Life cycle cost modelling of next generation offshore wind farms

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Overview of presentation

Development of offshore wind energy in Europe

2013

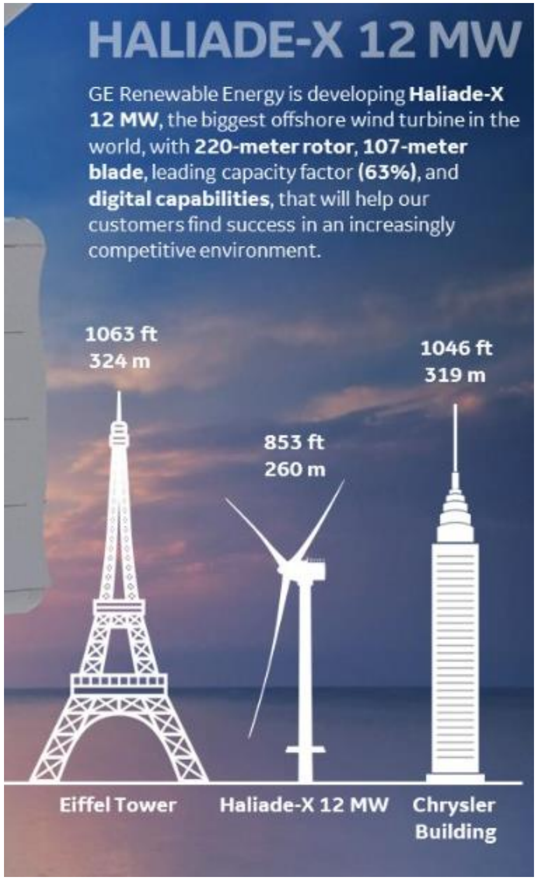
- Europe installed 418 new offshore wind turbines in 2013
- A total of 2,080 turbines were installed and grid connected accounting for 6.6 GW installed capacity
- The average size of offshore wind turbines was 4MW
- Average distance to shore was 30km and average water depth 20mWorks were carried out in 21 wind farms with a further 22 GW of consented new projects

