DTU

Comparative analysis of offshore wind energy cost of energy utilizing the DTU Wind Offshore Cost Model

EERA Deepwind’2021 Conference

13-15 January, 2021

Witold Robert Skrzypiński, Søren Oemann Lind, and Katherine Dykes

DTU Wind Energy

Offshore Wind Energy Cost Modelling

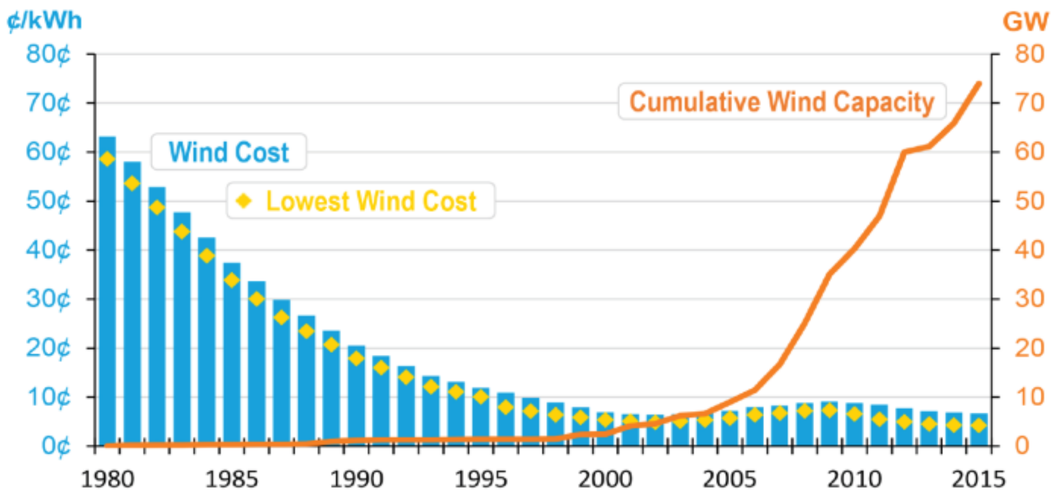
- LCOE Modelling Background and Approaches
- Topfarm Overview
- DTU Wind Energy Offshore Cost Model
- Analysis for Select Sites
- Summary and Future Work

Offshore Wind Energy Cost Modelling

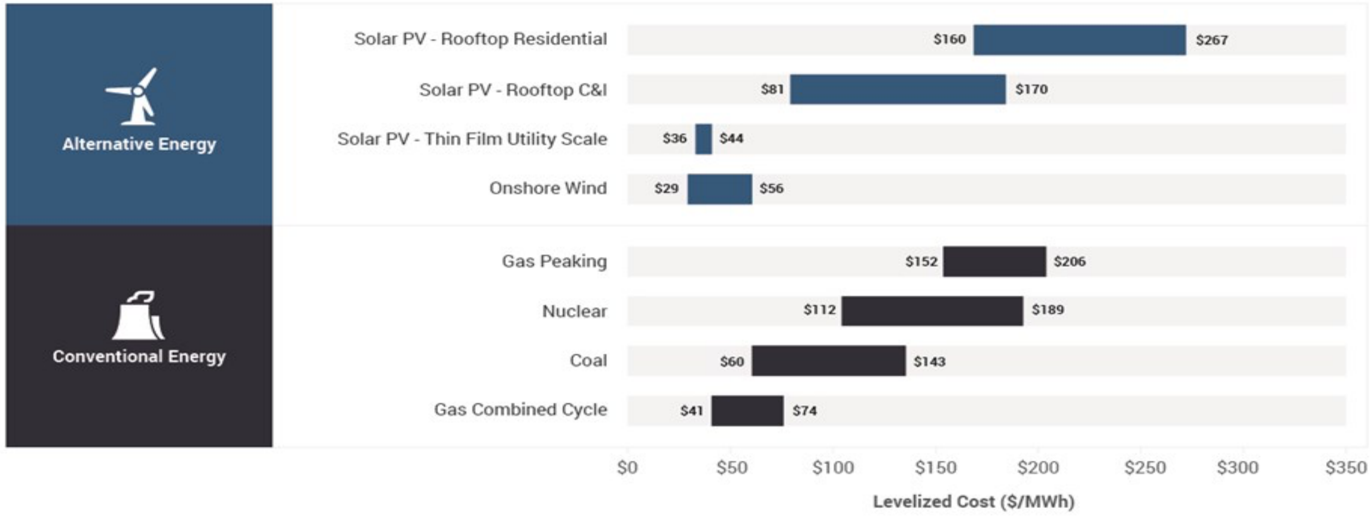
- LCOE Modelling Background and Approaches
- Topfarm Overview
- DTU Wind Energy Offshore Cost Model
- Analysis for Select Sites
- Summary and Future Work

