	2475	2.06	737	0.61	122.1
9W	3949	3.29	2496	2.08	736	0.61	115.1

The innovations and optimisations were sequentially applied to the baseline scenarios to evaluate the impact of each of them on the LCOE. Table 6-5 shows the LCOE reduction achieved by each innovation, discussed below:

- **Layout optimisation** resulted in a significant improvement of the LCOE, with common reductions between 2-3%. The reduction achieved in site A were slightly lower, but this may be caused by the bumpy seabed; improved algorithms are expected to result into reductions in the previous range. On the other hand, the great seabed slope of site B explains the high LCOE reduction ins scenarios 4-5, especially for expensive mooring systems. The optimised turbine positions were very close in shallow water areas, increasing the wake losses, but greatly reducing the mooring system and cable costs.

- **WindCrete reuse** leaded to an LCOE reduction of 0.9% in Gran Canaria and 0.8% in Morro Bay. Although the relative reduction is greater in Gran Canaria, given that the Morro Bay design is more expensive, the absolute cost reduction if the latter is greater.
- **Peak-load-reducing devices** for the station keeping system did not have a homogeneous impact. In some scenarios (West of Barra and ActiveFloat in Morro Bay) their usage increased the overall cost of the system, therefore they were discarded. For WindCrete in Morro Bay the innovation effectively reduces the system cost, but the relative impact on the LCOE is low. Finally, the effectivity of the devices in Gran Canaria greatly reduced the overall cost of the studied cases.
- **Disruptive maintenance strategies** coupled with advanced monitoring leaded to significant cost reductions as well as increased availability of the wind farms. The effect was very high in West of Barra because the downtime was greatly reduced, as the weather windows in the site are short and the new strategies allow faster repairs, especially for MCE. The LCOE reduction in Morro Bay was lower but high compared to other optimisations.
- **The advanced control for life extension** also reduced the LCOE, as a consequence of increasing the lifetime of the wind farms to 30 years. 4-turbine scenarios did not benefit from this optimisation because the wake effect in such scenarios is minimal, and reduced fatigue would lead to reduced AEP.

Table 6-5. LCOE reduction by optimisation.

Reference scenario (Number of turbines, site)	Layout	WindCrete	Mooring	O&M	Control
1A (4WT, WB)	1.9%	0.0%	0.0%	15.6%	0.0%
2A (20WT, WB)	1.6%	0.0%	0.0%	13.8%	3.7%
3A (80WT, WB)	1.0%	0.0%	0.0%	13.6%	3.7%
4A (4WT, GC)	13.2%	0.0%	0.9%	2.5%	0.0%
4W (4WT, GC)	4.2%	0.9%	0.7%	2.8%	0.0%
5A (20WT, GC)	14.5%	0.0%	1.4%	2.1%	3.6%
5W (20WT, GC)	4.8%	0.9%	0.9%	2.5%	3.1%
7A (4WT, MB)	2.2%	0.0%	0.0%	6.4%	0.0%
7W (4WT, MB)	2.7%	0.8%	0.1%	6.8%	0.0%
8A (20WT, MB)	2.1%	0.0%	0.0%	5.6%	3.7%
8W (20WT, MB)	2.1%	0.8%	0.1%	5.8%	3.4%
9A (80WT, MB)	2.3%	0.0%	0.0%	5.6%	3.7%
9W (80WT, MB)	2.7%	0.8%	0.1%	5.8%	3.4%

The joint effect on the LCOE of all the innovations and optimisations can be observed in Table 6-6. While the baseline LCOE was relatively good, ranging 61 to 133 €/MWh, the optimised scenarios lay between 54 €/MWh and 122 €/MWh, thanks to an LCOE reduction of 8% to 20%.

Table 6-6. LCOE improvement achieved for all the analysed reference scenarios.

Reference scenario	Baseline LCOE [€/MWh]	Optimised LCOE [€/MWh]	LCOE reduction
1A	99.5	82.3	17%
2A	93.5	76.4	18%
3A	95.3	78.5	18%
4A	79.6	66.8	16%
4W	61.1	56.1	8%
5A	80.2	63.8	20%
5W	60.8	53.8	12%
7A	133.0	121.8	8%
7W	124.8	112.3	10%
8A	119.0	105.9	11%
8W	112.2	99.1	12%
9A	122.1	108.3	11%
9W	115.1	100.9	12%

As it can be seen in the previous Table 6-6, there is great dispersion on the obtained LCOE values; Table 6-7 shows disaggregated values that help understanding the reasons. The lowest LCOE is achieved in Gran Canaria, where strong winds and moderate seas lead to high-capacity factors and relatively low initial investments, and no offshore substations are needed because the offshore site is close to shore (8 km).

Table 6-7. Main LCOE parameters in the optimised scenarios.

Reference scenario	Site	Capacity [MW]	CAPEX [M€/MW]	OPEX [M€/MW]	DECEX [M€/MW]	Capacity factor
1A	**West of Barra**	**60**	3.83	1.65	0.80	68.3%
2A		**300**	3.76	1.75	0.65	68.8%
3A		**1200**	3.78	1.70	0.64	67.0%
4A	**Gran Canaria**	**60**	3.16	1.78	0.79	72.4%
4W		**60**	2.63	1.78	0.24	73.2%
5A		**300**	3.13	1.90	0.64	71.0%
5W		**300**	2.58	1.90	0.14	71.5%
7A	**Morro Bay**	**60**	3.73	1.66	0.78	45.1%
7W		**60**	3.43	1.66	0.37	45.2%
8A		**300**	3.60	1.76	0.66	47.7%
8W		**300**	3.34	1.76	0.25	47.6%
9A		**1200**	3.52	1.72	0.61	45.6%
9W		**1200**	3.26	1.71	0.22	45.6%

West of Barra presents intermediate LCOE values because the distance between the site and the onshore substation is greater (around 40 km), and the substructures are bigger to withstand extreme sea conditions; on the other hand, strong winds allow a high-capacity factor despite the increased cable losses.

