Comparative Levelized Cost of Energy Analysis

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Motivation

Trends in the Offshore Industry:

- Distance to shore ↑
- Water depth ↑
- Turbine size ↑

Prototypes have already proven **technical** feasibility of FOWTs

**Current Challenge:**
Design of **Economic** FOWT Concepts

LCOE Evaluation required

Source: EWEA, 2014
Berger, 2013
**General Methodology - Economic Evaluation**

**Approach:**

**Life-Cycle Cost Analysis**

1. Project Management and Consenting
2. Production and Acquisition
3. Installation
4. Operation and Maintenance
5. Decommissioning
Levelized Cost of Energy (LCOE)

\[ LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}} \]

- **LCOE**: Levelized cost of electricity in €ct/kWh
- **I₀**: Capital expenditure (CAPEX) in €ct
- **Aₜ**: Annual operating costs (OPEX) in year \( t \)
- **Mₑₑ**: Produced electricity in the corresponding year in kWh
- **i**: Weighted average cost of capital (WACC) in %
- **n**: Operational lifetime in years
- **t**: Individual year of lifetime (1,2,…n)

**Life-Cycle Analysis** approach combined with LCOE to enable an economic assessment and comparison among substructure types.

Source: EWEA, 2009
LCOE-Tool – Input Parameter

Implemented Substructure Types:

- Generic steel FOWTs
- Bottom-fixed Solutions
- AFOSP Concept (Concrete Structure)

Site- and Substructure-specific LCOE

- Capital costs (CAPEX)
  - Consenting/Development
  - Project Management
  - Turbine Nacelle
  - Turbine Rotor
  - Support Structure
  - Substation
  - Array/Export Cables
  - Installation
  - Insurance
  - Etc.

- Operating costs (OPEX)
  - Operations and Maintenance
  - Operating Phase Insurance
  - Transmission Charges
  - Seabed Rent
  - Etc.

- Decommissioning costs (DECEX)
  - Included: Revenues from recycling and resale

- Annual energy production
  - Capacity Factor
  - Losses
  - Availability
  - Net AEP

- Weighted average cost of capital
  - Capital structure
  - Equity and debt return

- Timing
  - Phasing of capital and operating costs and energy production over time
  - Replacement cycles (Substructure, Turbine)

Directly depending on parameters like "water depth", "distance to nearest operation port" and installed "turbine size"

Manual entries
LCOE-Tool – Level of Detail

Management activities
- Project Consenting and Development
- Project Management
- Construction Phase Insurance

Grid connection
- Array/Export Cables
- Internal Substation

Turbine Nacelle
- Gearbox
- Electrical Connection
- Generator
- Main Bearing
- Power Electronics
- Yaw System
- Low-speed Shaft
- Others (Mainframe, Aux System, Cover)

Substructure and Tower
- Monopile
- Jacket
- Floating Foundation

Source: EnBW, 2013
Ramboll Wind, 2013
Main parameters:
- Water depth
- Turbine size
- Distance to shore

Input Window

Data sheet for bottom-fixed solutions

Data sheet for AFOSP-concept

CAPEX, OPEX and DECEX depending on the main parameters

LCOE calculation

Result Window

Manual entries:
- Goss load factor
- Losses
- Availability
- WACC etc.

Basic Costs

Scaling Factor

199 €/MW \times 1 \times 1.11 = 221 €/MW
<table>
<thead>
<tr>
<th>Summarized Cost categories</th>
<th>Bottom-fixed</th>
<th>Floating</th>
<th>Example Cost functions</th>
<th>Comments/Key assumptions</th>
</tr>
</thead>
</table>
| Jacket (Monopile in water depths < 35m) Transition Piece | $f(w,t)$ | - | ![Graph](image1.png) | • Cost calculation based on weight estimation of jacket/monopile structures  
• Specific material and manufacturing costs: 5.8 €/kg |
| Pin Piles Transition Piece | $f(w,t)$ | - | ![Graph](image2.png) | • Conservative approach, due to higher wave loads for deep water sites  
• Costs for material and manufacturing: 2 €/kg |
| Floating Foundations | - | $f(t)$ | ![Graph](image3.png) | • AFOSP: Based on material/production cost estimation  
• Floating: Mean value of several floating concepts |
| Turbine (Rotor + Nacelle) | $f(t)$ | $f(t)$ | ![Graph](image4.png) | • Turbine model independent from considered type of foundation  
• As an example for an Rotor-respectively Nacelle-component, the cost function of the gearbox and the turbine blades are illustrated |
SWE