Levelized Cost of Energy (LCOE) Background

- LCOE indicates relative competitiveness of technology solutions
- LCOE reductions primarily ocurr through:
  - R&D innovation
  - Technology learning (i.e. learning curves)
- Wind energy LCOE competitive now with most other technologies



Top: NREL 2019
Bottom: Lazard 2019



LCOE Calculation

- LCOE is calculated as a function of overall project costs through the project lifetime adjusted to annual carrying charges, the annual operational expenditures, and the average annual energy production over the lifetime:

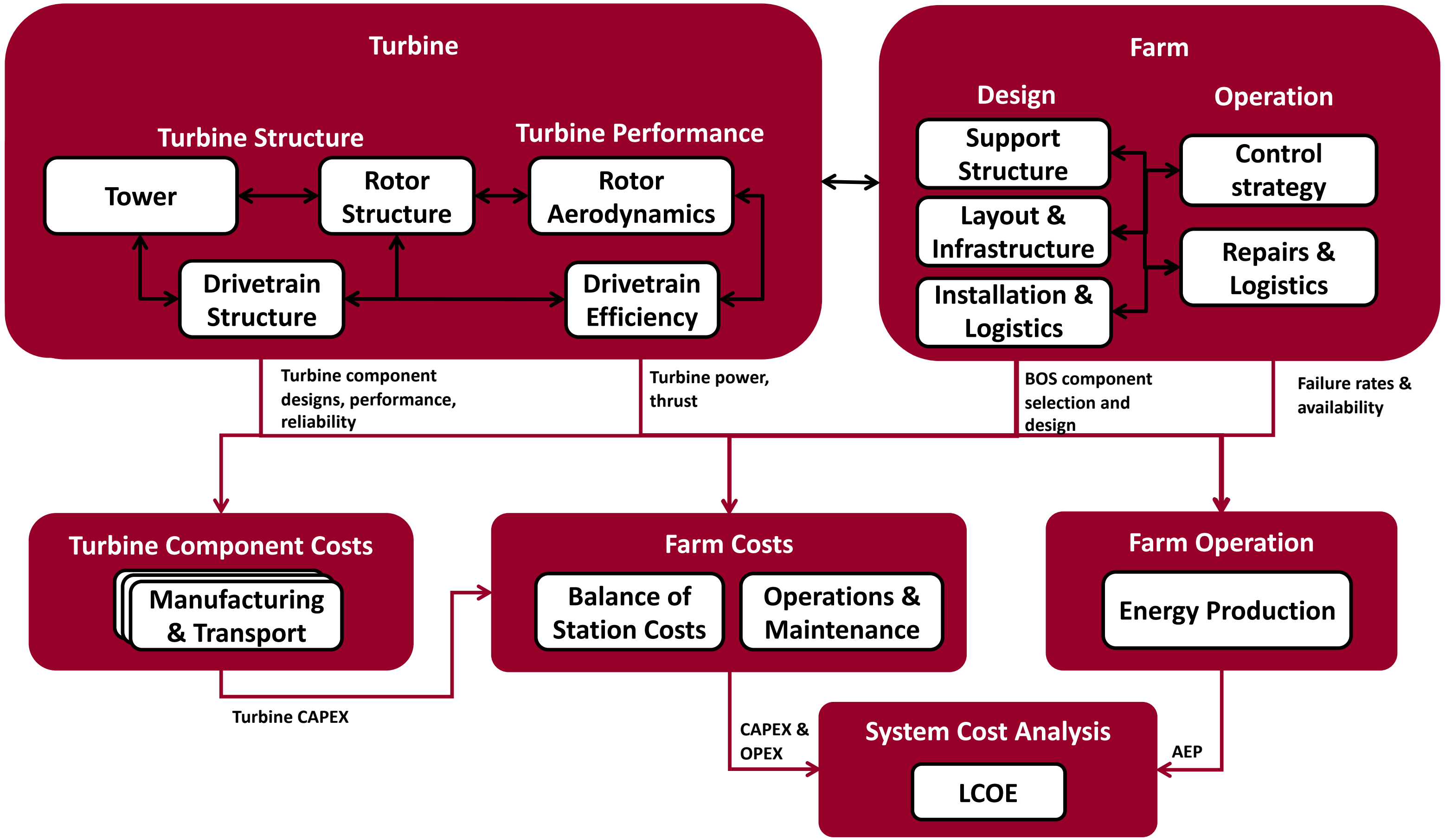
$$LCOE = \frac{\mathrm{FCR} * \mathrm{CAPEX} + \mathrm{OPEX}}{\mathrm{AEP}}$$