Morro Bay site presents the lower LCOE because it is located around 50 km off the coast, the winds are weaker, and the water depth is greater than in any other site. It can also be observed that WindCrete scenarios benefit from the extended lifespan of the substructures, leading to a significant reduction on the DECEX. Finally, it can also be seen that in Gran Canaria WindCrete has a lower CAPEX, mainly due to a cheaper mooring system, but only ActiveFloat's meet FLS.

The fact that WindCrete station keeping system does not meet FLS restricts the comparison between the platforms. Figure 6-3 shows the variation of the LCOE depending on the wind farm capacity grouped (averaged) by site. It can be observed that increasing the capacity from 60 to 300 MW leads to significant cost reductions, mainly due to economies of scale and relatively lower mobilisation costs. However, such effects are not enough to further reduce the LCOE for the largest scenarios, where the wake effects are greater and the restrictions of distance to shore push the wind farms out at sea.

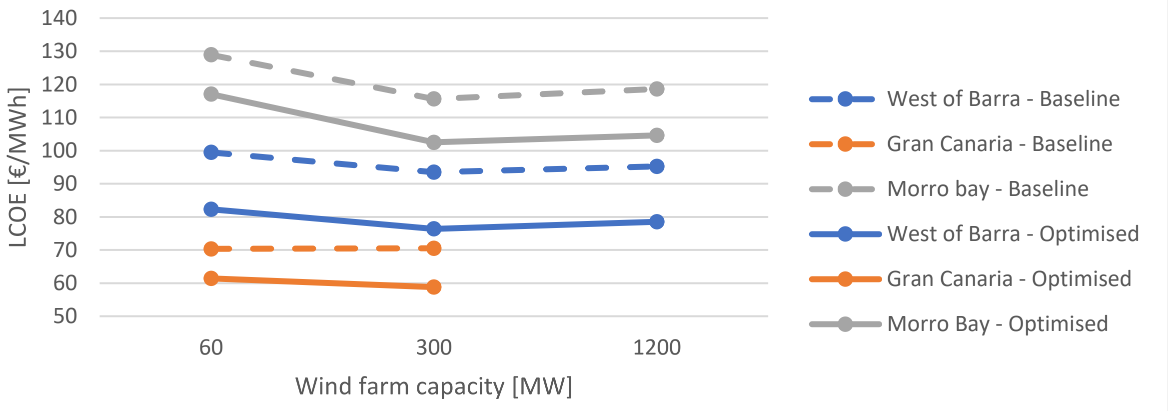

Figure 6-3. Variation of the LCOE with the wind farm capacity.

6.3 Life-cycle assessment

The model that generated the initial LCA results calculated in D6.2 [1] have also been updated to include the refinements described in chapter 4, defining the new baseline. Such baseline is then compared against the scenarios including all the optimisations. It must be remarked that the goal of the optimisations was reducing the LCOE but, as it will be shown, that also has a positive impact on the environmental impact of the windfarms.

6.3.1 Updated baseline

The overall environmental impacts on the main indicators after the model's refinement are shown in Table 6-8 the following table. It can be observed that the energy payback time is only around a 5% of the projects' lifetime. Analysing the overall life cycle impacts, it can be seen a warming potential between 9 and 16 kg CO_2 eq./MWh which is a positive result even before applying the optimisations. The highest impacts are associated to Morro Bay site, given the highest length of both the array and export cables. Conversely, Gran Canaria site presents the lowest impacts, although the long and heavy mooring lines of ActiveFloat lead to higher impacts.

Table 6-8. Overall LCA results of the updated baseline.

Reference scenario	EPBT [years]	EROI	GWP [kg CO_2 eq/MWh]	PED [MJ/MWh]	AP [kg SO_2 eq/MWh]	ATP [CTUe/MWh]
1A	1.41	17.8	13.76	203	0.0522	0.185
2A	1.38	18.1	13.62	199	0.0510	0.185
3A	1.42	17.6	14.06	205	0.0524	0.190
4A	1.28	19.5	12.59	185	0.0433	0.171
4W	0.92	27.1	9.29	133	0.0314	0.164
5A	1.35	18.5	13.27	195	0.0457	0.176
5W	0.96	26.0	9.68	138	0.0324	0.170
7A	1.59	15.7	15.42	229	0.0610	0.270
7W	1.65	15.1	16.40	238	0.0571	0.275
8A	1.44	17.3	14.15	208	0.0556	0.255
8W	1.50	16.6	15.10	217	0.0520	0.260
9A	1.51	16.6	14.81	217	0.0581	0.268
9W	1.57	15.9	15.80	226	0.0543	0.273

Table 6-9 includes the updated global warming potential by life cycle stages as a main metric. In all scenarios the manufacturing stage represents the highest impacts because of the effect of extracting, transporting and processing the materials for all the windfarm components. However, it can be seen significant differences between scenarios due to the different quantities needed, mainly driven by the distance to shore, water depth and extreme wind-wave conditions (as the substructures and mooring lines are designed based on these). Lower impacts are seen during phases of transport, installation, maintenance and decommissioning as these are only consequence of the fuel burnt by the required vessels to conduct such operations. In these stages, the distance between the offshore site and the ports, shipyards and dismantling areas are relevant. Finally, during the end-of-life stage it can be seen a bonus on the carbon footprint. Such values are mainly caused by the materials being partially recycled, having a significant weight on the overall results.

Table 6-9. Detailed GWP of the updated baseline [kg CO_2 eq/MWh].

Reference scenario	Manufacturing	Transport & installation	Maintenance	Decommissioning	End of life
1A	12.67	2.58	1.58	0.83	-3.90
2A	12.26	2.67	1.56	0.88	-3.75
3A	12.60	2.77	1.64	0.91	-3.86
4A	10.48	1.72	1.33	2.38	-3.32
4W	6.75	1.24	1.33	1.57	-1.60
5A	11.23	1.80	1.37	2.49	-3.61
5W	7.08	1.31	1.36	1.62	-1.70
7A	12.35	1.94	2.53	1.66	-3.06
7W	11.05	2.40	2.52	2.83	-2.40
8A	11.03	1.85	2.38	1.53	-2.63
8W	9.79	2.31	2.37	2.64	-2.01

9A	11.53	1.93	2.55	1.55	-2.75
9W	10.24	2.40	2.54	2.72	-2.10

6.3.2 Analysis including optimisations

Applying the innovations and optimisations leaded to an average decrease of 5% in the EPBT and an average increase of 18% in the EROI as shown in Table 6-10. In some cases, the EPBT slightly increased; this effect occurred in windfarms where the optimisations did not compensate the increased PED due to the extended lifetime. On the other hand, the EROI benefitted from this extension and increased in all scenarios.

