LIFES50+

# Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m

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## Deliverable *2.8 Expected LCOE for floating wind turbines 10MW+ for 50m+ water depth*

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## Disclaimer

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## Abbreviations

| | |
|---|---|
| BOW | Bottom-fixed Offshore Wind |
| BOWF | Bottom-fixed Offshore Wind Farm |
| CAPEX | Capital Expenses |
| DECEX | Decommissioning Expenses |
| FC | Fixed Costs |
| FOW | Floating Offshore Wind |
| FOWF | Floating Offshore Wind Farm |
| FOWT | Floating Offshore Wind Turbine |
| LCC | Life Cycle Cost |
| LCOE | Levelized Cost of Energy |
| O&M | Operation and Maintenance |
| OPEX | Operation and Maintenance Expenses |
| TRL | Technology Readiness Level |
| VC | Variable Costs |
| WP | Work Package |

## Executive Summary

The levelized cost of energy (LCOE) calculation is a method used to obtain the cost of one unit energy produced and is typically applied to compare the cost competitiveness of different power generation technologies and concepts. The method has been used in the LIFES50+ project to evaluate economically the floating offshore wind turbine (FOWT) concepts. The objective of this document is to present the LCOE results that were obtained in the project and the potential cost reductions based on optimization and industrialization studies.

The document introduces with a review on LCOE values of FOWTs obtained in the literature and then presents the results of the phase 1 concept evaluation of the LIFES50+ project. Furthermore, a sensitivity analysis outlines the parameters that most influence the LCOE in order to highlight potential components for cost reductions. In phase 2 of the project, the 2 selected FOWT concepts have been optimized based on the performed experimental test campaigns and numerical modeling. An evaluation at the end of the phase has resulted in a mean LCOE reduction of the optimized concepts by about 2%. Besides a mean decrease in manufacturing cost, a significant reduction in transport and installation costs could be achieved.

The document reports further an outline on potential cost reductions through industrialization and quantifies the LCOE reduction that can be achieved by economies of scale in substructure unit costs. As the sensitivity analysis has highlighted the discount rate to be one of the most influencing parameters on the LCOE, its impact on the concept evaluation is assessed. It has been found that a 3% lower discount rate can achieve a LCOE reduction of about 18% to 20% depending on the offshore site studied.

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# 1 Introduction and objectives

The levelized cost of energy (LCOE) calculation is a method used to obtain the cost of one unit energy produced and is typically applied to compare the cost competitiveness of different power generation technologies. The method has been used in the LIFES50+ (www.lifes50plus.eu) project to evaluate economically the four floating offshore wind turbine (FOWT) concepts. The LCOE model sets in relation the life cycle cost (LCC) to the total energy provided as shown below [1].

$$\mathrm{LCOE} = \frac{\text{Life cycle cost}}{\text{Electrical energy provided}} = \frac{\mathrm{CAPEX}_0 + \sum_{\mathrm{t}=1}^{\mathrm{n}} \frac{\mathrm{OPEX}_{\mathrm{t}}}{(1+r)^t} + \frac{\mathrm{DECEX}_{\mathrm{n}}}{(1+r)^n}}{\sum_{\mathrm{t}=1}^{\mathrm{n}} \frac{\mathrm{E}_{\mathrm{t}} - \mathrm{L}_{\mathrm{t}}}{(1+r)^t}}$$

The LCC includes all costs occurring in the lifetime of a floating offshore wind farm (FOWF) such as the capital expense (CAPEX) for the initial investment in the power plant, the expenses during the operation and the maintenance phase ($\mathrm{OPEX}_t$) as well as the decommissioning expenses ($\mathrm{DECEX}_n$) at the end of lifetime. CAPEX includes the manufacturing, transportation and installation and the cost entailed at the beginning of a project life cycle before the plant starts to operate. The energy provided refers to the total energy generated ($E_t$) during the lifetime minus the energy losses ($L_t$) that occur in generation, collection and transmission of the energy [2]. Since the costs occur in different years (t) they have to be discounted to their present value with the discount rate (r). The LCOE methodology as well as the calculation of the LCCs and energy losses are described in detail in the deliverable D2.2 [3]. The objective of the present deliverable is to provide the LCOE values that have been obtained in the project for the FOWT concepts. The document is structured as follows. At first, a literature review on existing studies concerning the economic evaluation of FOWTs is presented. This serves to provide an understanding of the potential range of LCOE values that could be achieved and enables the comparison to the results obtained in the project. Section 3 presents the LCOE results that have been obtained during the phase 1 concept evaluation. Furthermore, the parameters are presented that possess the highest influence on the LCOE, which have been identified previously by a comprehensive sensitivity analysis. Section 4 describes the optimization of the FOWT concepts performed during phase 2 of the project and the updated LCOE values. Sections 5 to 7 outline the potential cost reductions that could be achieved by industrialization and economies of scale as well as decreased economic risk for commercial FOWFs. Finally, Section 8 concludes with the main findings of this deliverable.

# 2 LCOE literature review

FOWTs possess the potential to provide competitive LCOE values by having the ability to harness the best possible wind resources without depth constraints and using larger wind turbines to increase power generation [4]. Furthermore, the ability to mount the turbine on the floating substructure dockside and to tow the fully assembled structure by tug boats to the offshore site provides a significant potential for cost reduction along the life cycle, because expensive heavy lift jack-up vessels are avoided [5]. However, since only a few prototypes have been constructed so far, there is a lack of information on the LCOE of large scale FOWFs. Myhr et al. [6] have estimated the LCOE for a number of different FOWT concepts made of steel and supporting a 5MW wind turbine.

The findings have shown LCOE values ranging between 106€/MWh and 288€/MWh. Further research has been proposed to investigate possible cost reductions and to study the impact of different site conditions. Castro et al. [7] have developed in 2013 a methodology for the economic evaluation of FOWFs. The emphasis has been more on the modeling of the life cycle cost and less on the computation of the power generation and losses in the system. Ebenhoch et al. have calculated in 2015 the LCOE of a FOWF based on a 4MW Spar buoy concept and obtained a LCOE of about 176 €/MWh [8]. Figure 1 presents a range of LCOE values for FOWTs that were found in literature and a comparison is made to other types of energy generation technologies.

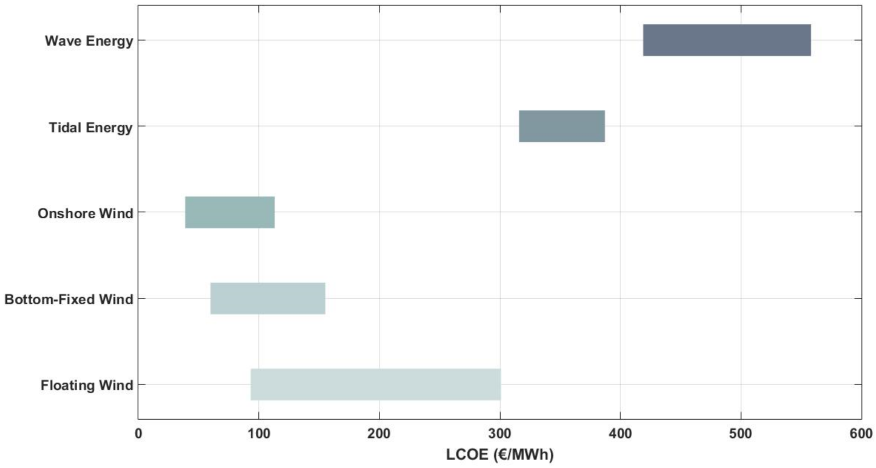

**Figure 1: LCOE comparison between energy generation technologies. Reference LCOE range for FOW is based on [6], for wave and tidal energy from [9], for BOW from [10] and for onshore wind from Duan [11].**

Figure 1 shows that floating offshore wind (FOW) can be a high competitive solution to conventional bottom-fixed offshore wind (BOW) and other marine technologies. However, in order to be competitive in the long-term, floating wind energy needs to follow the cost reduction pathways that onshore and BOW energy have already experienced. FOW can also benefit from economies of scale of the well-developed BOW sector since many components are shared by both technologies [4]. Moreover, to reduce the LCOE of FOW, concepts that have been proven in test campaigns and demonstration projects need to be developed further to commercial projects [12]. Figure 2 shows a forecast on how the LCOE of FOW could reduce in the upcoming years based on estimates of the expert survey performed in the IEA Wind Task 26 [13].