  – FCR: A coefficient that captures the average annual carrying charges including return on installed capital, depreciation, and corporate income taxes. It is a function of a number of inputs including rate of return on equity, debt interest rates, debt fraction, inflation and tax rates, and depreciation period and fraction
  – CAPEX: Total capital expenditure (CapEx) to achieve commercial operation up to the plant gate
  – OPEX: Annual expenditures to operate and maintain equipment that are incurred on a per-unit-capacity basis
  – AEP: The amount of energy produced in a given year per megawatt capacity after system losses and availability are taken into account

Dykes et al 2017. Enabling the SMART Wind Power Plant of the Future Through Science-Based Innovation. NREL/TP-5000-68123

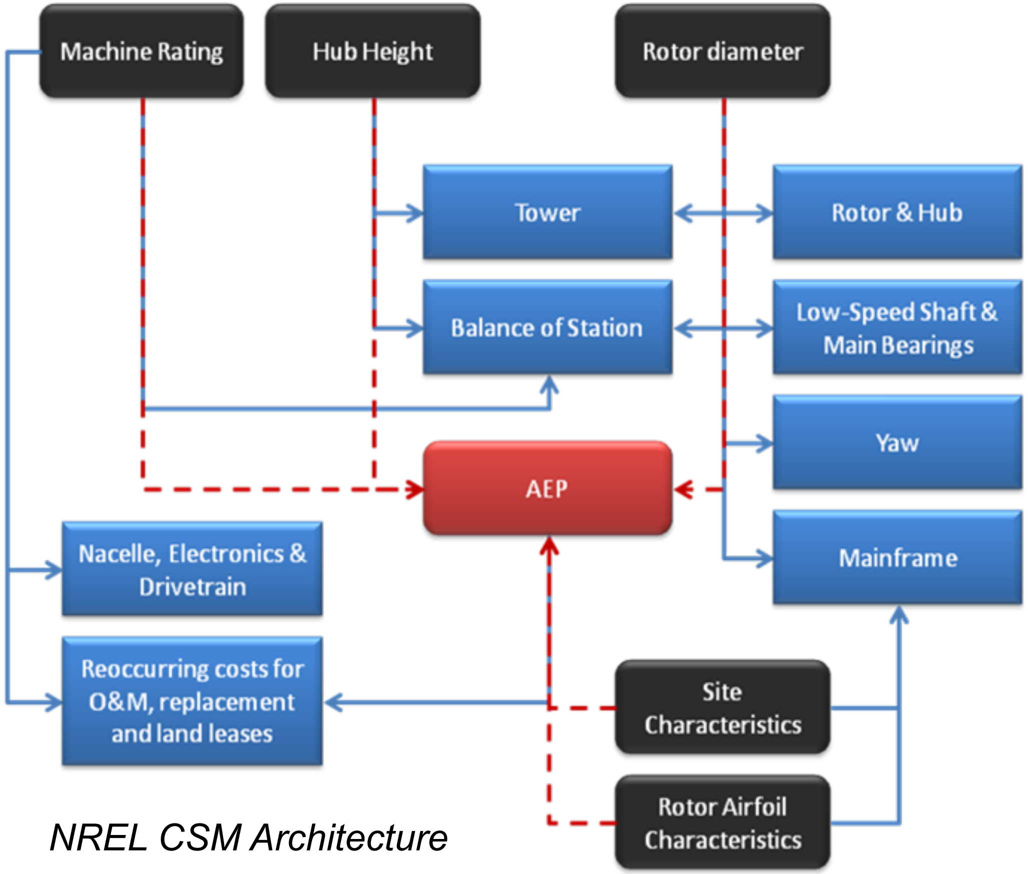
Modelling LCOE

- Modelling of LCOE is complex and involves a large scope and timeframe with many sub-systems and disciplines including both physical and cost modelling of the system
  - Significant couplings
    - E.g. farm layout → support structures, collection system, energy production
    - E.g. control strategy → energy production, reliablity
  - LCOE modeling a constant balance of fidelity (computational cost) and accuracy (believability)



Cost Modelling Approaches

1. Empirical models
   - Largely models based on historical data (often collected through NDA) through “Curve fits” or simple functional representations of costs based on small number of inputs
   - Benefits: easy to use and low computational costs
   - Challenges: quickly obsolete and hard to adapt to new technical, site and market contexts
   - Examples: NREL Cost and Scaling Model (CSM); DTU Offshore Wind Cost Model



NREL CSM Architecture
Fingersh et al 2006

Cost Modelling Approaches

2. Process- or task-based models
   - Explicitly model key activities required in different project sub-activities (i.e. site preparation, installation of different major sub-systems, operations & maintenance)
   - Benefits: moderate computational cost, adaptable for new technologies, site and market contexts
   - Challenges: difficult to capture time-dependent features affecting tasks
   - Examples: NREL Land Based Balance of System Cost Model; NREL Offshore Renewables Balance-of-system Installation Tool ('ORBIT'); ORE Catapult COMPASS