Table 6-10. Optimised EPBT and EROI including variation vs. baseline.

Reference scenario	EPBT [years] (relative percentage variation)	EROI [adim] (relative percentage variation)
1A	1.35 (-3.9%)	18.5 (+4.1%)
2A	1.36 (-1.5%)	22.1 (+21.8%)
3A	1.40 (-1.3%)	21.4 (+21.6%)
4A	1.13 (-12.0%)	22.1 (+13.6%)
4W	0.82 (-11.3%)	30.6 (+12.7%)
5A	1.22 (-10.1%)	24.6 (+33.5%)
5W	0.89 (-7.2%)	33.6 (+29.3%)
7A	1.56 (-2.2%)	16.1 (+2.2%)
7W	1.51 (-8.5%)	16.5 (+9.3%)
8A	1.46 (+1.5%)	20.5 (+18.3%)
8W	1.45 (-3.9%)	20.7 (+24.8%)
9A	1.52 (+0.6%)	19.8 (+19.2%)
9W	1.49 (-4.9%)	20.1 (+26.2%)
Average	**1.32 (-5.0%)**	**22.0 (+18.2%)**

As an average, all environmental impact metrics were reduced compared to the baseline scenarios as shown in Table 6-11. While GWP, PED and AP were reduced a 15%, ATP decreased an 11%. All averages reflect a positive effect of the LCOE optimisations as they also reduced the environmental impacts of the studied windfarms. Finally, analysing Table 6-12 it can be seen that the greatest GWP reductions are achieved due to lower materials supply and increased lifetime.

Table 6-11. Optimised overall environmental impacts including variation percentage with respect to the baseline.

Reference scenario	GWP [kg CO_2 eq/MWh]	PED [MJ/MWh]	AP [kg SO_2 eq/MWh]	ATP [CTUe/MWh]
1A	13.2 (-3.7%)	195 (-3.9%)	0.0502 (-3.9%)	0.180 (-2.7%)
2A	11.2 (-17.8%)	163 (-17.9%)	0.0421 (-17.4%)	0.150 (-18.8%)
3A	11.6 (-17.7%)	168 (-17.7%)	0.0434 (-17.1%)	0.154 (-18.9%)
4A	11.2 (-10.7%)	163 (-12.0%)	0.0370 (-14.6%)	0.172 (+0.6%)
4W	8.1 (-12.9%)	118 (-11.3%)	0.0272 (-13.4%)	0.164 (-0.3%)
5A	10.1 (-23.9%)	146 (-25.1%)	0.0331 (-27.6%)	0.147 (-16.5%)

5W	7.4 (-23.6%)	107 (-22.7%)	0.0243 (-25.0%)	0.141 (-16.8%)
7A	15.1 (-2.1%)	224 (-2.2%)	0.0597 (-2.1%)	0.265 (-1.8%)
7W	14.6 (-10.7%)	218 (-8.5%)	0.0519 (-9.1%)	0.269 (-2.0%)
8A	12.0 (-15.3%)	176 (-15.4%)	0.0475 (-14.7%)	0.210 (-17.6%)
8W	11.9 (-21.4%)	174 (-19.9%)	0.0419 (-19.3%)	0.215 (-17.4%)
9A	12.4 (-16.0%)	182 (-16.1%)	0.0493 (-15.2%)	0.219 (-18.2%)
9W	12.3 (-22.3%)	179 (-20.8%)	0.0434 (-20.0%)	0.223 (-18.1%)
Average	**11.6 (-15.2%)**	**170 (-14.9%)**	**0.0424 (-15.3%)**	**0.193 (-11.4%)**

Table 6-12. Optimised carbon footprint [kg CO_2 eq./MWh] by life cycle stage including variation percentage with respect to the baseline.

Reference scenario	Manufacturing	Transport & installation	Maintenance	Decommissioning	End of life
1A	12.11 (-4.5%)	2.51 (-2.8%)	1.53 (-2.7%)	0.81 (-3.1%)	-3.71 (-4.9%)
2A	9.75 (-20.5%)	2.16 (-19.3%)	1.55 (-0.7%)	0.71 (-19.2%)	-2.97 (-20.8%)
3A	10.11 (-19.8%)	2.23 (-19.4%)	1.59 (-3.2%)	0.74 (-19.4%)	-3.09 (-19.9%)
4A	7.89 (-24.7%)	1.74 (+1.2%)	1.35 (+1.3%)	2.41 (+1.2%)	-2.15 (-35.4%)
4W	6.01 (-11.0%)	1.24 (+0.0%)	1.33 (+0.1%)	1.57 (+0.0%)	-2.06 (+28.9%)
5A	7.03 (-37.4%)	1.50 (-16.7%)	1.47 (+7.5%)	2.08 (-16.7%)	-1.97 (-45.5%)
5W	5.21 (-26.4%)	1.08 (-17.3%)	1.46 (+6.8%)	1.34 (-17.3%)	-1.70 (-0.0%)
7A	12.07 (-2.3%)	1.90 (-2.0%)	2.49 (-1.8%)	1.62 (-2.0%)	-2.98 (-2.5%)
7W	10.75 (-2.7%)	2.36 (-1.8%)	2.48 (-1.7%)	2.78 (-1.8%)	-3.73 (+55.1%)
8A	8.98 (-18.6%)	1.51 (-18.2%)	2.39 (+0.5%)	1.25 (-18.2%)	-2.14 (-18.8%)
8W	7.98 (-18.5%)	1.90 (-17.8%)	2.39 (+1.1%)	2.17 (-17.8%)	-2.59 (+28.6%)
9A	9.35 (-18.9%)	1.57 (-18.7%)	2.49 (-2.4%)	1.26 (-18.7%)	-2.23 (-19.0%)
9W	8.29 (-19.0%)	1.96 (-18.4%)	2.49 (-2.0%)	2.22 (-18.4%)	-2.69 (+28.1%)
Average	**8.89 (-17.2%)**	**1.82 (-11.6%)**	**1.92 (+0.2%)**	**1.61 (-11.6%)**	**-2.61 (-2.0%)**