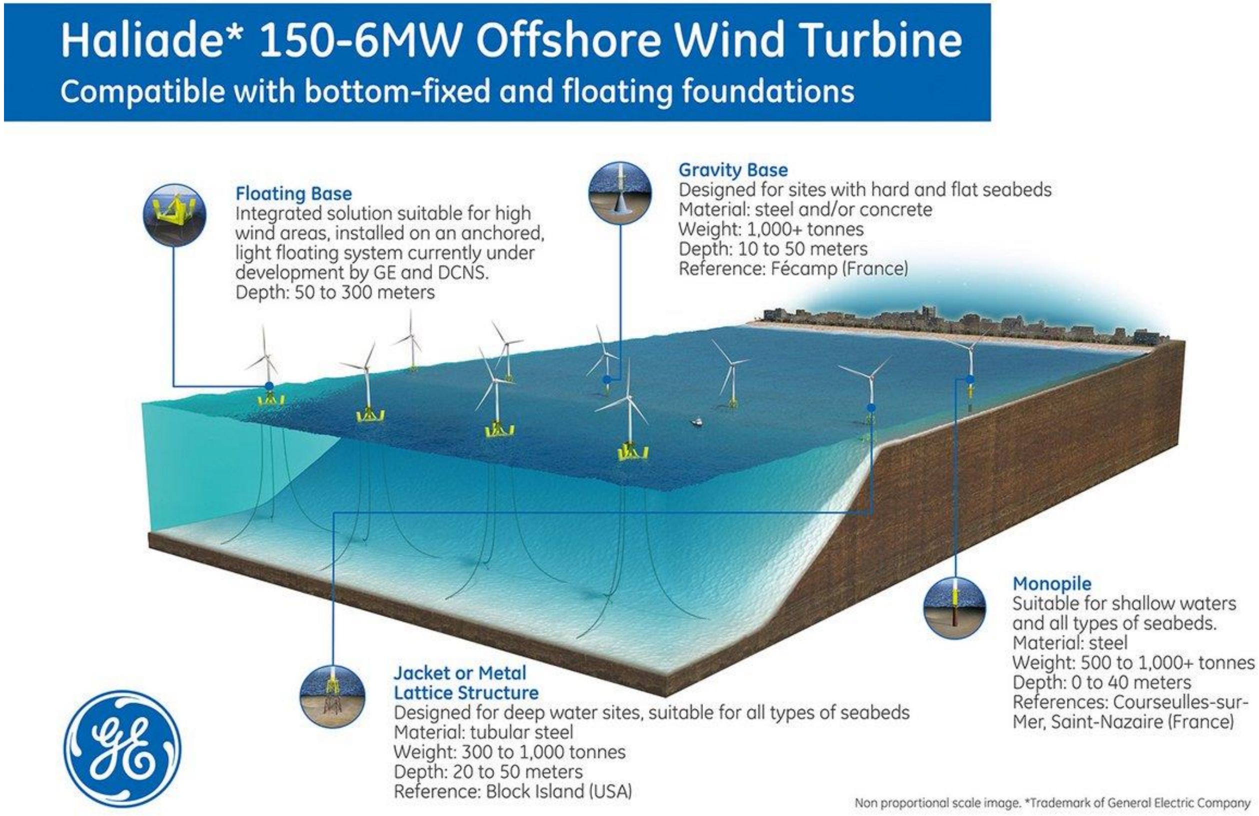
2018

- Europe installed 2.6 GW of new offshore wind energy capacity in 2018
- €10.3bn of investments made for 4.2 GW of additional capacity
- Total capacity grew by 18% to 18.5 GW
- 15 new offshore wind farms were completed last year
- The UK and Germany accounted for 85% of the installations: 1.3 GW and 969 MW respectively
- The average offshore turbine size was 6.8 MW, 15% up on 2017
- The largest turbine in the world was connected in the UK (the V164-8.8 MW from MHI Vestas Offshore Wind)

http://www.ewea.org/Statistics/

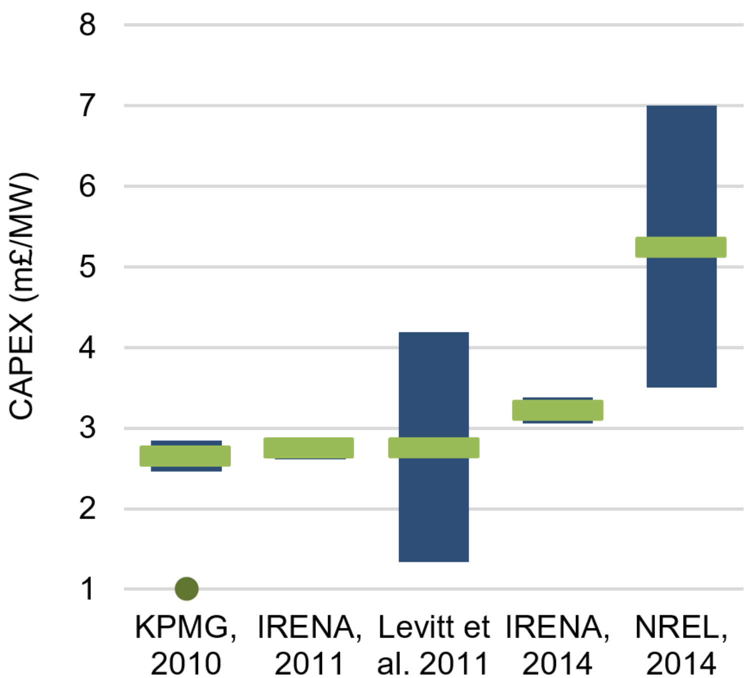
Next generation wind farms - Haliade-X 12 MW

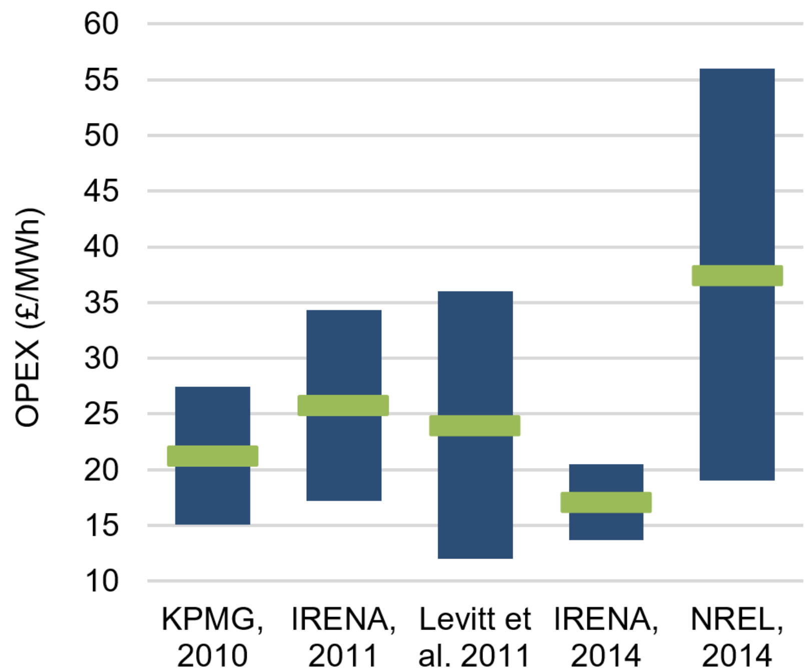




https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine

Uncertainty in cost data





Range and average values of capital costs (£m/MW) in existing literature compiled and converted to 2015 £ currency (Sources: [1]–[5])

Range values of operating costs (£/MWh) in existing literature compiled and converted to 2015 £ currency (Sources: [1]–[5])