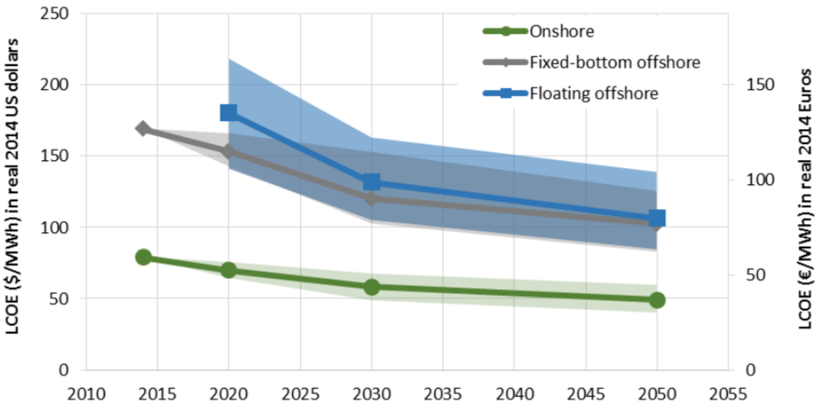

**Figure 2: IEA Wind Task 26 expert estimates of median-scenario LCOE for all three wind applications [13].**

# 3 LIFES 50+ previous results

## 3.1 Phase 1 concept evaluation

Phase 1 of the LIFES50+ project had the objective to develop and upscale 4 FOWT concepts able to carry large offshore wind turbines of 10MW rated capacity. At the end of phase 1, a multi-criteria assessment was performed in order to select 2 FOWT concepts for the second phase. The LCOE has been the economic criteria considered for the evaluation besides life cycle assessment and risk. The evaluation has been done considering an entire 500MW FOWF with 50 units of the DTU 10MW reference wind turbine. The evaluation has been performed for 3 sites with different met-ocean conditions. These are Golfe de Fos (moderate conditions), Gulf of Maine (medium conditions) and West of Barra (severe conditions). The environmental conditions of the sites are described in more detail in the deliverable D1.1 [14]. The evaluation procedure is explained in the deliverable D2.2 [3].

A comprehensive questionnaire was prepared to collect the cost data that is required to compute the LCOE. This includes detailed information concerning the manufacturing, transportation, installation, operation and maintenance as well as decommissioning of the FOWF. The concept designers were responsible to provide the cost data that concern the components of the FOWF that are influenced by their concept such as the substructure, tower, power cables and anchor & mooring system. A separate questionnaire was filled by the consortium to provide the information concerning the components that are common for all the designs. Figure 3 illustrates the components of the FOWF that are design specific and the ones that are common.

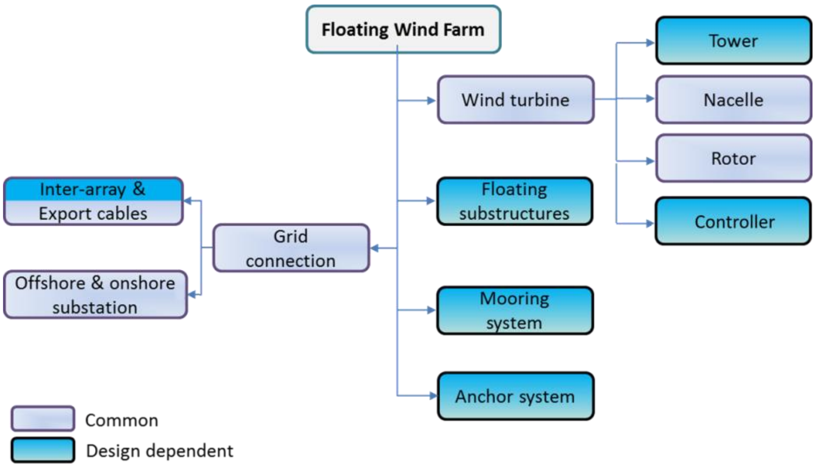

Figure 3: Design dependent and common components of a FOWF.

The questionnaires have been introduced in the evaluation tool FOWAT (Floating Offshore Wind Assessment Tool) to perform the calculations for the 4 concepts and the 3 offshore locations. The concepts were optimized for each site, meaning that each concept owner developed 3 designs and submitted 3 different questionnaires. The tool has been developed as part of the project and is described in the deliverable D2.2 [3].

In Figure 4, the LCOE results of phase 1 are presented as a range for the 3 offshore sites. The range is defined by the maximum, mean and minimum values obtained by the 4 FOWT concepts. The LCOE calculations have been made for a 500MW FOWF with a 25 years lifetime and considering a 10% discount rate.