7 Experimental testing design verifications

Within the framework of WP5, a fully coupled experimental test program has been conducted. Deliverable D5.3, [16], summarizes the results obtained from them. Apart from creating a benchmarking database which will be the base of the numerical modelling strategy, this test program aims to verify the designs conducted and contribute to set future engineering process towards optimised floating designs.

The physical experiments were focused on the seakeeping of WINDCRETE and ACTIVEFLOAT floating concepts under different environmental conditions, including waves, current and wind actions. The test program has been conducted at the CCOB (Cantabria Coastal and Ocean Basin) a Singular Techno-Scientific Facility (ICTS) from the Ministry of Science and Innovation and managed by FIHAC.

Considering the dimensions of the basin, as well as the wave generator capabilities, the selected test scales are 1:55 for the WINDCRETE platform and 1:40 for the ACTIVEFLOAT one. Hence, physical experiments are conducted at 165 meters of water depth in WINDCRETE case and at 120 m in ACTIVEFLOAT case (3 m at model scale).

The test program evaluated the dynamic performance of both technologies, with separate test plans for each platform. The physical experiments were grouped into (1) Dry Characterization tests, (2) Wet Characterization tests, (3) Installation tests, (4) Wave tests, (5) Current tests, (6) Wind tests, and (7) Coupled tests (Wave + Current + Wind). Over 120 tests were conducted following DNV recommendations.

WP1 defined acceptance criteria to measure the design quality based on industry requirements. The acceptance criteria proposed by WP1 summarized in [17]. WP2 focused on designing an innovative mooring system that included a set of requirements that needed to be fulfilled by the concept. The main design parameter (minimum breaking load – MBL) for both concepts for the specific site of Gran Canaria are published in D2.2, [5] and summarised in D5.3, [16].

Based on the lab results and WP1 acceptance criteria, the following conclusions were drawn regarding CAPEX, OPEX, and LCOE perspectives.

WINDCRETE

- The maximums acceleration observed are below the limits given by the acceptance criteria. The maximum acceleration took place during a severe sea state at rated speed. Because of that, the design is expected to provide satisfactory dynamic conditions for both, severe and operating conditions of the RNA. Therefore, the LCOE might not be affected by unexpected shutdowns because high acceleration rates. Moreover, tilts are limited too, therefore dynamic of the platform seems to be aligned with the expected design values.
- From the mooring point of view, the maximum loads have been observed on line 1. However, it is important to notice that the maximum load was below the design tension Td for mooring systems. Therefore, the results observed are aligned with the design.
- From the OPEX point of view, a set of low energetic tests have been conducted. Those tests were focused on the characterization of the dynamic performance of the concept for O&M conditions, which are limited by the accessibility criteria of Hs<3m as reference value from the industry. In those cases (Hs=2.75m and Tp= [9 - 14]), both motions and accelerations were significantly limited. First, pitch and roll showed values below 0.1°; while yaw angles where below 0.1° as well. Moreover, at the nacelle, the displacements where limited as well with motions below 2 m in all the cases and the maximum acceleration experienced was 0.8m/s2. Therefore, the O&M seems to be not influenced by the dynamics of the platform. Moreover, the limited acceleration observed shows a limited impact over the expected workability.

ACTIVEFLOAT

- There is no maximum acceleration at the Nacelle over 2.94 m/s^2 in surge in all the analysed cases. Therefore, the maximums acceleration observed are below the limits given by the acceptance criteria. Again, the maximum acceleration observed took place during a severe sea state at rated speed. Because of that, the design is expected to provide satisfactory dynamics conditions for both, severe and operating conditions RNA. Therefore, similar conclusions can be achieved like in the case of WINDCRETE. Therefore, the LCOE seems to not be affected by unexpected shutdowns because high acceleration rates. Moreover, the accelerations and tilts are limited too, therefore dynamic of the platform seems to be aligned with the expected values.
- Like in the case of WINDCRETE, it is important to notice that the maximum load was below the design tension Td for mooring systems. Therefore, the results observed are aligned with the design.
- From the OPEX point of view, a set of low energetic tests have been conducted like in the case of WINDCRETE focused on the characterization of the dynamic performance of the concept for O&M conditions (Hs=2.75m and Tp= [9 - 14]). In those cases, both, motions and accelerations, were significantly limited. First, pitch and roll showed values below 0.1°; while yaw angles where below 0.1° as well. Moreover, at the nacelle, the displacements where limited as well with motions below 4 m in

all the cases and the maximum acceleration experienced was 0.4 m/s2. Therefore, the O&M seems to be not influenced by the dynamics of the platform. Moreover, the limited acceleration observed shows a limited impact over the expected workability.

From the results obtained from the laboratory experiments, in general terms it can be concluded that they are aligned with the expected design values. Therefore, there is no expected impact over CAPEX, OPEX or LCOE based on the laboratory observations.

8 LCOE projections in standardised / industrialised cases

Floating offshore wind is a novel technology with specific challenges. That is why it is difficult to transfer experiences from onshore wind and bottom-fixed offshore wind. Published market projections on cost reductions for floating offshore wind show that learning rates from other technologies can only be roughly estimated for a few aspects.

Moving from single prototype design to serial production requires standardization in designs, optimised manufacturing and assembly concepts and technologies, optimised floating offshore supply-chain and modularization. This will lead to improvements resulting in lower CAPEX:

- Optimised integrated designs.
- Increasing size of wind turbine components and better performance under varying wind conditions lead to higher capacity factors.
- Material research to reduce relative weight and consequently the costs of components.
- Realization of commercial-scale floating offshore windfarm projects.