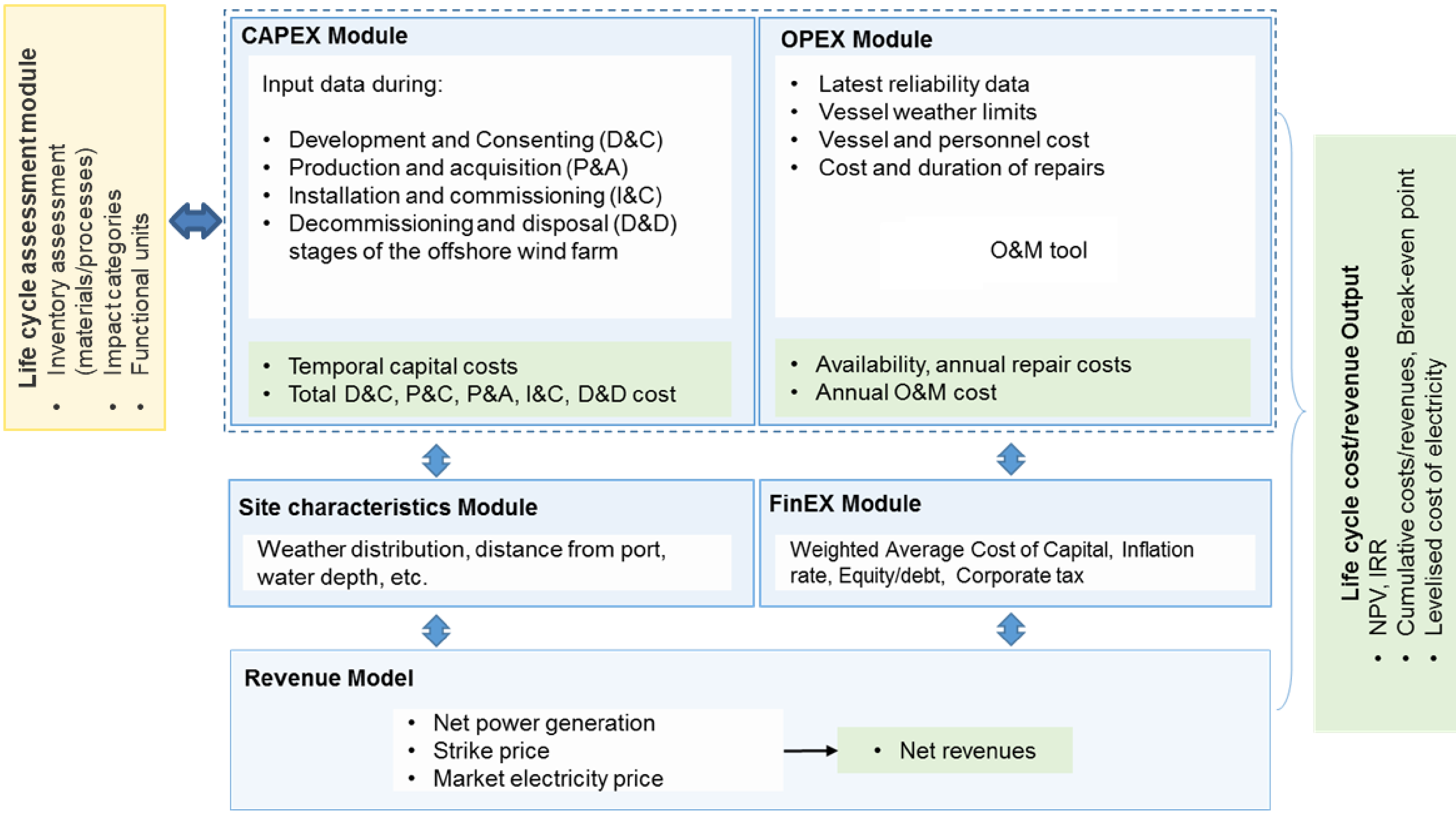
Review of existing cost models

Model	Institution/Owner	Year	Commercial	Software	Model output	Ref
›s *et al*	CENTEC, Univ. of Lisbon (Portugal)	2018	No	GRIF (Petri Net)	Costs, Availability	[38]
O&M ss	ECN	2017	Yes	Not specified	Accessibility	[39], [40]
di *et al*	Univ. of Exeter (UK)	2017	No	Not specified	Costs, Availability	[41]
ihl and ısen	Alborg Univ. (Denmark)	2017	No	Not specified	Cost, Availability RCM	[42]
al	Universities of Playmouth, Stirling, Liverpool (UK), and Le Havre (France)	2016	No	Xpress IVE	Costs, Optimal maintenance	[43]
ıko *et al*	Univ. of Hamburg, Bremen Univ. of Applied Sciences (Germany)	2015	No	BPMN 2.0, DESMO-J (Java)	Costs	[44], [45]
erud *et al*	Univ. of Stavanger (Norway)	2014	No	AnyLogic (Java)	Costs Availability	[46]
lcob	NOWITECH	2013		Not specified	Costs Availability	[36]
oodie *et al*	Univ. of Strathclyde (UK)	2013	No	MATLAB	Costs Availability	[47]
et al	Univ. of Michigan (USA)	2010	No	DESJAVA	Costs Availability	[48]
s	DNV	2010	Yes	Not specified	Net present value	[49]
OX	Systecon	2010	Yes	Not specified	Costs Optimal maintenance	[50]
rola tool	Iberdrola	2010	Yes	Not specified	CAPEX/OPEX Power	[51]
OST	BMT	2009	Yes	Not specified	Net present value	[51]
E	ECN	2009	Yes	MATLAB	Costs	[52], [53]
ard *et al*	KTH Chalmers (Sweden)	2009	No	GAMS, MATLAB	Costs	[54], [55]
el- rez and ısen	Alborg Univ. (Denmark)	2008	No	Not specified	Costs	[56], [57]
	GL Garrad Hassan (DNV)	2007	Yes	Not specified	Costs Lost production	[37]
O&M	ECN	2007	Yes	Excel @Risk	Costs	[35], [58], [59]
adwaj *et al*	Loughborough Univ. TWI Ltd (UK)	2007	No	Excel @Risk	Net present value	[60]
awus *et al*	Robert Gordon Univ. (UK)	2006	No	Excel, Cristal Ball	Net present value	[61]
OFF-model	ECN	2004	No	Excel @Risk	Costs	[62]
ens *et al*	Universite Libre de Bruxelles (Belgium)	2004	No	GRIF (Petri Net)	Costs Availability	[63]
TOFAX	TU Delft (Netherlands)	1997	No	Excel	Costs Availability Power	[35]

