# Cost comparison between bottom-fixed and floating offshore wind turbines

Calculating LCOE based on full hours of utilization and corresponding break-even points

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## Abstract

Originally this article was supposed to be a comparison between the technological differences of bottom-fixed offshore wind turbines (BOWT) and floating offshore wind turbines (FOWT). However, several authors already contributed to this topic and came to the conclusion that the higher levelized costs of energy (LCOE) prevent FOWTs from successfully entering the energy market [1, 2]. Multiple sources seem to agree on this conclusion but often do not provide the reader with further information regarding the LCOE. This is the reason why this article understands itself as an in depth cost comparison between BOWTs and FOWTs. For this purpose, individual LCOE are calculated for the upcoming FOWT technologies such as spar-buoy (SPAR), tension-leg platform (TLP) and semi-submersible platform (semi-sub) as well as conventional BOWTs using the wind turbines hours of full utilization (HOFU). The resulting functions are visualized graphically in order to determine break-even points between BOWTs and FOWTs. Finally, a sensitivity analysis is carried out to determine the influence of the weighted average costs of capital (WACC).

**Keywords:** cost comparison, bottom-fixed, floating, offshore wind turbines, LCOE, break-even point

## 1 Introduction

Bottom-fixed foundations have become established as the technical standard for offshore wind turbines. However, floating foundations have been emerging and are becoming more relevant. The different floating foundation types can be divided into three categories:

- spar-buoy (SPAR),
- tension-leg platform (TLP) and
- semi-submersible platform (semi-sub).

Even though this article will not go into further detail regarding the technological differences between floating offshore wind turbines (FOWTs) and bottom-fixed offshore wind turbines (BOWTs), figure 1 gives a brief overview of the different foundation types.

All foundation types have their individual advantages and disadvantages. However, the upcoming FOWTs have a number of general advantages over the BOWTs:

- The possibility of using deeper waters increases the offshore wind power potential.
- Extended options for onshore pre-assembly lead to a reduced number of offshore operations, which are constrained to weather-windows and require expensive installation vessels [4].
- Instead of a solid foundation, a few cable attachment points are used, which reduces the irreversible environmental damage to the seabed and the noise pollution during installation.

However, these advantages are offset by higher levelized costs of energy (LCOE) which prevent FOWTs from successfully entering the energy market [1, 2]. Thus the question arises whether FOWTs will ever be able to compete with BOWTs from a cost point of view. To answer this question a procedure for calculating the LCOE for FOWTs and BOWTs and an afterwards carried out comparison with the goal of calculating break-even points based on the wind turbines hours of full utilization (HOFU) was developed and shall be explained in the now following chapter.

## 2 Material and Methods

### 2.1 Levelized costs of energy

For calculating the LCOE the following formula [5] was used:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E}{(1+i)^t}} \tag{1}$$

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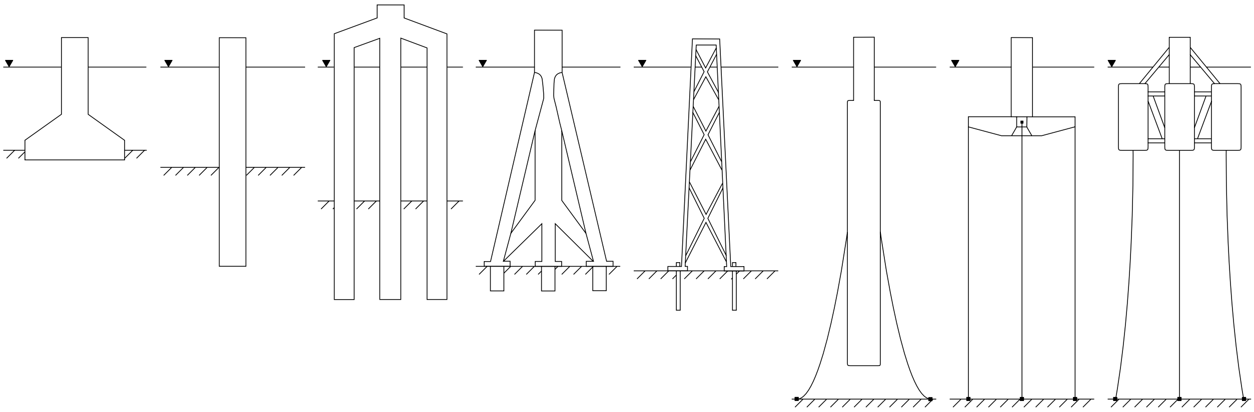