Furthermore, increasing experience in the installation and operation of FOWT will lead to optimised concepts for wind farm control for FOWT and optimised concepts and procedures for O&M.

According to [18]:

- Most cost savings for offshore wind will be from ‘other fixed cost’ (non-turbine material costs, as well as labour, overhead and tax costs) and O&M cost, as experience of installing and operating offshore wind turbines builds up.
- Best estimate for learning rate for wind turbines is 16% for every doubling of cumulative additions.
- 30% learning rates for O&M costs of offshore wind farms.
- For ‘other fixed costs’, learning rates of 11% are expected for floating offshore wind.
- Raising these learning rates by 50% raises wind output by 11%, while halving the rates reduces output by around 11%.

The costs of any technology generally decrease as it advances from a novel technology to an established technology. Typically, the cost reductions are greater at the beginning, being less relevant once the technology is mature. Figure 8-1 shows a qualitative curve of the technology costs reflecting this trend. As floating offshore wind is a nascent technology where the largest pilots only include few turbines, large cost savings are expected in the coming years.

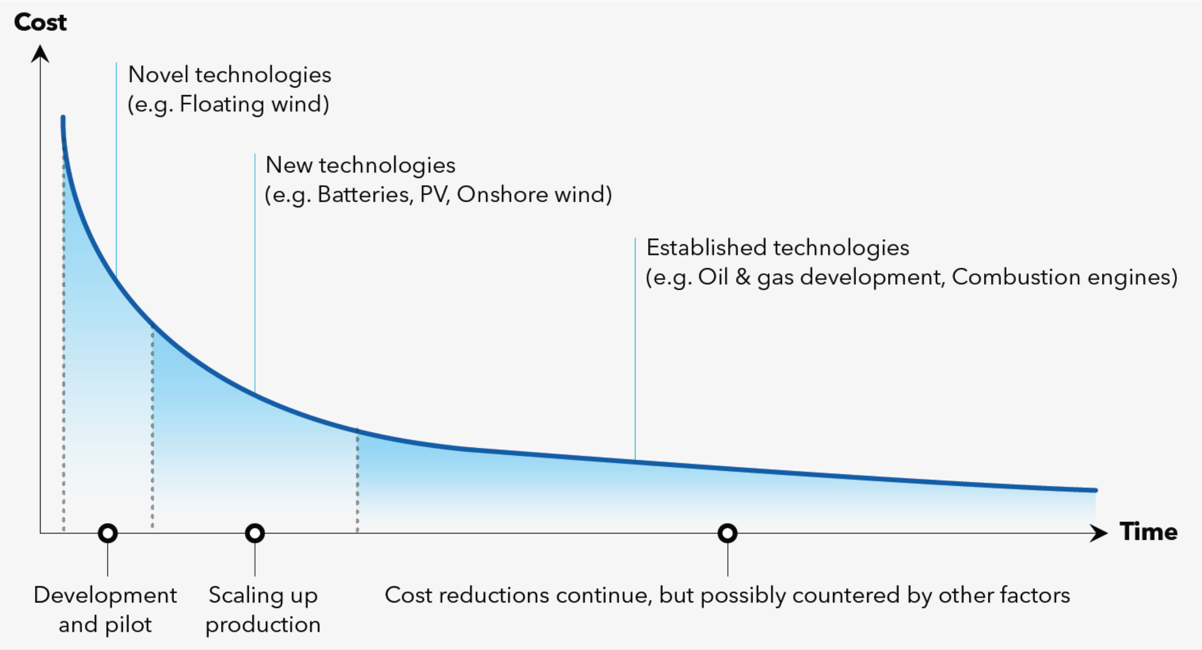

Figure 8-1. Evolution of the costs of technology, [18].

Figure 8-2 shows the expected evolution of the LCOE of floating offshore wind according to different sources (it must be noted that DNV and ETIP predictions are overlapped in 2050) and an exponential trendline obtained minimizing sum of squares. Although the sources do not completely match, the trend is clear, aiming at 40-50 €/MWh by 2050.

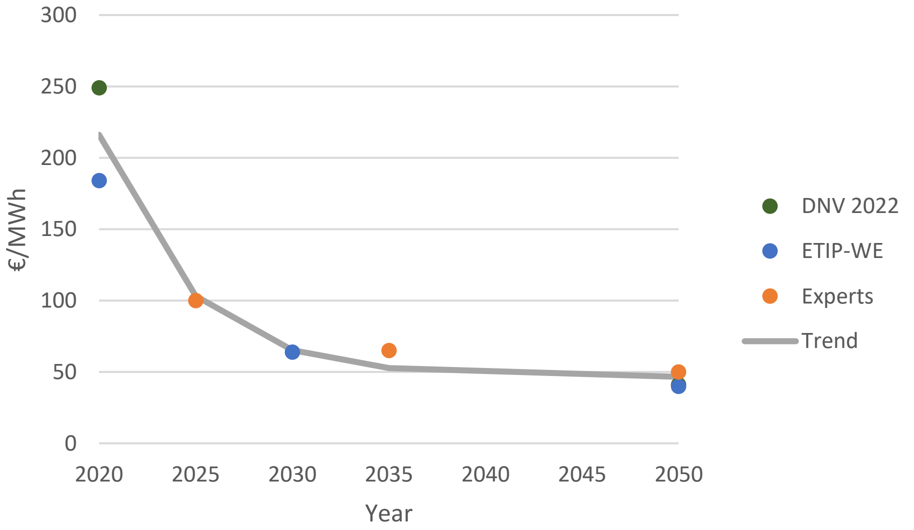

Figure 8-2. Expected floating offshore wind LCOE learning curves [19], [20], [21], and estimated trend.

The scenarios studied in this report are not currently feasible, as there are some technologies involved that need validation before being commercially available, such as floating substations or 15 MW turbines. All the involved technology could be available in the coming years. Assuming that the optimised windfarms could be installed by 2027, according to the calculated trendline, the expected LCOE reductions on the different sites studied are shown in the following figure.