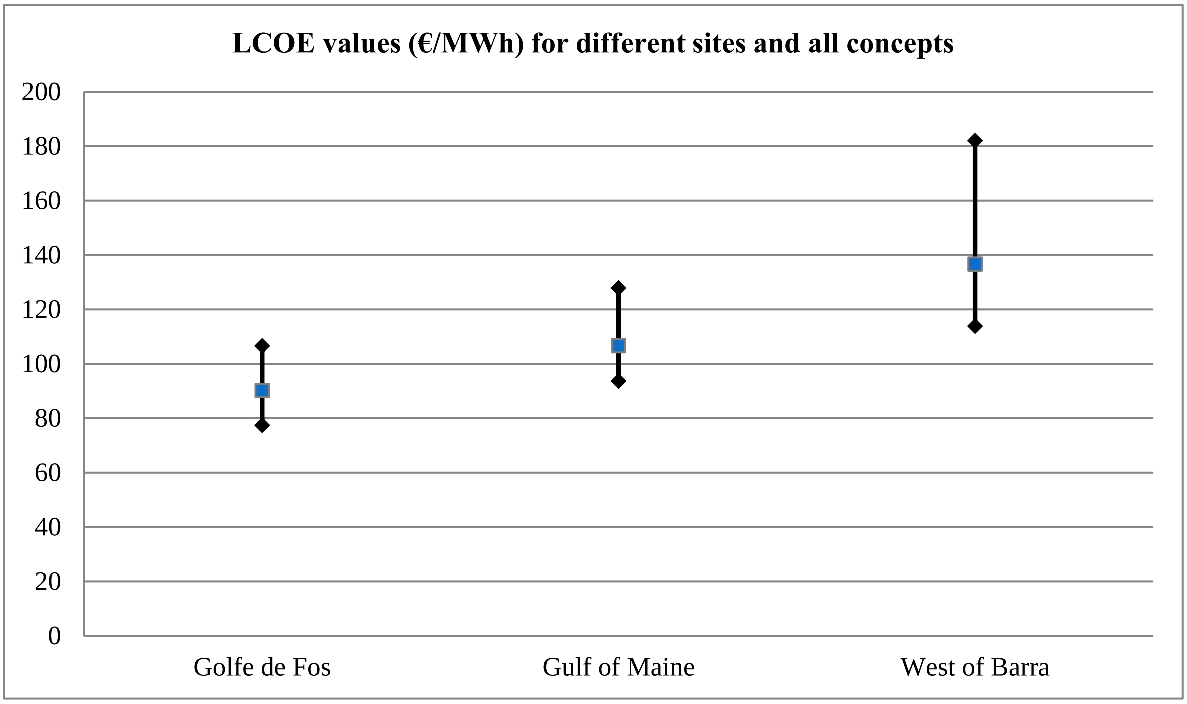

**Figure 4: LCOE values of phase 1.**

It can observed that the LCOE range for West of Barra (from 114€/MWh to 182€/MWh) is much higher than for Golfe de Fos (from 77€/MWh to 107€/MWh) and Gulf of Maine (from 94€/MWh to 128€/MWh). One of the contributors to the higher LCOE is the remote location of the site resulting in an increased distance to the onshore substation and the port. The larger distance requires a longer export cable (Golfe de Fos – 38km, Gulf of Maine – 57.8km and West of Barra – 180km), which results in higher energy losses for West of Barra and increases the cost of the cable. Furthermore, transport and installation tasks are affected, as well as operation and maintenance (O&M) and decommissioning. Also, West of Barra has harsher environmental conditions, which impacts the costs. For instance, due to severe met-ocean conditions the substructure has to be more robust. Besides that, reduced weather windows in West of Barra impact the installation and transportation activities and costs. Moreover, soil conditions in West of Barra are more challenging than in Golfe de Fos and Gulf of Maine since the seabed in West of Barra consists of rocks while at the other sites it is basically sand and mud. This may require a different anchor type and depending on the FOWT concept this can impact the manufacturing and especially the installation cost of anchor and mooring lines. The lowest LCOE values have been obtained for Golfe de Fos as it provides moderate met-ocean conditions combined with favourable soil conditions and the shortest distance to shore.

A breakdown of the LCCs for the 3 offshore sites is presented in Figure 5. The costs are derived from all concepts and are presented as a range consisting of the minimum and maximum values. The mean values are illustrated as a bar chart.

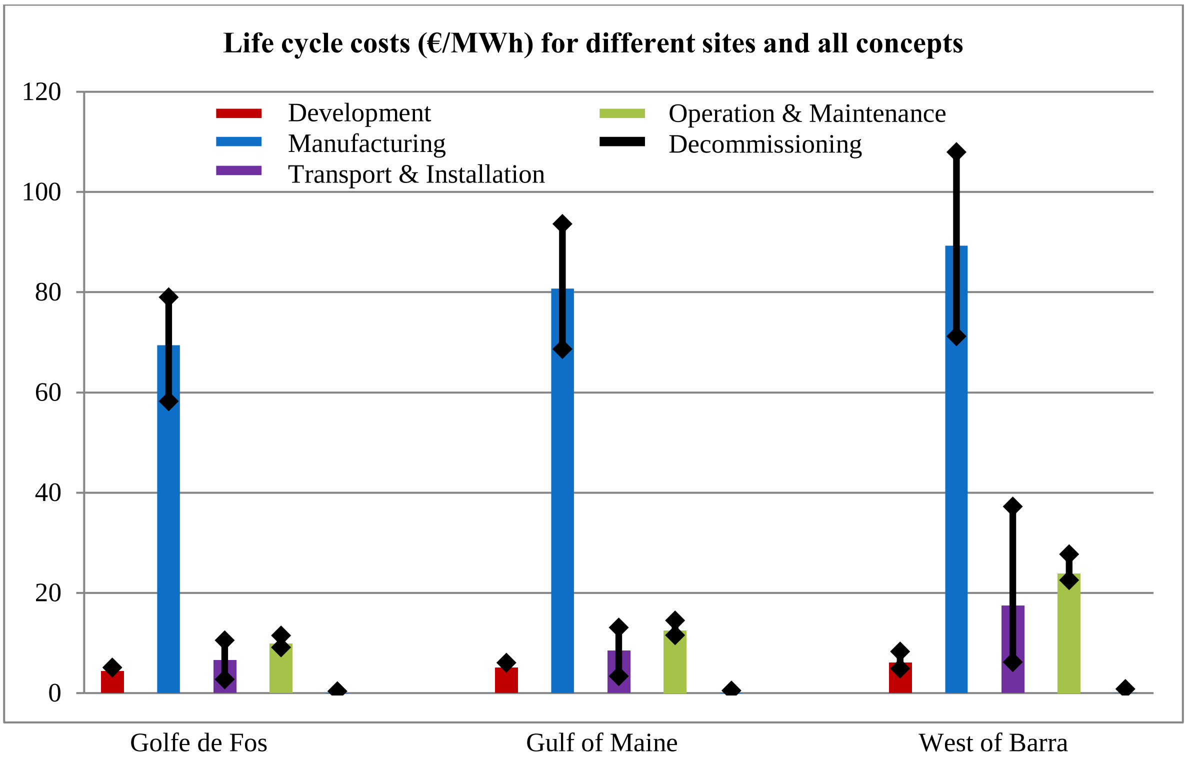

Figure 5: Life cycle cost breakdown of phase 1.

As Figure 5 illustrates, the manufacturing phase possesses the highest share of the LCC at all 3 sites. Such a result is expectable since the cost includes the manufacturing or acquisition of individual components of the floating offshore wind farm such as wind turbines, substructures, mooring lines, anchors, power cables and the substation. Furthermore, it includes the storage cost in the port as well as the load-out process. An increase of the life cycle costs for Gulf of Maine and West of Barra is observable with respect to Golfe de Fos based on increased design requirements for more severe conditions and the longer distances to shore. For instance, the mean manufacturing cost for West of Barra is about 28% higher than for Golfe de Fos and 11% higher than for Gulf of Maine. The manufacturing cost includes all components of the FOWF. For the floating substructure, the manufacturing cost has increased on average by 22% for West of Barra in comparison to Golfe de Fos due to the requirement of a more robust structure. An increase in transport & installation cost as well as O&M costs can also be seen.

As the CAPEX (consisting of development, manufacturing and transport and installation cost in Figure 5) represents the highest share of the LCC, it would be of interest to analyze its cost composition. Next, a breakdown of the CAPEX is presented in Figure 6 for a reference FOWF of the project and it is compared to a bottom-fixed offshore wind farm (BOWF).

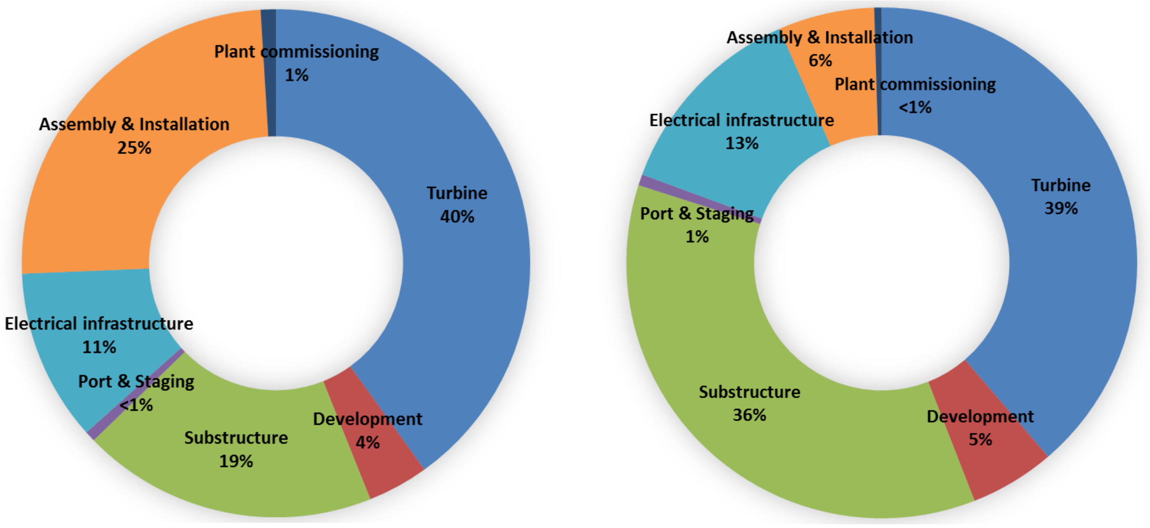

**Figure 6: CAPEX breakdown; left: BOWF based on 4.14MW wind turbines [15], right: Reference FOWF based on 10MW wind turbines.**

The comparison between the CAPEX of the BOWF and the FOWF may not be fully accurate since the wind farms are based on wind turbines with different power capacities. However, some general conclusions can be drawn. For instance, the share of turbine cost is nearly the same despite having turbines with higher power ratings installed in the FOWF. Likewise, the share representing the electrical infrastructure has increased only marginally. However, the substructure cost has a larger portion of the CAPEX for the FOWF since it includes not only the floating structure but also the anchor and mooring system. The share of assembly and installation, on the other hand, is lower since FOWTs enable an assembly in the port and a cost-effective installation offshore by using simple tug boats rather than Jack-up vessels that are used for bottom-fixed wind turbines.