Fig. 1: BOWT and FOWT foundation types from left to right: gravity, monopile, tripile, tripod, jacket, SPAR, TLP, semi-sub (own illustration based on [3])

| | |
|---|---|
| $LCOE$ | levelized costs of energy in €ct/kWh |
| $CAPEX$ | capital expenditures in €ct |
| $OPEX$ | operational expenditures in €ct |
| $E$ | generated energy in year t in kWh |
| $i$ | weighted average costs of capital in % |
| $n$ | operational lifetime in years |
| $t$ | individual year of lifetime (1, 2, ... n) |

Life cycle cost breakdowns show that the share of decommissioning expenditures in the total costs of an offshore wind turbine range from

- 1 % for BOWTs [6] up to
- 4-8 % for FOWTs [7].

Therefore, the decommissioning expenditures will not be taken into further consideration.

## 2.2 Costs of BOWTs

CAPEX and OPEX values according to [8] will be used for calculating the LCOE. A distinction is made between two possible scenarios:

- lower limit → best recent value (BRV)
- upper limit → global average (GA)

However, the different BOWT foundation types (figure 1) will not be further subdivided.

| | BRV | GA | |
|---|---|---|---|
| CAPEX | 2435 | 3485 | k€/MW |
| OPEX | 17.2 | 28.7 | €/MWh |

Tab. 1: CAPEX and OPEX values for BOWTs [8]

## 2.3 Costs of FOWTs

In contrast to BOWTs, FOWTs are not yet commercialized as many current projects are just in the pilot status. The different technical readiness levels (TRL) make a comparison between the LCOE for BOWTs and FOWTs difficult, since the TRL has a direct influence on the LCOE (compare figure 2).

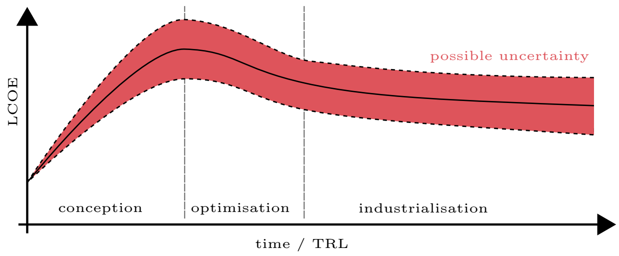


Fig. 2: schematic cost development through time (own illustration based on [4])

In order to answer the question if FOWTs will ever be able to compete with BOWTs from a cost point of view, the different TRLs of the two technologies must be adapted to each other. This can be accomplished by either adjusting the LCOE for BOWTs according to their already completed cost development or by estimating the future cost development for FOWTs. The latter approach was used in [4] for calculating CAPEX and OPEX values based on a list of several FOWT projects with different TRLs. Uncertainties and differences between the individual projects were taken into account using two possible scenarios:

- lower limit → minimal deviation (MIN)
- upper limit → maximum deviation (MAX)

The results, which will be used for calculating the LCOE, are shown in table 2. Different CAPEX values are available for the individual foundation types. The OPEX value, on the other hand, is identical for all technologies.

| | | MIN | MAX | |
|---|---|---|---|---|
| CAPEX | SPAR | 2860 | 3025 | k€/MW |
| | TLP | 2915 | 2970 | |
| | semi-sub | 2750 | 3080 | |
| OPEX | | 88 | 121 | k€/MW/a |

Tab. 2: CAPEX and OPEX values for FOWTs [4]

## 2.4 Calculating the LCOE

The LCOE were calculated by inserting the following parameters into to formula 1:

- corresponding CAPEX and OPEX values according to the tables 1 and 2, [1]
- a constant value for $i$ = 7 % (WACC), [2]
- as well as an operational lifetime of $n$ = 20 a. [3]

The amount of generated energy $E$ can be calculated by multiplying the wind turbines performance and the hours of full utilization (HOFU).

Since the wind turbines performance does not only affect the amount of generated energy $E$, but also has a direct influence on both CAPEX and OPEX (compare units in tables 1 and 2), the LCOE according to formula 1 do not change by varying the wind turbines performance. Any wind turbine performance can therefore be assumed for the calculation. However, varying the HOFU only affects the amount of generated energy $E$ and therefore changes the LCOE. For this reason the LCOE were calculated as a function of the HOFU. The thus resulting functions for the individual floating foundation types are examined in more detail in the now following chapter.