Features of a high fidelity cost/revenue model

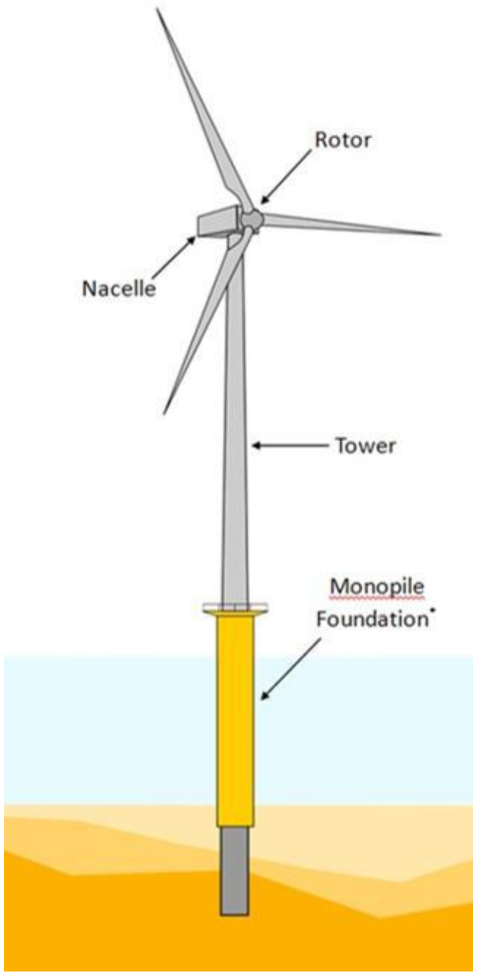
- A high-fidelity model should predict the different costs of a typical OW farm in a lifecycle-phase-sequence pattern, by:
  - adopting the most up-to-date **parametric equations** found in the literature;
  - developing **new parametric equations** where latest data are available;
  - accurately predicting **operation and maintenance costs** in conjunction with latest reliability data through appropriate engineering models;
  - Considering the **real time of money** through accounting for the time that expenses and revenues have occurred;
  - **considering uncertainty** of key variables in a systematic way and assigning confidence levels on the expressions of estimated KPIs.

Integrated cost revenue model



Production and acquisition phase (P&A)

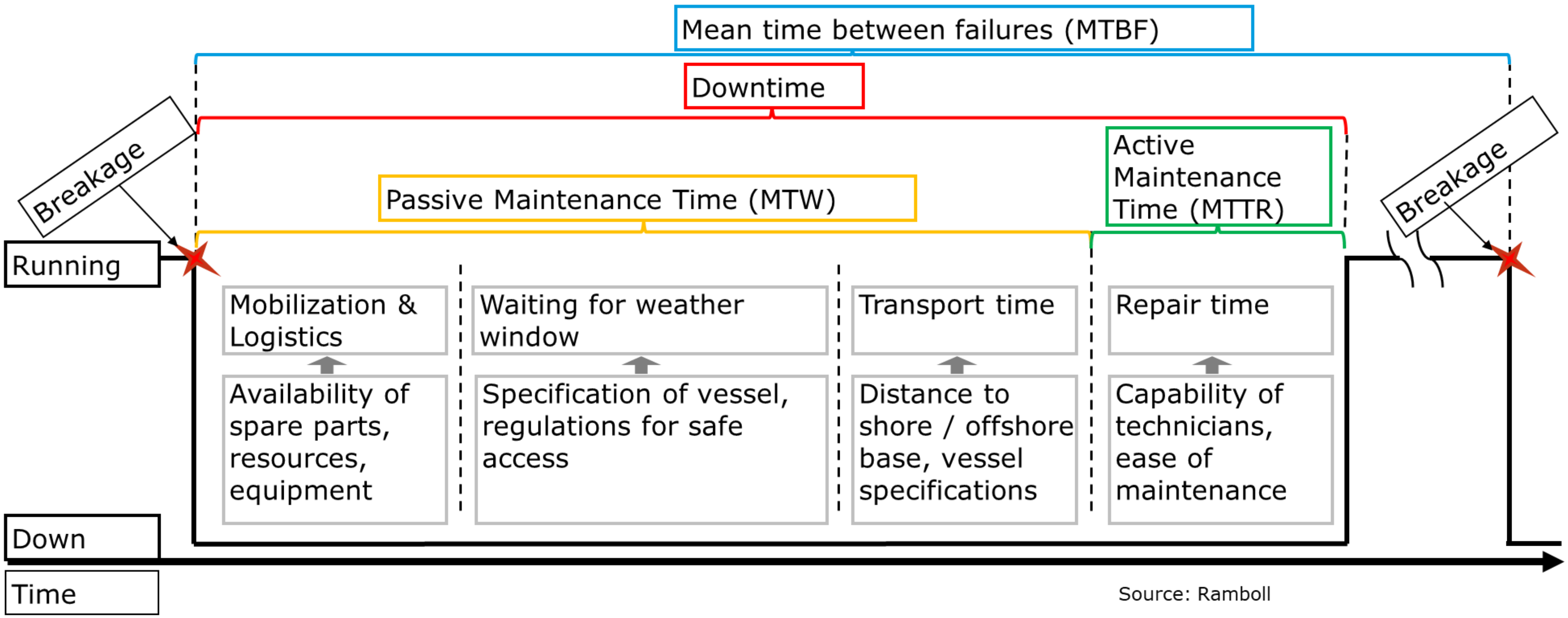
- Turbine cost is function of the wind turbine capacity
- BOP (Balance of the Plant)
  - Foundation cost is a function of the wind turbine capacity (PWT), the water depth (WD), the hub height (h) and the rotor diameter (d)
  - Electric system
    - Cable costs are functions of the number of the wind turbines (NWT), the rotor diameter (d), and the distance from shore (D)
      - Array cables
      - Offshore export cables
      - Onshore export cables
    - Substation cost is a function of number of the wind turbines, rated power of transformer (ATR), the nominal voltage transformer (Vn) and the wind farm capacity (PWF)
  - Control system