## 3.2 Sensitivity analysis

A sensitivity analysis has been performed in phase 1 of the LIFES50+ project to identify the parameters that influence most the LCOE value. The complete analysis is presented in the deliverable D7.6 [16]. In the study over 325 parameters have been included and they are based on the input data asked in the LCOE questionnaire with some additional parameters to consider energy losses and financial parameters. The sensitivity analysis has been carried out for the 4 FOWT concepts, considering an entire FOWF and the 3 offshore locations. The complete description of the results can be found in the deliverable D7.6. In this report only the main findings are reported that are important to consider for the further studies performed on the LCOE. Figure 7 shows summarized the parameters that have the highest influence on the LCOE.

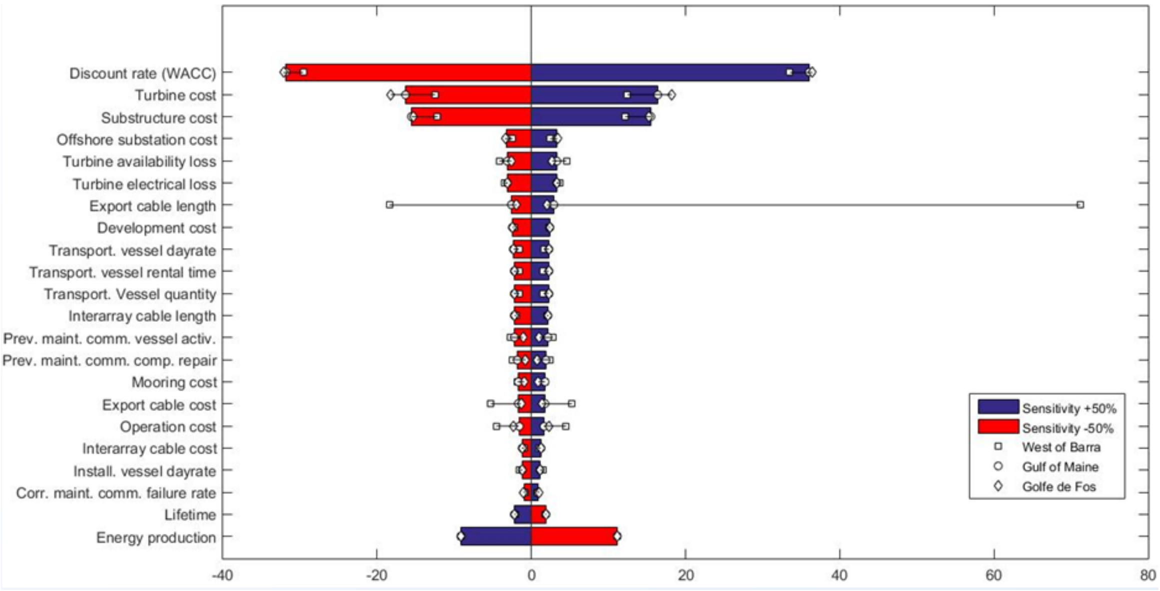

**Figure 7: Main influencing parameters on the LCOE.**

The figure shows that most of the parameters that have the highest influence on the LCOE are related to CAPEX that occur in the manufacturing and acquisition of components such as the cost of the turbine, substructure, power cables and mooring system. This coincides with the finding of manufacturing being the highest share in the life cycle costs. Consequently, in order to reduce costs and the LCOE a cost optimized design is required. Parameters concerning installation and transportation activities present also a significant influence on the LCOE. The associated costs could eventually be decreased with higher experience in the sector as well as commercialization of the technology. Besides the parameters that are concept specific, common parameters have also a large influence on the LCOE such as the cost for the turbine and the offshore substation as well as the export cable. Therefore, in order to have a large impact on the LCOE, a reduction of the costs of all components of a FOWF is required. However, the parameter that has the highest influence and would potentially make the highest impact is not related to the component cost of a FOWF. The discount has the largest influence on the LCOE independent of the FOWT concept and site conditions. Hence, a lower rate based on decreased risks for commercial projects may have more or at least the same importance than reducing CAPEX.

# 4 Cost reduction due to optimization in phase 2

The findings of phase 1 have pointed out that design dependent components have a large influence on the LCOE of a FOWF. In particular, the manufacturing of the FOWT has a significant share of the total costs. In phase 2 of the project, the 2 selected FOWT concepts (semi-submersible steel and semi-submersible concrete) have been optimized based on the experimental test campaigns performed in the ocean basin and wind tunnel and the numerical modelling of work package WP3 and WP4.

The optimization has resulted for instance in a change of the design or weight of the tower, reduction of the substructure size or change of the ballast system for some of the concepts. Furthermore, manufacturing activities have been adjusted based on optimized processes and transportation and installation procedures have been reviewed.

A detailed description of the concepts design optimization is provided in the deliverable D1.8 [17]. The concept developers have been asked to update the data collection questionnaires of phase 1 considering the performed optimization and the outcomes of the industrialization study. The questionnaires have been introduced again in the tool FOWAT to perform the calculations for both FOWT concepts and the 3 offshore locations. The LCOE values obtained by the optimized designs in phase 2 are presented in Figure 8 and compared to the results of phase 1.

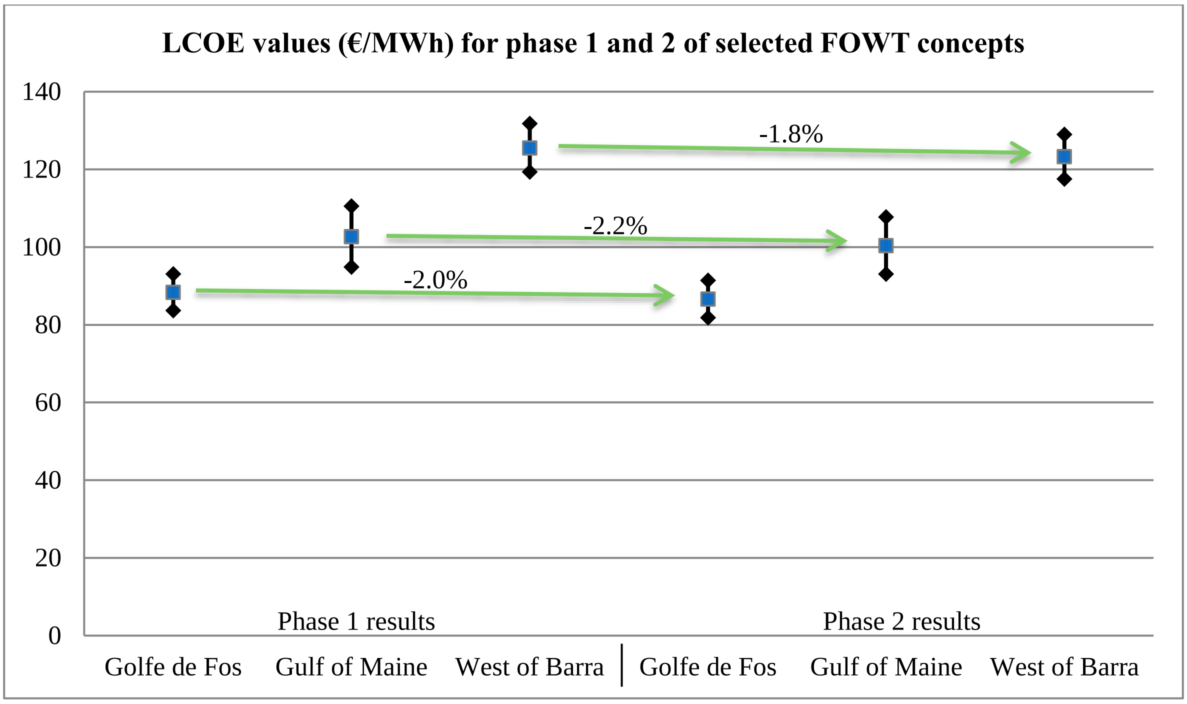

Figure 8: LCOE reduction obtained in phase 2.