LCOE-Tool – Cost functions/Key Assumptions

Specific cost / MW

Scale factor for base cost

Jacket (Monopile in water depths < 35m) Transition Piece

\[ f(w,t) = 446\,000 \text{ €/MW} \]

Water depth [m]

Specific cost [€/MW]

\[ y = (0.149x^2 - 5.342x + 342.299) \frac{5.8 \times 907.185}{5.5 \times 1000} \]

\[ y = 0.0796x + 0.6895 \]

\[ y = -0.0283x + 1.1273 \]

\[ y = 0.04x + 0.8341 \]

Scale Factor

\[ f(t) \]

- Floating Foundations: 1 252 000 €/MW
- Turbine (Rotor + Nacelle): 1 196 000 €/MW
Characteristics AFOSP-Concept

AFOSP-Characteristics:

- Monolithic concrete structure
- Less sensitive to corrosion
- Reduced O&M effort
- Lifetime extension of the substructure to 40 or 50 years
- Relatively simple to manufacture in an automated process (minimum of welds needed)
- Innovative, horizontal Installation process

**Diagram Description:**

- Project Development: 4-6 years
- Preparation and Construction: 1-2 years
- Operating Phase I: 2-4 years
- Operating Phase II: 5 years
- Decommissioning: 1-2 years

Total project duration: 47-62 years
Current mean LCOE – Fixed-Bottom

- Literature values
- Target LCOE bottom-fixed 13.47 [€ct/kWh]
- County specific data

Values adjusted for inflation

13.47 €ct/kWh
Current mean LCOE - Floating

- **Target LCOE-Floating Solutions 15.15 [€ct/kWh]**
- **LCOE [€ct/kWh]**
  - Manufacturer's information / Literature values
- **LCOE [€ct/kWh]**
  - Own calculation

<table>
<thead>
<tr>
<th>Difference</th>
</tr>
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<tbody>
<tr>
<td>Fixed - Floating: Δ = 1.7 €ct/kWh</td>
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</tbody>
</table>

- 15.15 €ct/kWh

- values adjusted for inflation
4. Results – Cost Breakdown

Reference Scenario
- Gross Load Factor: 51%
- Water depth: 150 m
- Distance to shore: 60 km
- Turbine size: 4 MW
- Wind farm capacity: 500 MW
- WACC: 9%

LCOE [€ct/kWh]

- Bottom-Fixed: 29.86*
- Floating: 23.04*
- AFOSP: 17.55*

150m water depth

*without sea bed rent
4. Results – Sensitivity Analysis Comparison
4. Results – Sensitivity Analysis AFOSP

Reference Scenario
- Gross Load Factor: 51%
- Water depth: 150 m
- Distance to shore: 60 km
- Turbine size: 4 MW
- Wind farm capacity: 500 MW
- WACC: 9%

The graph illustrates the sensitivity of LCOE (Levelized Cost of Energy) to various parameters. The LCOE is shown on the Y-axis in €ct/kWh, and the change in LCOE is shown on the X-axis in [%]. The parameters include:
- Gross Load Factor
- Water depth
- Distance to shore
- Turbine size
- O&M costs
- Concrete price
- WACC

Key points:
- A decrease of -50% in water depth results in a 6.3% increase in LCOE.
- A decrease of -50% in turbine size results in a 61% increase in LCOE.
- An increase of +30% in distance to shore results in a 11.7% increase in LCOE.
- An increase of +50% in turbine size results in a 22.5% decrease in LCOE.
- A decrease of -50% in O&M costs results in a 120 km decrease in distance to shore.
4. Results – Sensitivity Analysis Bottom-fixed

- Gross Load Factor: +51%  
- Water depth: +150 m  
- Distance to shore: +60 km  
- Turbine size: +4 MW  
- Wind farm capacity: +500 MW  
- WACC: +9%  

Change in LCOE [%]  
LCOE [€/MWh]  
Parameter variation [%]
6. Conclusion/Outlook

- Developed tool helps to optimize the design and reduce the costs of deep offshore wind farms, by analyzing key aspects already during the planning and pre-design phase
- The analyzed concrete design under reference scenario conditions does neither yet reach the estimated benchmark for bottom-fixed structures in shallow waters nor the one representing FOWTs
- Sensitivity analyses illustrate, that even small parameter variations can be decisive and have a huge impact on the total LCOE
- Future technical innovations, learning curve effects and supply chain enhancements are strongly needed for FOWTs to be competitive
- Using existing synergies with the oil and gas industry seems one promising step on the pathway to commercialization
Thank You For Your Attention

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References (Selection)


**Ramboll Wind (2013)**, T. Fischer, Cost-effective support structures for future deep water applications, Vortrag bei der EWEA Offshore Messe 2013 in Frankfurt