Installation and commission phase (I&C)

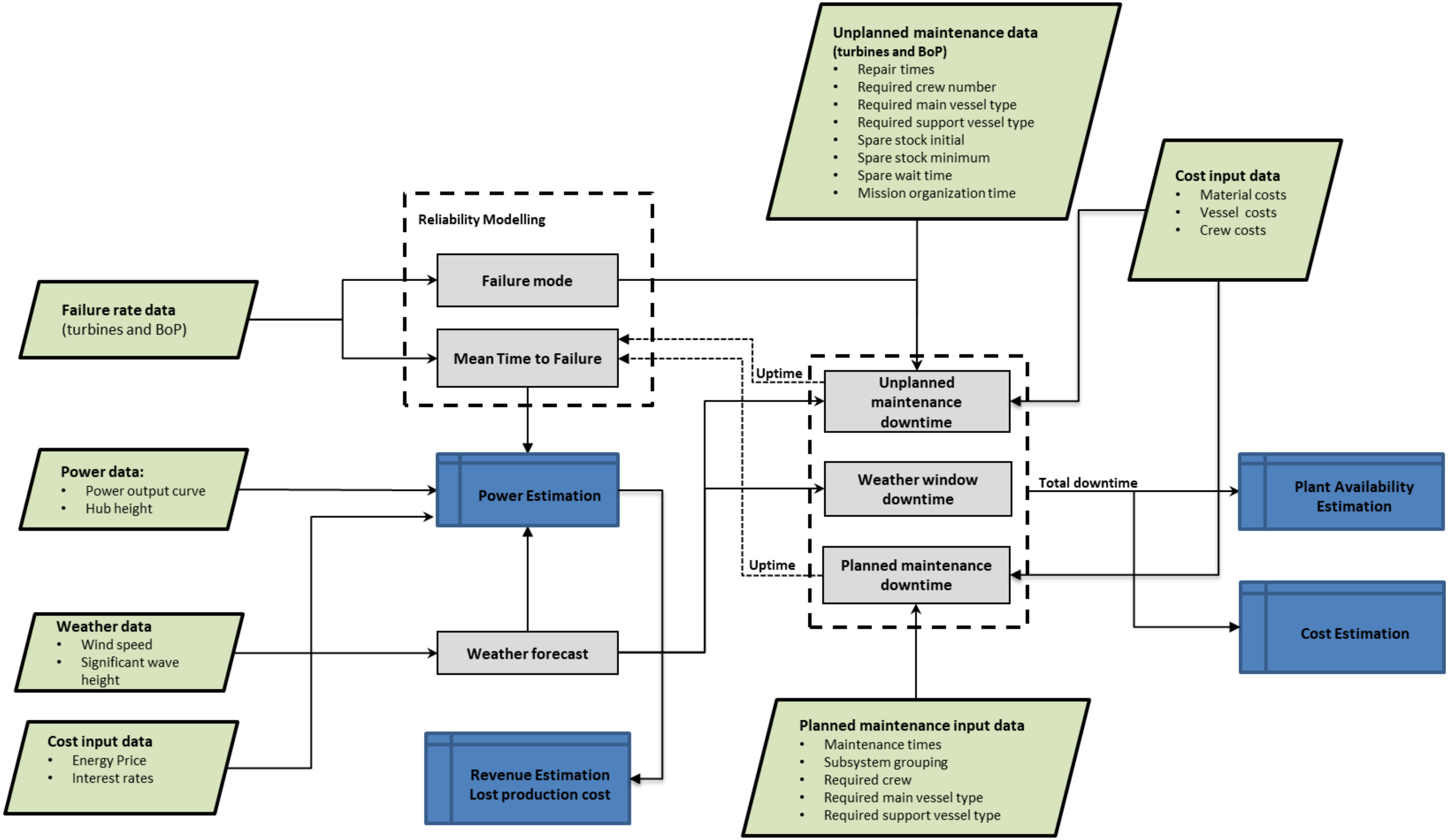
- This phase refers to all activities involving:
  - the transportation and installation of the wind farm components, as well as those related to the port,
  - commissioning of the wind farm and
  - insurance during construction.
- Once a suitable number of components are in the staging area, the offshore construction starts with installation of the foundations, transition piece and scour protection, followed by the erection of the tower and the wind turbines.
- Accordingly, the installation of the offshore substation, the array cables and finally the export cables and onshore substation takes place.