The optimization activities performed in phase 2 of the project have led to LCOE reductions by about 2% for the selected FOWT concepts. The mean LCOE value for Golfe de Fos has decreased from 88.4€/MWh to 86.7€/MWh, for Gulf of Maine from 102.7€/MWh to 100.4€/MWh and for West of Barra from 125.6€/MWh to 123.3€/MWh. It should be noted that the common components of the FOWF have not been subject to an optimization and therefore the costs have remained the same. A breakdown of the life cycle costs is given in Figure 9 and compared to phase 1.

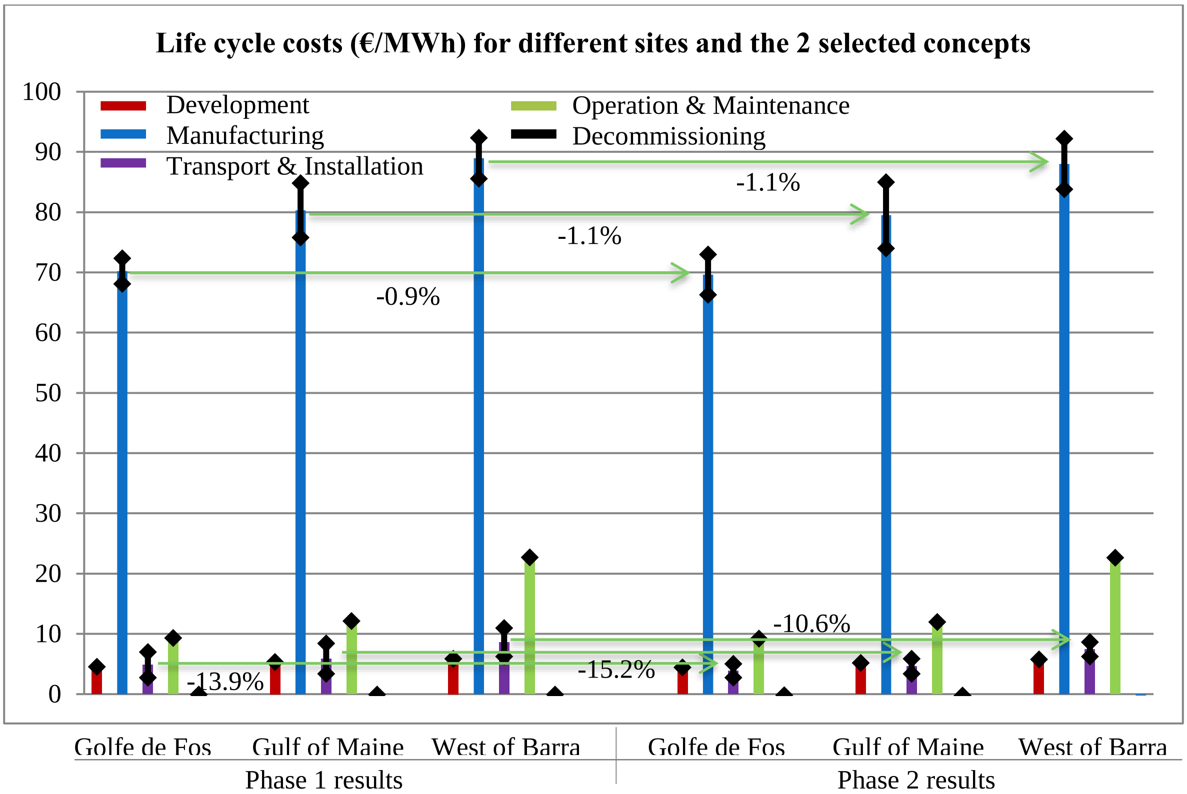

Figure 9: Life cycle cost comparison between phase 1 and phase 2

As Figure 9 shows, the mean manufacturing costs considering both selected concepts has decreased slightly by about 0.9% to 1.1%. As the optimization of phase 2 was based on the findings of the experimental test campaigns, many of the optimization activities had the main objective to improve the performance of the FOWT concepts, which would not necessarily results in significant component cost reductions. However, a reduction has been achieved of about 10.6% to 15.2% for the mean transport and installation cost.

# 5 Cost reduction potential through industrialization

In WP 5 of the LIFES50+ project a comprehensive industrialization study has been performed for the 2 selected concepts of phase 2. The study is described in detail in the deliverable D5.4 [18]. An outline on potential cost reductions through industrialization of FOWTs is presented in this section.

In general, as the qualitative Figure 10 from [19] indicates, overall costs from new and innovative technologies tend to increase from initial conception to detailed development and then decrease when the concept is optimised and industrialised. Thus, industrialisation is the key to reduce costs of FOWTs in the future through an increase of the output, cost savings regarding labour and improvements of overall quality. The industrialization stage is here indicated to take place beyond technology readiness level (TRL) 7 and adding another considerable reduction in cost, while in LIFES50+ the project aims at achieving TRL 5 for the selected concepts at the end of the project. A description of the different TRLs is provided in the Appendix.

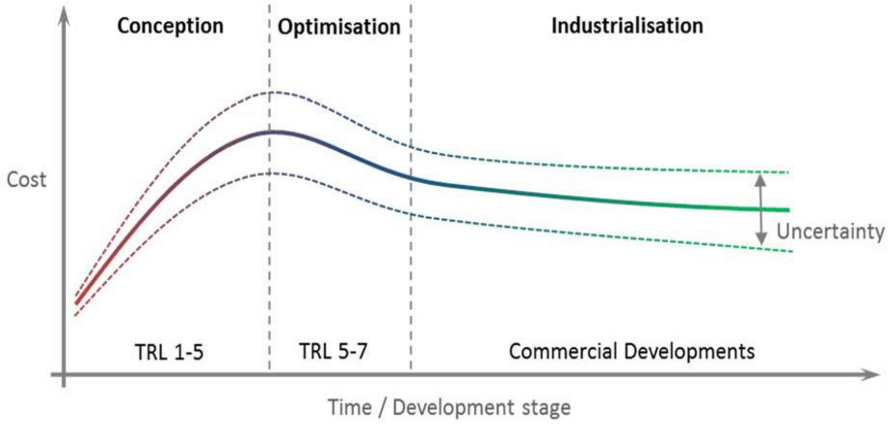

Figure 10: Potential of cost reduction in industrialisation phase [19].

A successful industrialization process is characterized by the following key requirements, which are adapted from [20]:

- Centralization of production at offshore hubs and shipyards for utilization of expensive equipment and facilities
- Mass production with distribution of fixed investments over a large number of units (economies of scale)
- Standardization of components, procedures and guidelines to increase production efficiency as well as reduction of uncertainties and risk
- Specialization regarding labour, software, procedures etc. in order to break down the production process into a large number of small homogeneous tasks and reach a higher productivity level
- Organization inducing high quality of planning, coordination and control functions with incorporation of risk and asset management strategies as well as quality assurance procedures
- Integration and coordination between design, production and marketing

In general, procurement costs of raw material used for production of the floating substructure (steel versus concrete) are influenced by several parameters.