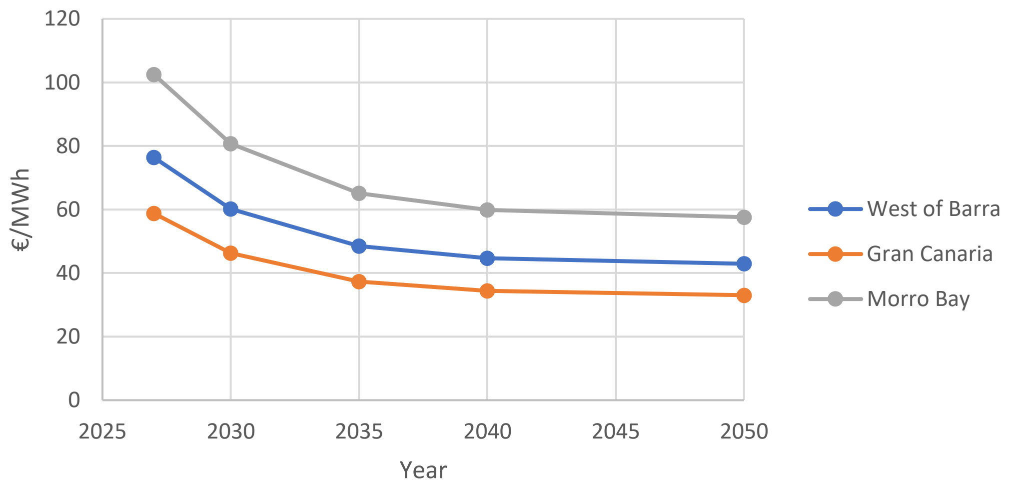

Figure 8-3. Estimated LCOE evolution of the optimised scenarios.

9 Conclusions

The COREWIND project had a primary objective of reducing the LCOE and improving the LCA of floating offshore wind installations. Specifically, the aim was to achieve a 15% reduction in LCOE for floating wind compared to the 2014 LCOE of €127/MWh for bottom-fixed installations [2]. To accomplish this, the project sought to attain an average LCOE of no more than €108/MWh for the floating wind scenarios, a goal that was successfully realized across all cases examined. This objective was accomplished through the identification of cost-effective solutions and the implementation of innovative research, modelling, and optimisation techniques for concrete-based floating substructure concepts.

Various solutions that impact both the LCOE and environmental LCA were examined throughout the entire value chain of a wind farm, focusing on three reference sites and two types of concrete floaters (semi-submersible and spar). These solutions encompassed aspects such as floater design, innovative station-keeping system and power cable designs, updated wind farm layouts and controls, optimised O&M strategies, and innovative maintenance approaches.

To evaluate the LCOE and LCA outcomes, an upgraded tool called FowApp was developed as part of this project. It facilitated the calculation of results for distinct concrete-based floating substructure scenarios, different met-ocean conditions, and various locations. The outcomes are presented using eight KPIs. The KPIs related to the LCOE include CAPEX, OPEX, DECEX and AEP. The KPIs used to describe the environmental performance include GWP, PED, EPBT and ROI.

For each reference sites, a baseline scenario was calculated and compared to an optimised scenario that included the explored cost reduction opportunities, updates, and optimisations, while considering economies of scale.

Based on the above information, the primary conclusions and outcomes of the project can be summarized as follows:

1- The average LCOE for the reference scenarios investigated was €99.7/MWh, which was reduced to €86.6/MWh through optimisation. The costs are expressed in relation to 2022.
2- The layout optimisation had a major effect on the optimised LCOE reducing it in average by 4.25% for all reference scenarios.
3- The O&M strategy optimisation allowed an average reduction on the OPEX of the different wind farm scenarios of 35.04% which resulted in an average LCOE reduction of 6.84%.
4- The improvements on CAPEX and DECEX had a high influence on the LCOE with an average reduction of 4.6 % and 23.9% respectively.
5- Through the optimisation of the LCOE, notable reductions in environmental impacts were achieved, resulting in all scenarios being below 20 gCO2 eq./kWh (with an average of 11 gCO2 eq./kWh). This outcome surpasses the initial project proposal's targets, making it an exceptional achievement.
6- The EPBT was reduced in average from 1.38 years to 1.32 years and the EROI was increased from 18.6 to 22.0, which equals to an improvement of 5.0% and 18.2% for both parameters respectively.
7- The COREWIND project facilitated the successful development of various tools, including the FowApp, which enables robust, practical, and comprehensive analyses of LCOE and LCA. Additionally, an O&M cost model was created to compare and optimize maintenance strategies specifically for floating offshore wind. Furthermore, a mooring design optimisation tool was developed to automate mooring design and optimize procurement costs.

The results from Task 6.3 allow to say COREWIND comes forward with the low-cost scenario expected by LCOE projections in 2025, which reflects what might be possible with greatly enhanced research, development and innovation. The study outcomes allow us to envision a reduction of LCOE up to €72/MWh in 2035, positioning COREWIND as a key project that paves the way for boosting concrete-based floating wind technology.

However, there are several additional areas that warrant further research in order to advance sustainable offshore floating technology. These areas include:

1- Development of advanced blade materials and composites to improve strength, durability and flexibility, allowing light and robust blades with longer lifetime in harsh marine environment, reducing maintenance costs, being recyclable and possibly reusable.
2- Enhancement of turbine designs to improve efficiency and lower costs.
3- Integration of advanced sensors, data analytics, and remote communication systems to allow real-time monitoring and condition assessment the wind farm, above and below water, in order to optimize maintenance schedules and minimizing downtime.
4- Exploration of innovative installation techniques that can minimize costs and minimize environmental impact, such as pre-assembly of floating foundations and turbines, which could potentially reduce installation costs by up to 50%.
5- Analyse technical, statistical, organizational or market factors to establish the main parameters that influence the economies of scale of floating wind farms.
6- Advancing and optimising fuel alternatives for maintenance vessels to reduce the environmental impact and increase the sustainability of these vessels, e.g., biofuels derived from renewable sources, hydrogen fuel cells, and electrification through battery-powered or hybrid systems.
7- Increase the lifespan of all windfarm components, including the subsea cables, to further reduce both the LCOE and the environmental impact.