Availability basics



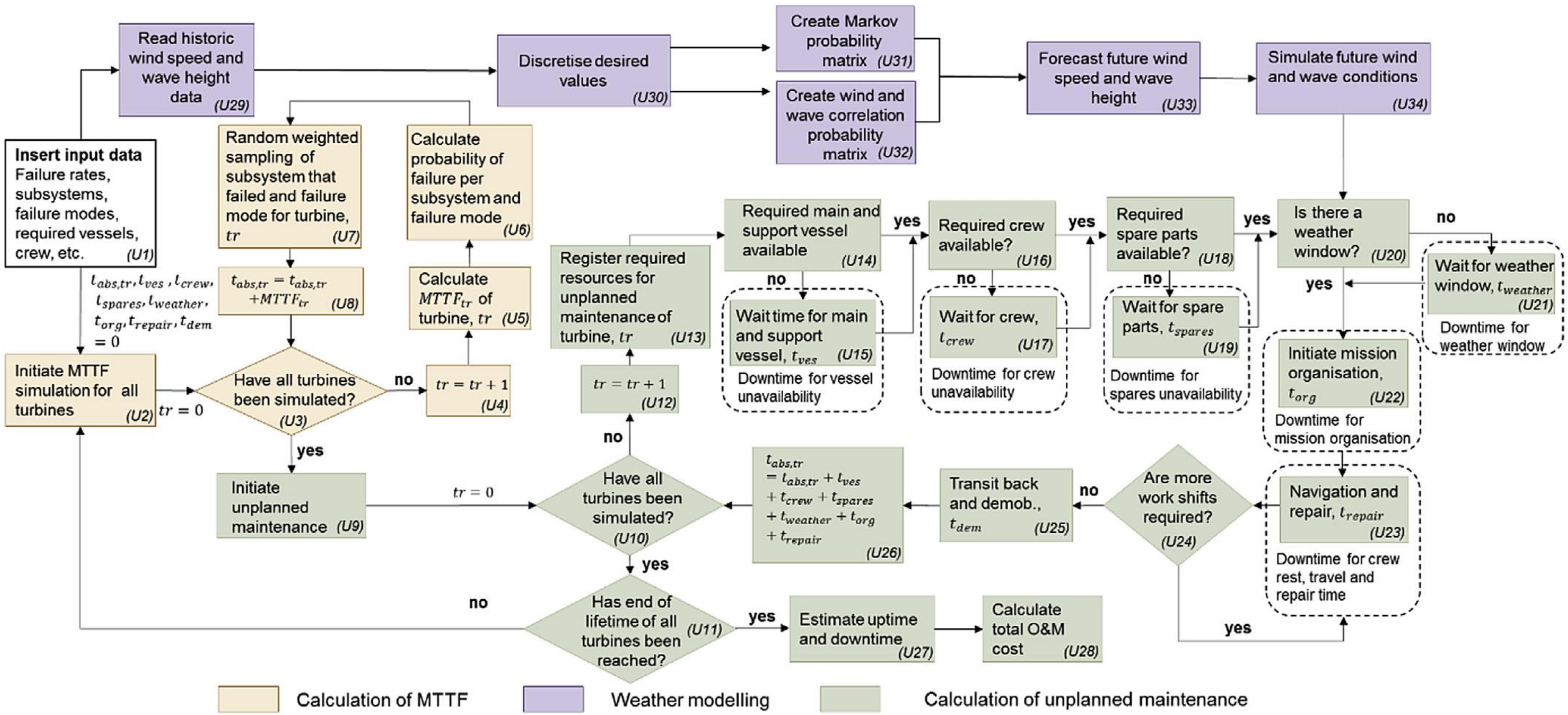
Source: Ramboll

O&M module



Unplanned maintenance data
(turbines and BoP)
• Repair times
• Required crew number
• Required main vessel type
• Required support vessel type
• Spare stock initial
• Spare stock minimum
• Spare wait time
• Mission organization time
Cost input data
• Material costs
• Vessel costs
• Crew costs
Reliability Modelling
Failure mode
Mean Time to Failure
Failure rate data
(turbines and BoP)
Uptime
Unplanned maintenance downtime
Weather window downtime
Planned maintenance downtime
Uptime
Total downtime
Plant Availability Estimation
Cost Estimation
Power data:
• Power output curve
• Hub height
Power Estimation
Weather data
• Wind speed
• Significant wave height
Weather forecast
Cost input data
• Energy Price
• Interest rates
Revenue Estimation
Lost production cost
Planned maintenance input data
• Maintenance times
• Subsystem grouping
• Required crew
• Required main vessel type
• Required support vessel type