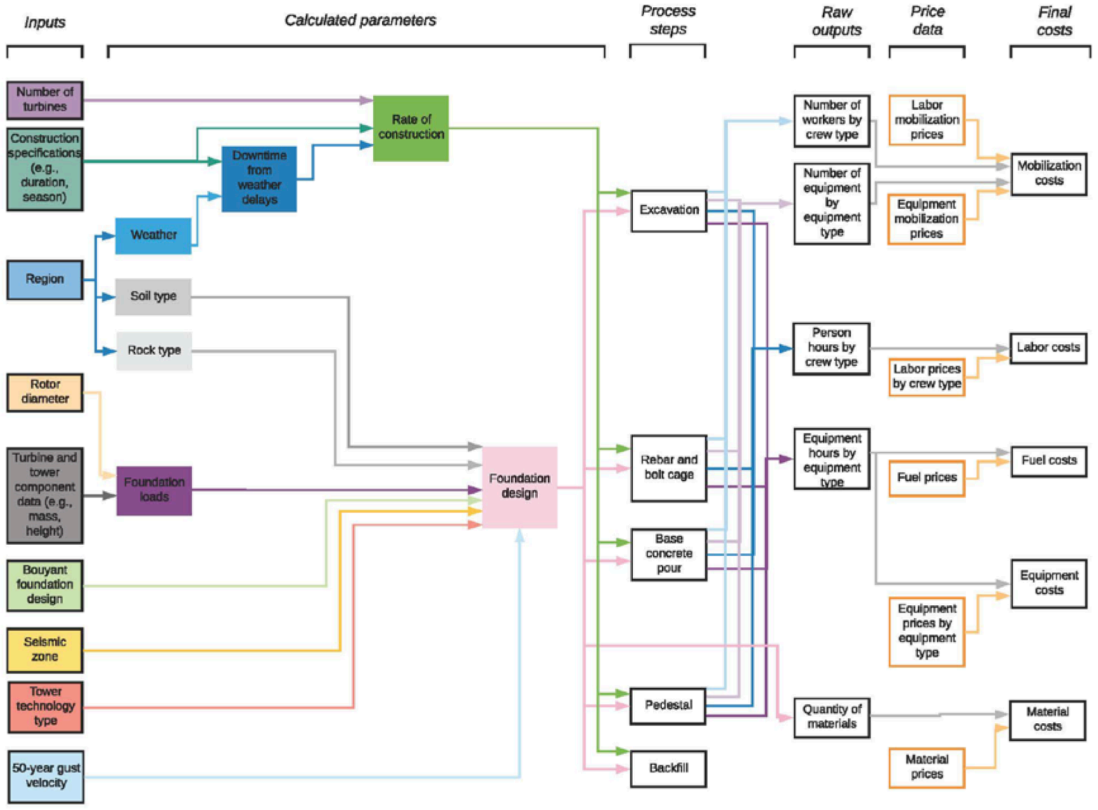


Figure 4. Process diagram for foundation construction

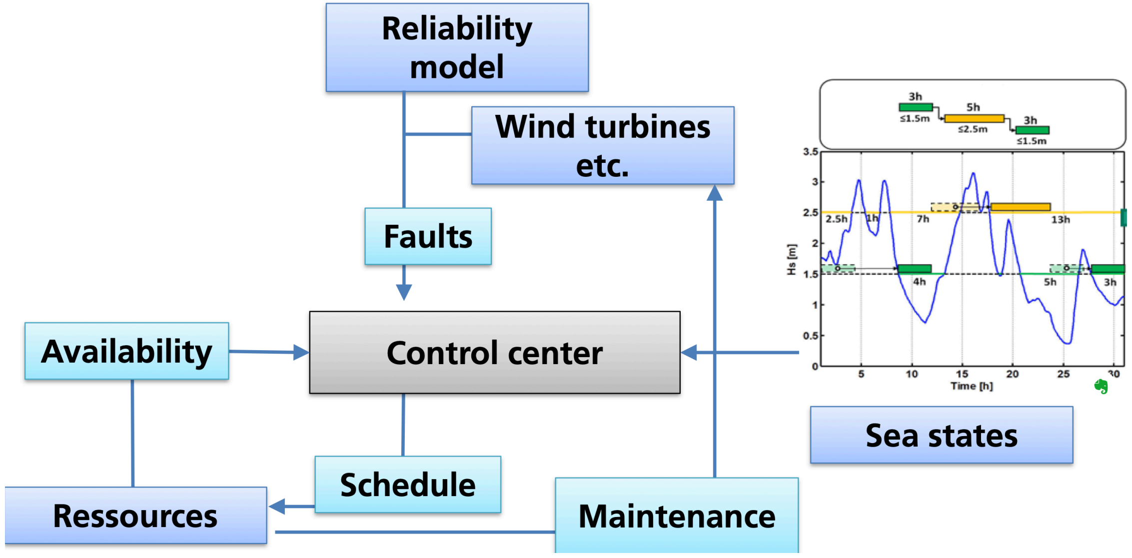
NREL Land-Based Wind Balance of System Cost Model (LandBOSSE) – foundation construction sub-process

Source: Eberle et al 2019

Cost Modelling Approaches

3. Schedule-based models
   - Explicitly take into account the sequencing between and within project development sub-activities; also may address geospatial/locational issues
   - Benefits: adaptable for new technologies, site and market contexts and address time-dependencies of activities (and their uncertainties)
   - Challenges: relatively high computational cost and require highly detailed information
   - Examples: Fraunhofer IWES Offshore TIMES and COAST 2.0; TNO O&M Calculator; University of Strathclyde Installation Tool and SPOC;

Approach – time series based simulation



Fraunhofer IWES Offshore TIMES schedule-based O&M tool[1]

[1] *Source*: https://www.rave-offshore.de/files/downloads/konferenz/konferenz-2018/Finale_Praesentationen/16342.pdf

Cost Modelling Approaches

- Model type selection depends on use-case (for example):

Preliminary site prospecting → Preliminary farm design → Detailed farm design and cost engineering

Parametric LCOE model → Task-based cost model → Schedule-based cost model

- Not one-to-one – may model some processes in different steps using different types of modelling approaches (mix-and-match)
- Assessing turbine and farm innovations properly depends on extent of impact to balance of system and operations & maintenance processes and adequacy of model to capture impacts

Offshore Wind Energy Cost Modelling

- LCOE Modelling Background and Approaches
- Topfarm Overview
- DTU Wind Energy Offshore Cost Model
- Analysis for Select Sites
- Summary and Future Work

What is TOPFARM?