# 3 Results

The calculated LCOE as functions of the HOFU are shown in the figures 3, 4 and 5. The lower and upper limit scenarios according to the chapters 2.2 and 2.3 are represented by the dotted curves, which result in partially overlapping price corridors. Out of the points that make up the dotted curves arithmetic mean values were formed and then connected to the solid curves in order to determine exact intersections and thus being able to calculate break-even points. Since the HOFU depend on the wind turbine installation site but usually move within a typical range, the x-axis was limited to 3000-5000 h/a for a better overview.

[1] However, the units were first converted to €ct by multiplying the CAPEX and OPEX values with the wind turbine performance or the amount of generated energy $E$.

[2] A sensitivity analysis to determine the influence of this initially assumed value is carried out in chapter 3.

[3] The here assumed time span is based on the German EEG law, which states that financial support by the government for renewable energies is limited to 20 years.

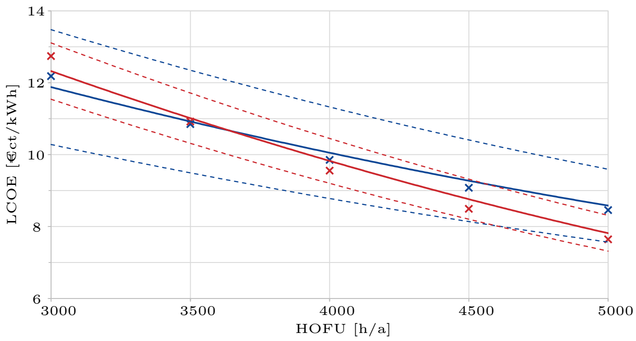


Fig. 3: comparing BOWT (blue) and SPAR (red)

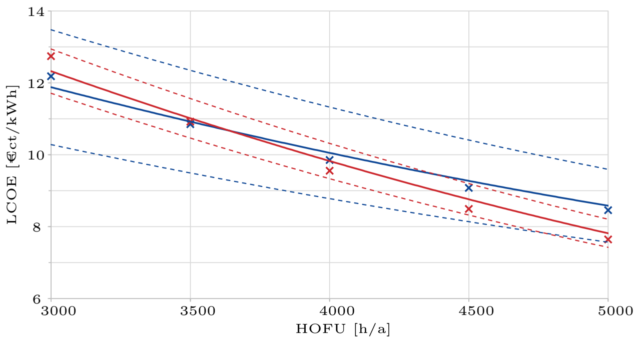


Fig. 4: comparing BOWT (blue) and TLP (red)

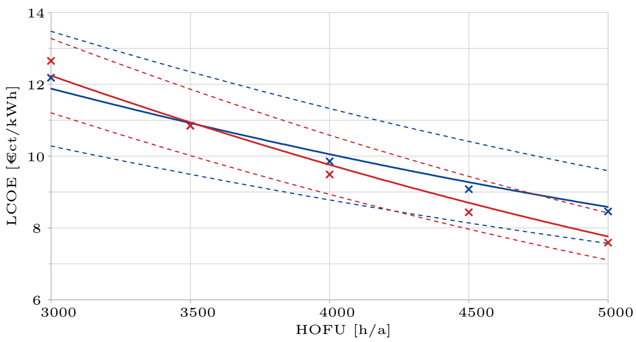


Fig. 5: comparing BOWT (blue) and semi-sub (red)

The break-even points for SPAR and TLP are on top of each other because the upper limit CAPEX value decreases by the same amount as the lower limit CAPEX value increases (compare table 2). Thus the TLP price corridor becomes tighter on both sides but the arithmetic mean stays the same.

Since the WACC depend on the market value of the company's equity and debt, a sensitivity analysis by calculating multiple break-even points for WACC values ranging from 4-10 % was carried out to take different financing structures into account (compare figure 6). The HOFU range from 3482 h/a up to 3656 h/a and are therefore subject to a relatively small change of 174 h/a. As expected, the LCOE are much more dependent on the WACC and therefore fluctuate between approximately 9-13 €ct/kWh.