O&M module



Read historic wind speed and wave height data (U29)
Discretise desired values (U30)
Create Markov probability matrix (U31)
Create wind and wave correlation probability matrix (U32)
Forecast future wind speed and wave height (U33)
Simulate future wind and wave conditions (U34)
Insert input data
Failure rates, subsystems, failure modes, required vessels, crew, etc. (U1)
Random weighted sampling of subsystem that failed and failure mode for turbine, tr (U7)
Calculate probability of failure per subsystem and failure mode (U6)
$t_{abs,tr}, t_{ves}, t_{crew}, t_{spares}, t_{weather}, t_{org}, t_{repair}, t_{dem} = 0$
$t_{abs,tr} = t_{abs,tr} + MTTF_{tr}$ (U8)
Calculate $MTTF_{tr}$ of turbine, tr (U5)
Initiate MTTF simulation for all turbines (U2)
$tr = 0$
Have all turbines been simulated? (U3)
no
$tr = tr + 1$ (U4)
yes
Initiate unplanned maintenance (U9)
$tr = 0$
Register required resources for unplanned maintenance of turbine, tr (U13)
$tr = tr + 1$ (U12)
no
Have all turbines been simulated? (U10)
yes
Has end of lifetime of all turbines been reached? (U11)
no
yes
Estimate uptime and downtime (U27)
Calculate total O&M cost (U28)
Required main and support vessel available (U14)
yes
no
Wait time for main and support vessel, t_{ves} (U15)
Downtime for vessel unavailability
Required crew available? (U16)
yes
no
Wait for crew, t_{crew} (U17)
Downtime for crew unavailability
Required spare parts available? (U18)
yes
no
Wait for spare parts, t_{spares} (U19)
Downtime for spares unavailability
Is there a weather window? (U20)
no
yes
Wait for weather window, $t_{weather}$ (U21)
Downtime for weather window
Initiate mission organisation, t_{org} (U22)
Downtime for mission organisation
Navigation and repair, t_{repair} (U23)
Downtime for crew rest, travel and repair time
Are more work shifts required? (U24)
no
yes
Transit back and demob., t_{dem} (U25)
$t_{abs,tr} = t_{abs,tr} + t_{ves} + t_{crew} + t_{spares} + t_{weather} + t_{org} + t_{repair}$ (U26)
Calculation of MTTF
Weather modelling
Calculation of unplanned maintenance

Decommissioning and Disposal Phase (D&D)

- Decommissioning and disposal cost of the wind farm include:
  - the removal of the wind turbine (nacelle, tower and transition piece) as well as the balance of the plant (foundations, scour protection, cables and substations)
  - the site clearance
  - the port preparation
  - the onshore transportation to the disposal sites
  - the disposal processes

Parameter	Value
Turbine and foundation removal - Inputs	
Remove time per turbine with a self-propelled jack up vessel	15h/turbine
Complete turbines (including foundations) capacity of a Jack Up vessel	5turbines/trip
Number of jack up vessels for the removal of the wind turbines	3
Number of workboats employed for the decommissioning of the turbines	2
Number of technicians per workboat	5
Offloading time of turbines/monopiles	8h/item
Time to cut the foundation	6h/foundation
Time to lift the item and place on the deck	11h/item
Turbine and foundation removal - Outputs	
Total duration of each trip which equals the sum of the travel time to and from site, the removal time of turbines and monopile, the loading time and the intra-field movement time of the jack up vessel	244h
Total time per trip (adjusted to weather and working hours)	26days
Total effective days for turbines and monopiles removal divided by the number of vessels, $T_{Effectdays,TF-Rem}$	243days
Total cost of hiring technicians and workboats during the decommissioning of the wind turbines, $C_{vessel,dd}$	£4.13 million
Total cost for removing all wind turbines with monopiles, $C_{TF,dd}$	£83.5 million
Offshore substation removal - Inputs	
Pile diameters of jacket substructure	2.6m
Cutting rate of the pile	1h/m
Lifting time of topside substructure	3h
Cut time of topside	12h
Reposition time of vessel to each leg of the jacket substructure	8h
Offshore substation removal -Outputs	
Time to cut the 4 piles	10.4h
Total time for the removal of the two substations, $T_{Effectday,Substat-Rem}$	8.7days
Total cost for removing the two substations, $C_{offSubst,dd}$	£1.18 million
Cables removal	
Rate of removal of inner-array cables	600m/day
Rate of removal of export cables	875m/day
Cost of cables removal, $C_{cables,dd}$	£11.9 million
Site clearance	
$Area = -51.5 + 0.41 \cdot d + 0.65 \cdot n_{WT}$, in km	83.37km²
Total cost for site clearance, $C_{clear,dd}$	£5.38 million

Revenue module

- It calculates the cash inflows taking into account the following factors:
  - Net energy production,
  - Strike price,
  - Market electricity price.
- Operator sells electricity under a Power purchase agreement to a licenced supplier or trader at an agreed reference market price

- Financial support for offshore wind in the UK:
- Contracts for Difference scheme
  - CfD states that the power producer is paid the difference between a pre-determined "strike price" and the reference market price
  - The Low Carbon Contracts (LCCC), a government-owned Company pay the difference between strike price and the agreed reference price
  - 15 year contract term
  - Strike price is set by the clearing price from an auction.