TOPFARM is the DTU Wind Energy software platform for optimization of wind farm design and operational strategies in both onshore and offshore applications

TOPFARM Applications

- The TOPFARM framework offers:
  - State-of-the-art capabilities in the modeling of wind farm physics and costs
  - Fast and efficient computational framework leveraging gradients (when possible) but allowing for a diverse set of novel techniques for solving wind farm MDAO problems
  - Flexibility and reconfiguration-ease for specific problem applications
    - onshore or offshore, various types of constraints and design considerations, easy integration of addtional models
  - Customization for a wide-variety of use cases from pre- to post-construction for both research and industry needs

Cost Modelling in TOPFARM

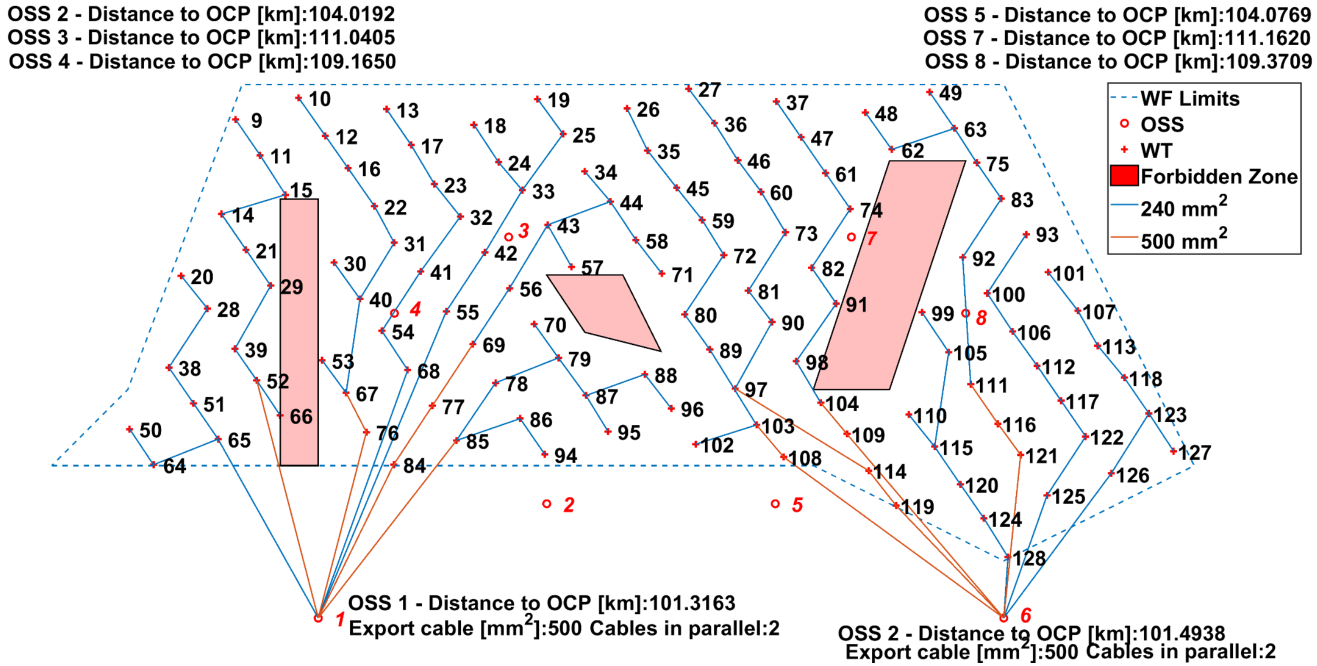
- TOPFARM Cost Models:
  - NREL Cost and Scaling Model – widely used, publicly available cost model from the early 2000s
    - Based on detailed WindPACT design studies
    - Consistently updated cost factors by NREL through 2012
    - Built for land-based technology and later adapted to offshore
  - DTU Offshore Cost Model
    - New model targeting offshore applications
    - Based on empirical data calibrated for 2017 €
    - Currently undergoing updates