This report is part of Task 6.3 and reflects the work conducted during the final phase of the COREWIND project, aimed at achieving the objectives outlined in WP6. These objectives are in alignment with the technical work packages WP2 to WP5.

Acknowledgement

OWC have contributed to this work in order to achieve realistic results based on valid methods and assumptions related to the transmission system.

Special thanks to Daniele Caruso, Mariangela Sfouni and James Davidson.

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ANNEXE A: Classical station keeping system layout

Table A- 1: ActiveFloat West of Barra – Mooring system composition – 12 lines catenary.

Component	Material	Quantity[unit]	Mass [unit]
Chain 125mm R5	Steel	3153 [m]	310.94 [kg/m]
Nylon Superline 240mm	Nylon	1407 [m]	32.5 [kg/m]
Clump weight type1	Steel	24 [-]	2.5 [t]
Clump weight type2	Steel	24 [-]	6.0 [t]
Clump weight type3	Steel	186 [-]	12.0 [t]
Shackles 142mm R4S	Steel	48 [-]	1.055 [t]

Table A- 2: ActiveFloat Gran Canaria – Mooring system composition – 9 lines catenary.

Component	Material	Quantity[unit]	Mass [unit]
Chain 150mm R4S	Steel	1842 [m]	447.8 [kg/m]
Chain 120mm R4	Steel	3684 [m]	286.6 [kg/m]
Shackles 142mm R4	Steel	6 [-]	1.3 [t]
Shackles 132mm R4	Steel	12 [-]	0.675 [t]

Table A- 3: ActiveFloat Morro Bay– Mooring system composition – 3 lines semi-taut.

Component	Material	Quantity[unit]	Mass [unit]
Chain 140mm R4S	Steel	250 [m]	390.0 [kg/m]
Chain 130mm R4S	Steel	500 [m]	336.0 [kg/m]
Polyester 147mm 855TN	Polyester	3000 [m]	14.9 [kg/m]
Shackles 137mm ORQ	Steel	4 [-]	0.75 [t]
Shackles 142mm R4	Steel	8 [-]	1.055 [t]

Table A- 4: WindCrete Gran Canaria– Mooring system composition – 3 lines catenary.

Component	Material	Quantity[unit]	Mass [unit]
Chain 111mm R4S	Steel	700 [m]	245.2 [kg/m]
Chain 111mm R3	Steel	300 [m]	245.2 [kg/m]
Chain 100mm R3S	Steel	1500 [m]	199.0 [kg/m]
Shackles 114mm R4S	Steel	2 [-]	0.475 [t]
Shackles 100mm R4S	Steel	6 [-]	0.321 [t]
Shackles 92mm R4S	Steel	4 [-]	0.284 [t]

Table A- 5: WindCrete Morro Bay– Mooring system composition – 4 lines semi-taut.

Component	Material	Quantity [unit]	Mass [unit]
Chain 102mm R4S	Steel	195 [m]	207.0 [kg/m]
Chain 95mm R4	Steel	540 [m]	179.6 [kg/m]
Chain 90mm R4	Steel	400 [m]	161.2 [kg/m]
Polyester 193mm 855TN	Polyester	1105 [m]	25.4 [kg/m]
Polyester 205mm 855TN	Polyester	3060 [m]	28.6 [kg/m]
Shackles 110mm R4S	Steel	4 [-]	0.431 [t]
Shackles 96mm R4S	Steel	12 [-]	0.284 [t]
Shackles 92mm R4S	Steel	16 [-]	0.258 [t]

ANNEXE B: Cost-optimised station keeping system: Use of peak load reduction system

Table B- 1: ActiveFloat West of Barra – Mooring system composition – 12 lines catenary + System1.

Component	Material	Quantity[unit]	Mass [unit]
Chain 114mm R4	Steel	1335 [m]	258.62 [kg/m]
Chain 100mm R4S	Steel	1518 [m]	199.00 [kg/m]
Nylon Superline 240mm	Nylon	1407 [m]	32.5 [kg/m]
Clump weight type1	Steel	24 [-]	2.5 [t]
Clump weight type2	Steel	24 [-]	6.0 [t]
Clump weight type3	Steel	186 [-]	12.0 [t]
Shackles 114mm R4	Steel	42 [-]	0.475 [t]
Shackles 110mm R4	Steel	42 [-]	0.431 [t]

Table B- 2: ActiveFloat Gran Canaria – Mooring system composition – 3 lines catenary + System1.

Component	Material	Quantity[unit]	Mass [unit]
Chain 90mm R4	Steel	950 [m]	161.2 [kg/m]
Chain 56mm R3	Steel	1800 [m]	62.4 [kg/m]
Shackles 90mm R4	Steel	4 [-]	0.243 [t]
Shackles 52mm R4	Steel	8 [-]	0.055 [t]

Table B- 3: ActiveFloat Morro Bay – Mooring system composition – 3 lines semi-taut + System1.

Component	Material	Quantity [unit]	Mass [unit]
Chain 130mm R3	Steel	192.5 [m]	336.3 [kg/m]
Chain 95mm R4	Steel	362.5 [m]	179.6 [kg/m]
Polyester 190mm 855TN	Polyester	787.4 [m]	24.7 [kg/m]
Polyester 155m 855TN	Polyester	1476.6 [m]	16.4 [kg/m]
Buoys type 1	Polyurethane foam	2	5.6 [t]
Buoys type 2	Polyurethane foam	9	11.2 [t]
Shackles 117mm R4	Steel	16 [-]	0.505 [t]
Shackles 96mm R4	Steel	28 [-]	0.284 [t]

Table B- 4: WindCrete Gran Canaria – Mooring system composition – 3 lines catenary + System1.