For example, main impacts on the steel price are:

- Selected supplier, e.g. steel made in China is less expensive compared to Europe
- Quality, e.g. in general ship building steel but some parts may require higher quality
- Special requirements, e.g. surface condition, material tests and certificates, required tolerances
- Costs of transportation, e.g. number of transports, distance and means of transportation
- General development of steel price in the world market, e.g. variable price over the production time

Potentially, costs are further reduced through use of modularization and pre-fabrication of steel sub-blocks and pre-fabricated rebarring or pre-cast concrete blocks at specialized production sites. This reduces the complexity within the process and allows easier handling and transportation reducing logistics and equipment costs. The use of heavy-duty equipment required for logistics and transportation, like gantry cranes, towing vessels, etc. can be minimized.

By means of an increased automation and process improvement (lean strategies) of the production, the throughput (ton per month) and, thus, the output of floating substructures (units per month) can be accelerated, which, in turn, results in cost reductions. Regarding concrete, its in-situ characteristic enable production at any site which leads to potentially faster site preparations and lower investments in setting up a large production plant. Moreover, new technologies are expected through “Industry 4.0” innovations which hold enormous potential for cost reductions in industrial, automated manufacturing processes.

In general, making the process faster using automation and digitalization will only lead to the reduction of variable costs (VC), which are similar to OPEX. Moreover, production costs, especially the fixed costs (FC), which behave similarly to CAPEX, can be further reduced by achieving economies of scale by manufacturing large number of units (mass production). Moreover, processes involving large scale in general have other inherent benefits as follows which indirectly lead to cost savings:

- Purchasing economies:

Average costs can be potentially reduced by buying raw materials in bulk or from specialized suppliers. Better negotiation is also possible when the ordering quantity is high. Procurement costs will drop as well due to the use of bulk transportation like ships instead of trucks.

- Managerial economies:

The fixed costs related to the management structure can be significantly reduced. Costs associated to administrative, marketing and research and development expenses can be minimized. This allows the companies to hire experts or more experienced project managers that usually cost more.

- Technological economies:

Economies of scale reduce costs, in turn releasing funds for investments in advanced technologies which make the entire manufacturing process more efficient and eventually reduce variable costs.

- Better Funding:

Large scale projects also stand in a better position for attracting potential investors and receiving support/benefits/tax reductions/discounts from the government, which may affect the overall CAPEX. This will allow them to mature their technologies faster and gain an upper hand during market entry and commercialization efforts.

Note that there exists a certain level of ambiguity in the way different entities (suppliers, manufacturers, designers across different industries) define their costs. Manufacturers typically categorize various cost centres in the manufacturing processes as FC and VC, which is different to how the OPEX and CAPEX are generally defined in offshore wind. The most commonly used understanding of OPEX in offshore wind relates to costs incurred once the wind turbine is operating, meaning all costs like labour, vessel rent, spare parts etc. for operation, maintenance and repairs during the operational lifetime of the wind farm. CAPEX covers all procurement costs before the operational phase begins, for example costs for the wind turbine generator, floating substructure, installation etc. Developing a cost model with appropriate distribution of fixed and variable costs to the CAPEX and OPEX is recommended.

VC in manufacturing are influenced by the number of units and like OPEX have an inherent uncertainty involved within them. They include costs such as wages for labour, utilities and materials used for production, etc.  Whereas FC are similar to capital investments that remain constant for a certain number of units. FC are costs like rent, land, machinery etc. These costs remain constant and are independent to the output. It means that they do not have a direct relationship to the number of units being produced.

More importantly, VC increase at an almost proportional rate with the quantity relative to FC, which do not get influenced by the increasing rate of units. Whereas, the rate at which FC increase is substantially lower than that at which the number of units increase as shown by the example provided in Figure 11 below.

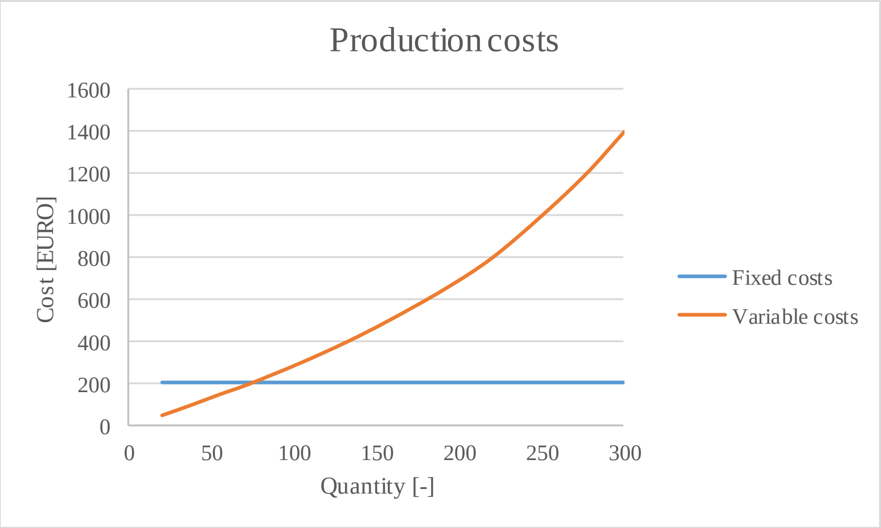

**Figure 11: Relative increase of exemplary fixed and variable costs with quantity [21].**

It must also be kept in mind that a certain capacity (i.e. a certain combination of land, rent and machinery) is limited to produce only a certain number of units. Any additional units above this threshold will require additional investments. So, one may expect the FC to remain constant only till a certain output after which a level shift (stepwise increase) will occur.

# 6 Cost reduction due to economies of scale

The concept developers were asked to fill out the data questionnaires besides the 50 units of 10 MW wind turbine configuration also for a 1 and 5 wind turbines configuration. The purpose was to assess the potential cost reduction that could be achieved by economies of scale from a demonstration (1 FOWT) to a commercial project (50 FOWTs). Section 3 has pointed out that the cost of the substructure represents a significant part of the CAPEX. Hence, this cost parameter is considered to assess economies of scale and the impact on the LCOE. The floating substructure costs for the 2 selected FOWT concepts are considered. The cost for anchor and mooring system is not considered. The cost reduction achieved for a production of 5 and 50 units with respect to 1 unit is shown in Figure 12. Furthermore, a trendline is derived and the cost reduction for a production of 100 substructures is predicted.