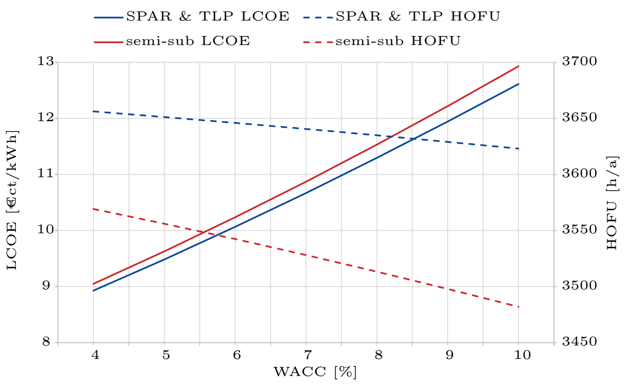


Fig. 6: influence of different WACC values on the break-even points

## 4 Conclusion

The figures 3, 4 and 5 can be used to carry out an initial rough economic comparison between BOWTs and FOWTs based on the HOFU achievable at the planned wind turbine installation site. A fundamental problem here, however, is that environmental impact scores lowly in regard to cost reduction potential [4].

Furthermore, the break-even points can be used to answer the initial question whether FOWTs will ever be able to compete with BOWTs from a cost point of view. However, this requires suitable figures for comparison. For this purpose the LCOE for German offshore wind energy was calculated by the Fraunhofer Institute for Solar Energy Systems and ranges from 7.5 €ct/kWh up to 13.8 €ct/kWh at 3200-4500 HOFU [9]. The in chapter 3 calculated break-even points overlap with this range, which shows that FOWTs will be able to compete with BOWTs in the future. However, this conclusion is based on an estimated cost development for FOWTs (compare chapter 2.3).

## 5 Outlook

In order to make the results of this article more useful for practical applications, further investigations will be necessary in the future. The following suggestions for improvement could serve as possible starting points:

- Instead of estimating a cost development for FOWTs, the already completed cost development of BOWTs could be used accordingly.
- Although the used procedure is sufficiently accurate, the result is only as good as the input data. A more in-depth analysis of the CAPEX and OPEX structures would lead to better results.
- In a few years the commercialization of the FOWTs will have progressed further and for projects that are currently being implemented more up-to-date data will be available with which the procedure can be repeated. This means that the results can be kept up to date and the uncertainties due to the estimated cost development can be reduced over time.

## References

[1] A.-D. Maimon. “Brief review about floating offshore wind turbines projects”. *Annals of” Dunarea de Jos” University of Galati.* 41 (2018), pp. 49–62. DOI: 10.35219/AnnUGalShipBuilding.2018.41.08.

[2] M. Andersen. “Floating Foundations for Offshore Wind Turbines”. PhD supervisor: Professor Søren R.K. Nielsen, Aalborg University Assistant PhD supervisor: Associate Professor Peter B. Frigaard, Aalborg University. PhD thesis. 2016. DOI: 10.5278/vbn.phd.engsci.00175.

[3] “Foundations types and depth limits - Alternative solutions”. *Windpower Monthly* (2013). URL: https://www.windpowermonthly.com/article/1210054.

[4] R. James and M. C. Ros. “Floating offshore wind: market and technology review”. *The Carbon Trust* (2015). URL: https://www.carbontrust.com/de/node/958.

[5] R. Ebenhoch, D. Matha, S. Marathe, P. C. Muñoz, and C. Molins. “Comparative Levelized Cost of Energy Analysis”. *Energy Procedia* 80 (2015). 12th Deep Sea Offshore Wind RD Conference, EERA DeepWind’2015, pp. 108–122. DOI: 10.1016/j.egypro.2015.11.413.

[6] A. Ioannou, A. Angus, and F. Brennan. “A lifecycle techno-economic model of offshore wind energy for different entry and exit instances”. *Applied Energy* 221 (2018), pp. 406–424. DOI: 10.1016/j.apenergy.2018.03.143.

[7] C. Maienza, A. Avossa, F. Ricciardelli, D. Coiro, G. Troise, and C. Georgakis. “A life cycle cost model for floating offshore wind farms”. *Applied Energy* 266 (2020), p. 114716. DOI: 10.1016/j.apenergy.2020.114716.

[8] A. C. Levitt, W. Kempton, A. P. Smith, W. Musial, and J. Firestone. “Pricing offshore wind power”. *Energy Policy* 39.10 (2011). Sustainability of biofuels, pp. 6408–6421. DOI: 10.1016/j.enpol.2011.07.044.

[9] C. Kost, S. Shammugam, V. Jülch, H.-T. Nguyen, and T. Schlegl. “Stromgestehungskosten Erneuerbare Energien” (2018). URL: https://www.ise.fraunhofer.de/de/forschungsprojekte/stromgestehungskosten-erneuerbare-energien.html.