Inputs	Outputs
Turbine rotor diameter	DEVEX
Turbine rated power	CAPEX
Turbine hub height	OPEX
Water depth	ABEX
Distance from shore	LCOE
Turbine Number	IRR
Project lifetime	NPV
Discount Rate	
Electricity Price	
AEP	

DTU Offshore Wind Cost Model I/O

TOPFARM Models – Cost Models

- Balance of system design models:
  - Infrastructure Roads and Cables can be included *in situ* via a minimimum spanning tree algorithm
  - Additional and more advanced methods support more detailed design of electrical infrastructure post-layout optimization
    - Use heuristics and meta-heuristics
    - Also possible to address contingencies
  - Full integration of models to TOPFARM in process



Deterministic integrated design – Collection and transmission system (Perez Rua et al 2020)

Offshore Wind Energy Cost Modelling

- LCOE Modelling Background and Approaches
- Topfarm Overview
- DTU Wind Energy Offshore Cost Model
- Analysis for Select Sites
- Summary and Future Work

DTU Wind Energy Offshore Cost Model

- DTU Wind Energy Offshore Cost Model Overview
  - Empirical model based on high-level “curve fit” functions to industry data (calibrated to 2017 € - currently being updated)
  - Major cost analysis includes:
    - DEVEX – environmental survey, sea bed survey, met mast, and development services
    - CAPEX – turbine, foundation (monopile or jacket), electrical system (array cables, substation and export cable), and DEVEX
    - OPEX – personnel, vessel and equipment rental, component repair and replacement
    - ABEX – abandonment expenditures

Inputs	Outputs
Turbine rotor diameter	DEVEX
Turbine rated power	CAPEX
Turbine hub height	OPEX
Water depth	ABEX
Distance from shore	LCOE
Turbine Number	IRR
Project lifetime	NPV
Discount Rate	
Electricity Price	
AEP	

DTU Offshore Wind Cost Model I/O

DTU Wind Energy Offshore Cost Model

- Cost breakdown structure for turbine and foundation in more detail:
  – Bill of Materials
  – Direct production costs (direct labor, production overhead)
  – Selling, General and Adminstirative (overhead, R&D nd SG&A)
  – Project Costs (financing, installation and commissioning, harbor storage and assembly,and transport)
  – Profit

Turbine Bill of Materials	
Blades	
Hub	Structure
	Pitch bearing
	Pitch system
	Secondary equipment
Drivetrain	
Nacelle	Cooling
	Converter
	Controller
	Yaw system
	Canopy
	Secondary equipment
Tower	Tower structure
	Tower, internal
	Power cables
	Secondary equipment
	Main transformer

DTU Offshore Wind Cost Model Turbine BOM

Offshore Wind Energy Cost Modelling

- LCOE Modelling Background and Approaches
- Topfarm Overview
- DTU Wind Energy Offshore Cost Model
- Analysis for Select Sites
- Summary and Future Work

Analysis for Select Sites

- IEA Wind Task 26 Comparative Cost Study Sites from 2017
  - Generic sites a representation of typical sites for a given country

Inputs	Denmark	Germany	Netherlands	UK
Turbine rotor diameter (m)	164	126	130	154
Turbine rated power (MW)	8	6	4.0	6
Turbine hub height (m)	105	95	88.5	108
Average water depth (m)	16	35	33	25
Distance from shore (km)	60	80	78	27

Miriam Noonan, Tyler Stehly, David Mora, Lena Kitzing, Gavin Smart, Volker Berkhout, Yuka Kikuchi.
2020. *IEA Wind TCP Task 26: Offshore Wind Energy International Comparative Analysis*. NREL/TP-6A20-71558. https://www.nrel.gov/docs/fy19osti/71558.pdf