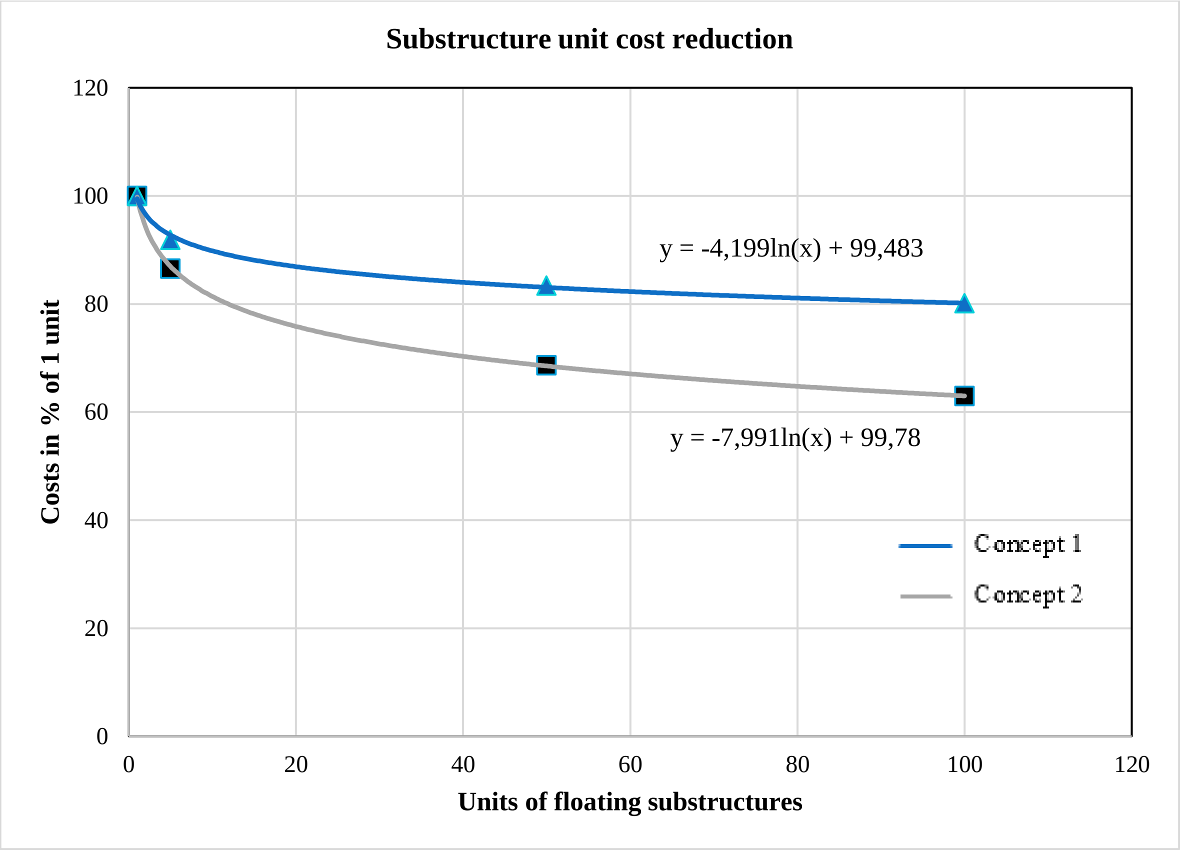

Figure 12: Cost reduction achieved by increased fabrication of substructures.

The presented cost reduction does not take into account any shortages in supply or restrictions to fabrication and storage capabilities. The reduction that could be achieved for a production of 100 units of substructures with respect to a single unit is about 20% and 37% according to the FOWT concept. The type of concept is confidential and can not be disclosed in this report. The reductions that could be achieved with respect to 50 units, which are used in phase 2 evaluation, are 4% and 8%, respectively.

Next, the LCOE is calculated considering the cost data of phase 2 for the 500MW FOWF and the reduction for the substructure cost achieved by a mass production of 100 units that could be applied in 2 FOWFs where each has 50 units. Hence, the 4% and 8% substructure unit cost reduction is applied. Figure 13 illustrates the reduction achieved by decreased substructure unit cost in reference to phase 2 results. Phase 1 results are also shown in order to highlight the cost reduction pathway obtained in the project.

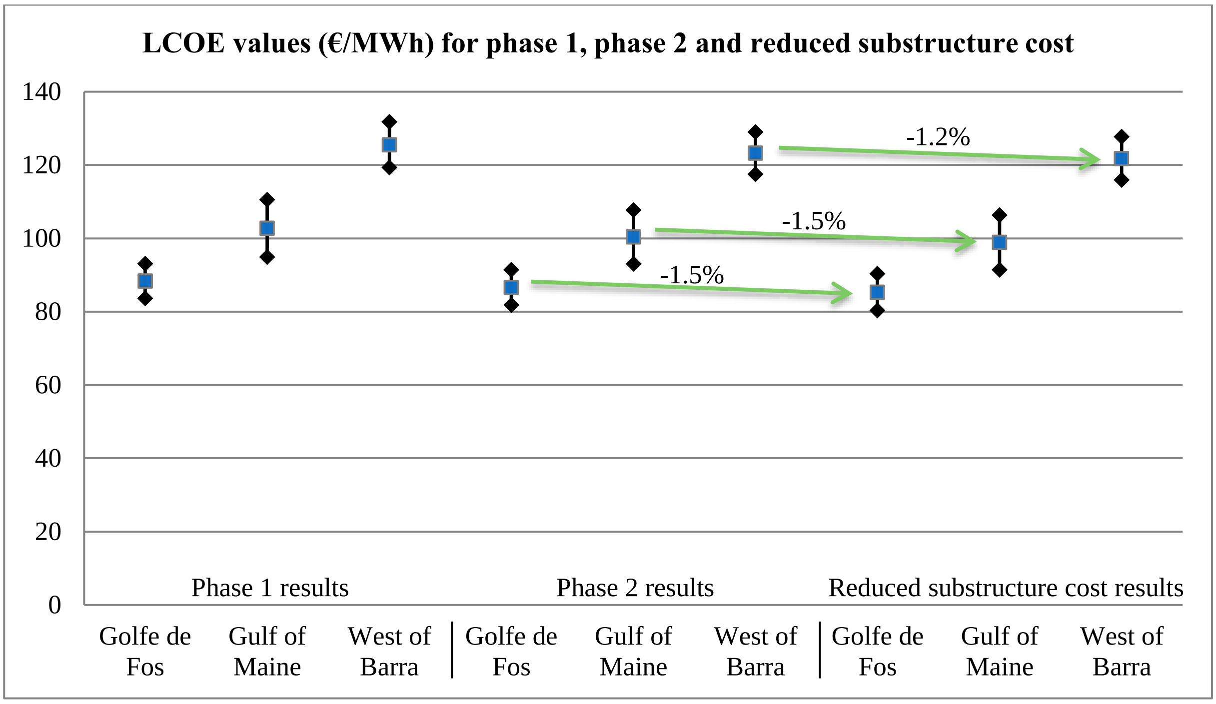

Figure 13: LCOE reduction achieved by decrease of substructure unit costs

The reduced substructure unit costs based on increased fabrication output causes the mean LCOE value to decrease by about 1.2% to 1.5% according to the different offshore sites.

## 7 Cost reduction due to discount rate

The discount rate reflects the weighted average cost of capital and is used in the LCOE calculation to discount future cash flows to their present value. It represents the market value of equity and debt and considers project risk and return yield [22]. The findings of the sensitivity analysis presented in Section 3 have shown that the discount has the largest influence on the LCOE. As a design independent parameter, it provides a significant potential to reduce the LCOE. A large employment of the FOWT technology and a full-scale commercialization could potentially reduce its value based on decreased risk for commercial projects and higher experience. In phase 1 and 2 evaluation of the FOWT concepts a discount rate of 10% was assumed. Recent studies [22-24] have shown that a 7% discount rate is a reasonable value for current and future offshore wind projects. Hence, this value is assumed for a commercial FOWF. The LCOE is calculated again for the 2 concepts and 3 sites assuming the reduction in the discount rate. The results are presented in Figure 14.