Component	Material	Quantity [unit]	Mass [unit]
Chain 88mm R3	Steel	750 [m]	154.1 [kg/m]
Chain 80mm R3	Steel	300 [m]	127.4 [kg/m]
Chain 78mm R3	Steel	1500 [m]	121.1 [kg/m]
Shackles 82mm R4	Steel	4 [-]	0.187 [t]
Shackles 70mm R4	Steel	8 [-]	0.125 [t]
Shackles 76mm R4	Steel	6 [-]	0.154 [t]

Table B- 5: WindCrete Morro Bay – Mooring system composition – 4 lines semi-taut + System1.

Component	Material	Quantity[unit]	Mass [unit]
Chain 106mm R3	Steel	745.5 [m]	223.6 [kg/m]
Chain 92mm R4	Steel	400.0 [m]	168.4 [kg/m]
Polyester 152mm 855TN	Polyester	1114.9 [m]	15.8 [kg/m]
Polyester 158m 855TN	Polyester	3152.7 [m]	17.1 [kg/m]
Shackles 96mm R4	Steel	22 [-]	0.284 [t]
Shackles 89mm R4	Steel	8 [-]	0.230 [t]

Table B- 6: ActiveFloat Gran Canaria – Mooring system composition – 3 lines catenary + System2.

Component	Material	Quantity[unit]	Mass [unit]
Chain 94mm R3S	Steel	950 [m]	175.8 [kg/m]
Chain 56mm R3	Steel	1800 [m]	62.4 [kg/m]
Shackles 90mm R4	Steel	4 [-]	0.243 [t]
Shackles 52mm R4	Steel	8 [-]	0.055 [t]

Table B- 7: ActiveFloat Morro Bay – Mooring system composition – 3 lines semi-taut + System2.

Component	Material	Quantity [unit]	Mass [unit]
Chain 135mm R3	Steel	200.0 [m]	362.7 [kg/m]
Chain 110mm R3	Steel	377.5 [m]	240.8 [kg/m]
Polyester 190mm 855TN	Polyester	835.0 [m]	24.7 [kg/m]
Polyester 155m 855TN	Polyester	1562.5 [m]	16.4 [kg/m]
Buoys type 1	Polyurethane foam	2	5.6 [t]
Buoys type 2	Polyurethane foam	9	11.2 [t]
Shackles 120mm R4	Steel	16 [-]	0.530 [t]
Shackles 98mm R4	Steel	28 [-]	0.301 [t]

Table B- 8: WindCrete Gran Canaria – Mooring system composition – 3 lines catenary + System2.

Component	Material	Quantity [unit]	Mass [unit]
Chain 100mm R3	Steel	670 [m]	199.0 [kg/m]
Chain 78mm R4	Steel	300 [m]	121.1 [kg/m]
Chain 72mm R4	Steel	1630 [m]	103.2 [kg/m]
Shackles 90mm R4	Steel	4 [-]	0.243 [t]
Shackles 76mm R4	Steel	8 [-]	0.154 [t]
Shackles 82mm R4	Steel	6 [-]	0.187 [t]

Table B- 9: WindCrete Morro Bay – Mooring system composition – 4 lines semi-taut + System2.

Component	Material	Quantity[unit]	Mass [unit]
Chain 100mm R3S	Steel	599.5 [m]	199.0 [kg/m]
Chain 100mm R3	Steel	562.5 [m]	199.0 [kg/m]
Polyester 165mm 855TN	Polyester	1138.5 [m]	18.7 [kg/m]
Polyester 155m 855TN	Polyester	3212.5 [m]	16.4 [kg/m]
Shackles 96mm R4	Steel	14 [-]	0.284 [t]
Shackles 90mm R4	Steel	16 [-]	0.243 [t]

ANNEXE C: Cost-optimised station keeping system: Shared mooring lines and Shared anchors

Table C- 1: ActiveFloat Gran Canaria – Mooring system composition – 3 FOWT – 9 lines catenary – Shared anchor.

Component	Material	Quantity[unit]	Mass [unit]
Chain 110mm R4	Steel	3825 [m]	240.8 [kg/m]
Chain 50mm R4S	Steel	5040 [m]	49.8 [kg/m]
Shackles 110mm R4S	Steel	2 [-]	0.431 [t]
Shackles 54mm R4S	Steel	4 [-]	0.057 [t]

Table C- 2: ActiveFloat Morro Bay – Mooring system composition – 3 FOWT – 9 lines semi-taut – Shared anchor.

Component	Material	Quantity[unit]	Mass [unit]
Chain 105mm R3S	Steel	825.0 [m]	219.4 [kg/m]
Chain 90mm R4	Steel	1197.3 [m]	161.2 [kg/m]
Polyester 169mm 855TN	Polyester	3825 [m]	19.5 [kg/m]
Polyester 146mm 855TN	Polyester	5085 [m]	14.7 [kg/m]
Buoys	Polyurethane foam	33 [-]	11.2 [t]
Shackles 110mm R4S	Steel	4 [-]	0.431 [t]
Shackles 90mm R4	Steel	8 [-]	0.243 [t]

Table C- 3: ActiveFloat Morro Bay – Mooring system composition – 3 FOWT – 10 lines semi-taut – Shared mooring lines.

Component	Material	Quantity[unit]	Mass [unit]
Chain 92mm R4S	Steel	40.0 [m]	168.4 [kg/m]
Chain 97mm R4S	Steel	752.0 [m]	187.2 [kg/m]
Chain 128mm R4	Steel	400.0 [m]	326.0 [kg/m]
Polyester 126mm 855TN	Polyester	3145 [m]	10.9 [kg/m]
Polyester 166mm 855TN	Polyester	3440 [m]	18.9 [kg/m]
Polyester 190mm 855TN	Polyester	2752 [m]	24.7 [kg/m]
Buoys type 1	Polyurethane foam	6 [-]	11.2 [t]
Buoys type 2	Polyurethane foam	1 [-]	5.6 [t]
Shackles 98mm R4S	Steel	8 [-]	0.301 [t]
Shackles 104mm R4S	Steel	16 [-]	0.400 [t]
Shackles 132mm R4S	Steel	8 [-]	0.675 [t]