Analysis for Select Sites

- Resulting LCOE in comparison to 2017 study:

LCOE (€/kWh)	Denmark	Germany	Netherlands	UK
Noonan et al 2020	0.092	0.099	0.102	0.115
DTU Offshore Wind Cost Model	0.094	0.116	0.145	0.096

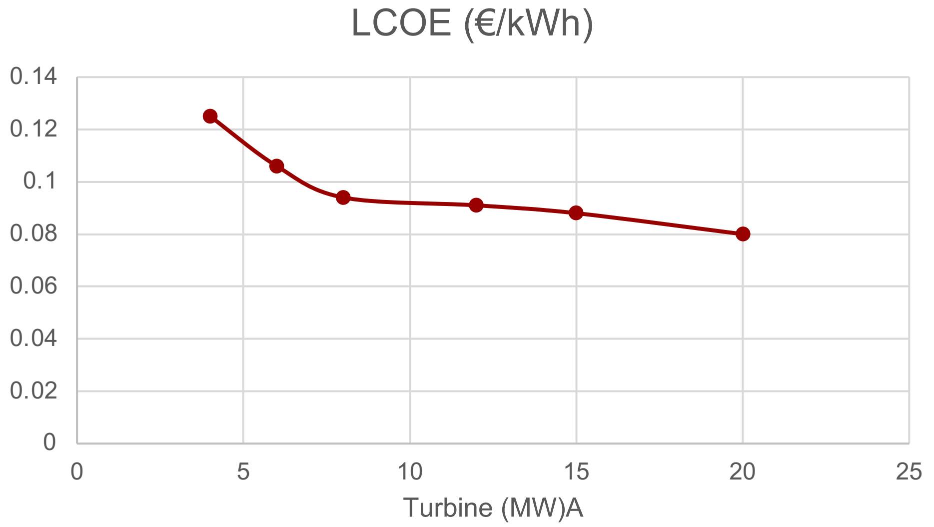
- DTU cost model favors larger size turbines (Germany versus Netherlands) and more heavily penalizes projects that are farther from shore and iin deeper water (Germany and Netherlands versus UK and Denmark) compared to 2017 study

- DTU cost model based on project data from Denmark (2017 analysis done both using country-specific analysis approach and generic analysis approach)

Analysis for Select Sites - Scaling

- Results for scaling machines using Denmark generic site:

Turbine (MW)	Rotor Diameter (m)	LCOE (€/kWh)
4	130	0.125
6	154	0.106
8	164	0.094
12	220	0.091
15	240	0.088
20	240	0.08



- Model suggests marginal decrease in LCOE for increased turbine size beyond 8 MW
  - May be due to calibration with historical data
  - Ongoing benchmarking underway with international consortium

Offshore Wind Energy Cost Modelling

- LCOE Modelling Background and Approaches
- Topfarm Overview
- DTU Wind Energy Offshore Cost Model
- Analysis for Select Sites
- Summary and Future Work

Summary

- LCOE continues to be a critical metric to evaluate the potential of new innovations, assess the economic viability of wind farm development, and compare across energy technology solutions

- Cost modelling to support LCOE assessment in offshore wind has evolved substantially with increasing model sophsitication and detail

- Simplified models built from data, abstraction from more detailed analysis, or a combination thereof are needed to support applications such as design optimization for wind turbine and farm applications

- The DTU offshore cost model is an empirical cost model to support wind farm design optimization in the DTU TOPFARM framework

- Analysis with the DTU cost model enables the assessment of the influence of some key design parameters on farm LCOE – however it is insensitive to others

Future Work

- DTU Offshore Cost Model undergoing further updates for different technological, site and market contexts

- More detailed design-based cost models are in development and will be used in conjunction with the DTU Offshore Cost Model for LCOE analysis

- Updated model will be integrated with open-source version of TOPFARM for use in wind farm design studies (formal release planned for later in 2021)

- A benchmarking effort across cost models from different organizations is underway – results likely to be presented at Wind Energy Science Conference 2021

Thank you for your attention

Correspondence: Katherine Dykes, kady@dtu.dk

DTU