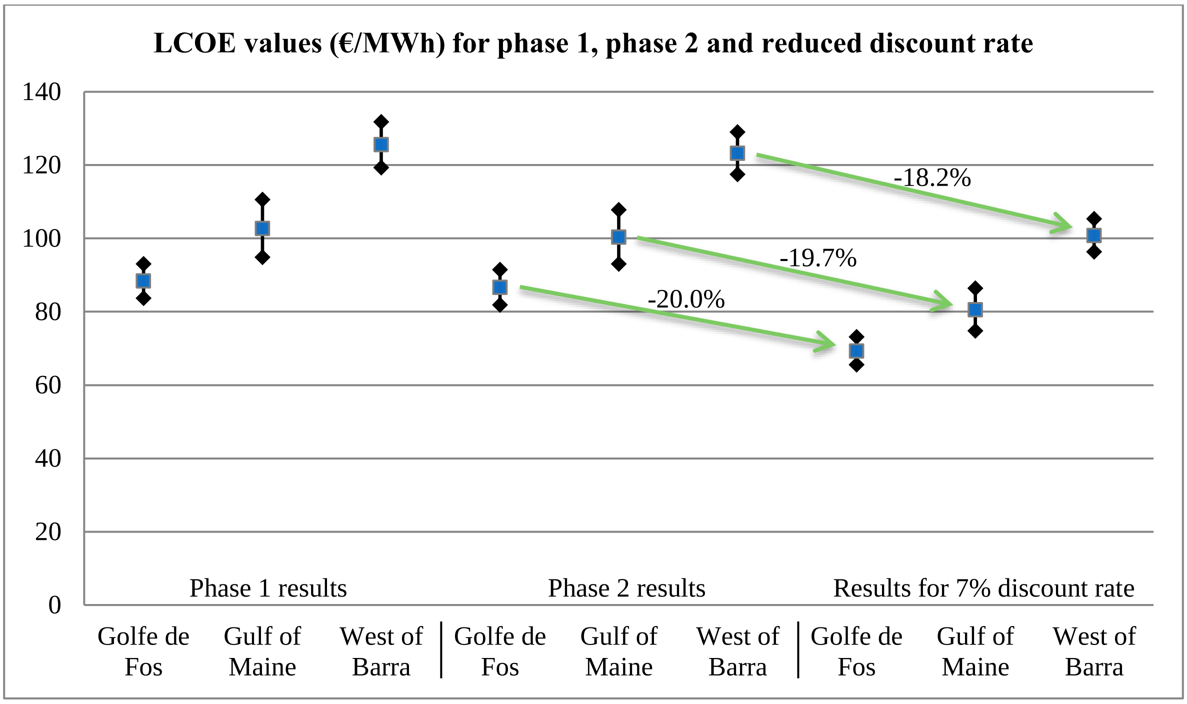

**Figure 14: LCOE reduction obtained by a decreased discount rate.**

It can be observed that the decrease of the discount results in a reduction of the LCOE value by about 18% to 20% according to the offshore site. The mean LCOE values have decreased for Golfe de Fos from 86.7€/MWh to 69.3€/MWh, for Gulf of Maine from 100.4€/MWh to 80.6€/MWh and for West of Barra from 123.3€/MWh to 100.8€/MWh. This demonstrates the high importance of financial parameters besides CAPEX and the need to de-risk the technology in order to achieve a significant reduction in the LCOE.

# 8 Conclusions

The aim of this document was to present the findings of the economic assessment of the FOWT concepts considered in LIFES50+ and the LCOE values obtained during the different evaluation phases. Furthermore, potential cost and LCOE reductions have been demonstrated by optimization of the concepts and a commercial employment of the technology.

At first, a literature review on LCOE values has been performed. The findings have shown that FOW can be a cost competitive solution to bottom-fixed offshore wind and other marine technologies. However, in order to be competitive in the long term the costs have to be reduced further. In Section 3, the LCOE results of phase 1 concept evaluation have been presented as a range for the 4 different FOWT concepts and for each of the 3 offshore sites. The results range from as low as 77€/MWh to as high as 182€/MWh depending on the offshore site and concept. Moreover, a breakdown of the LCCs has been presented and has shown that the manufacturing phase represents the highest contributor followed by O&M and transport and installation. A comparison of the CAPEX breakdown between a FOWF and a reference BOWF has highlighted the reduced contribution of assembly and installation for FOW. As manufacturing costs contributes the highest cost portion to the LCC, the manufacturing component costs have naturally the highest influence on the LCOE.

However, the findings of a sensitivity analysis have shown that the discount rate, as a design independent parameter, has an even higher impact on the LCOE. In phase 2 of the project, the 2 selected concepts have been optimized based on the experimental test campaigns in the ocean basin and wind tunnel and numerical modeling. The optimization has resulted in a mean LCOE reduction of about 1.8% to 2.2% with reference to the offshore site studied. The largest reduction was found in installation and transportation activities. However, depending on the concept a reduction was also achieved in manufacturing cost.

In Section 5, the potential cost reduction has been described that could be obtained by an industrialization of FOW followed by a quantification of the cost reduction in Section 6 that can be achieved by economies of scale in the substructure unit costs. The results have shown a decrease of the LCOE by 1.2% to 1.5% considering a production of 100 units of floating substructures for two FOWFs of 500MW. As the discount rate has been found to have the highest influence on the LCOE, its impact on the economic evaluation of the 2 selected concepts has been studied in Section 7. The reduced discount rate has resulted in a decrease by 18.2% to 20% of the LCOE value with respect to the offshore site. A lower discount rate could be achieved by reducing both the commercial and technology risk with more experience in the sector, improved numerical models and a large employment of the technology.

The findings presented in this document have shown that the FOWT concepts of the LIFES50+ project are highly competitive and provide LCOE values below the estimates of IEA Wind Task 26 expert survey and reference values in literature. Furthermore, the optimization of the concepts in phase 2 has resulted in an additional LCOE reduction. Moreover, different studies such as the impact of the discount rate and economies of scale have shown that commercialization of FOW is key for a further cost reduction.

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# 10 Appendix

TRLs are commonly used within industry as a measure of maturity for technology development. A description of the TRLs is provided in Table 1 and is based on the definition by The Crown Estate, (The Crown Estate, UK Market Potential and Technology Assessment for floating offshore wind power, 2013).

Table 1: TRL definitions

| TRL | | Technology status | Description |
|---|---|---|---|
| 1 | Proof of concept in the lab | Basic principles observed and reported | Scientific research begins to be translated into applied research and development. |
| 2 | | Technology concept and/or application formulated | Practical applications of basic key principles can be ‘invented’ or identified. The application is still speculative: there is no experimental proof or detailed analysis to support the proposal. |
| 3 | | Analytical and experimental critical function and/or characteristic proof of concept | Active research and development is initiated: analytical studies to set the technology into an appropriate context, and laboratory-based work to physically validate that the analytical predictions are correct. These should constitute “proof-of-concept” validation. |
| 4 | Concept development and scale testing | Technology / part of technology validation in a laboratory environment | Following successful “proof-of-concept” work, basic technological elements are integrated to establish that the “pieces” will work together to achieve concept-enabling levels of performance. The validation is relatively small scale compared to the eventual technology: it could be composed of ad-hoc discrete components in a laboratory. |
| 5 | | Technology / part of technology validation in working environment | At this level, the reliability / scale of the component being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications can be tested in a ‘simulated’ or somewhat realistic environment (which is almost always the working environment for energy technologies). |
| 6 | | Technology model or prototype demonstration in a working environment | A major step in the reliability / scale of the technology demonstration follows the completion of TRL 5. At TRL 6, a prototype going well beyond ad-hoc or discrete components is tested in a working environment. |
| 7 | Prototype demonstration | Full-scale technology demonstration in working environment | TRL 7 is a significant step beyond TRL6, requiring an actual system prototype demonstration in the working environment. The prototype should be near or at the scale of the planned operational system and the demonstration must take place in the working environment. |
| 8 | | Technology completed and ready for deployment through test and demonstration | In almost all cases, this level is the end of true ‘system development’ for most technology elements. This might include integration of new technology into an existing system. Represents the stage at which an example of the technology is tried and tested. |
| 9 | Commercial demonstration and system development | Technology deployed | In almost all cases, the end of last ‘bug fixing’ aspects of true ‘system development’ and represents the point at which the technology is proven, but not necessarily yet commercially viable in either a free or supported market. This might include integration of new technology into an existing system. This TRL does not include planned production improvement of ongoing or reusable systems. |