FinEx Module

- WACC and inflation

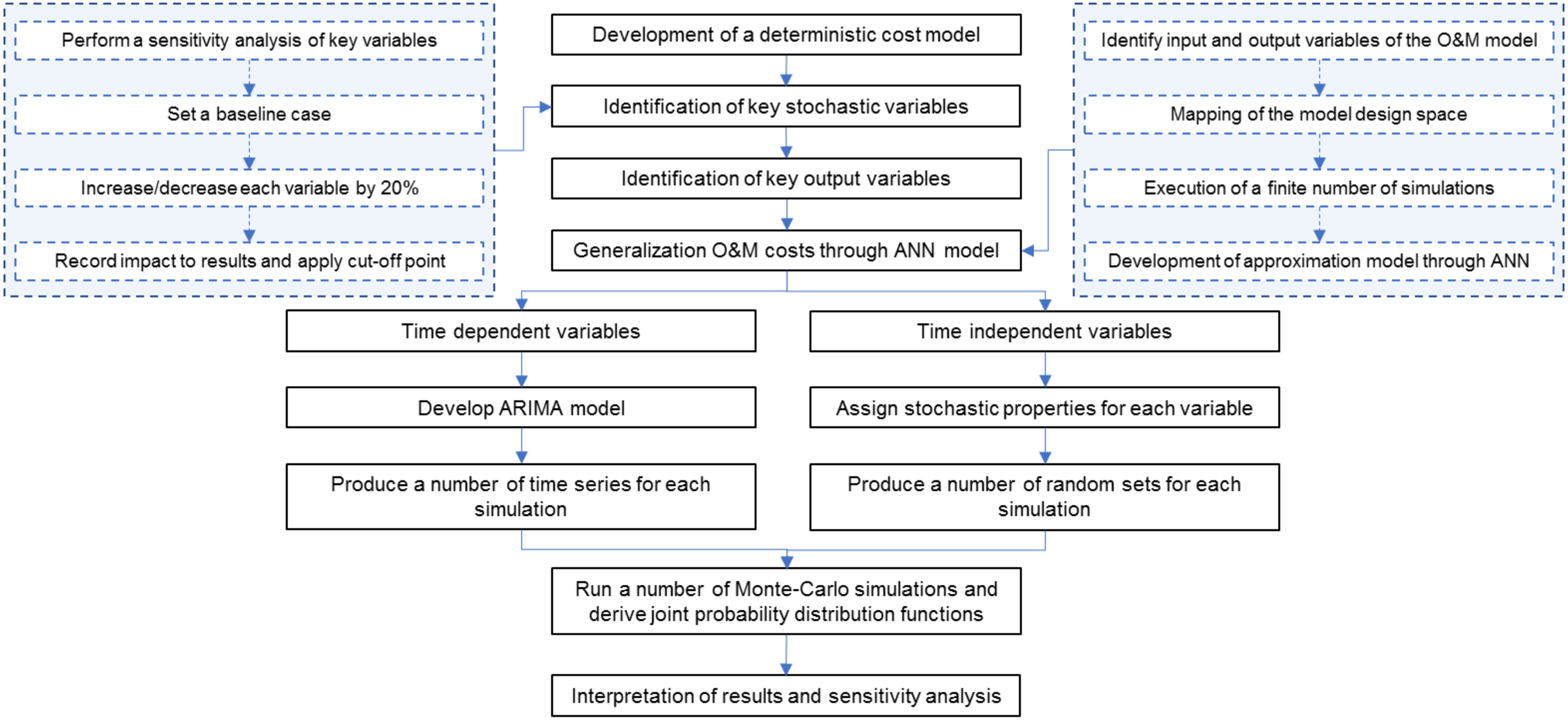
$$WACC = \frac{VE}{V} \cdot RoE + \frac{VD}{V} \cdot Rd \cdot (1 - tc)$$

- where, VE is the market Value of Equity, VD is the market Value of Debt, $V = VE + VD$, RoE denotes the Return on Equity, and Rd the interest rate on debt.

- Real discount rate (or else real WAAC) integrates the inflation adjustment and the discount of cash flows according to Fisher Equation :

$$WACC_{real} = \frac{1+WACC}{1+R_{infl}} - 1 \approx WACC_{nom} - R_{infl}$$

Stochastic expansion of cost revenue model



Case study: 504 MW offshore wind farm

Wind farm

- Total wind farm capacity, P_{WT}=504MW
- Projected operational life of the wind farm,n=25years
- Construction years, T_{constr}=5years
- Number of turbines, n_{WT}=140

Site characteristics

- Distance to port, D=36km
- Water depth, WD=26m

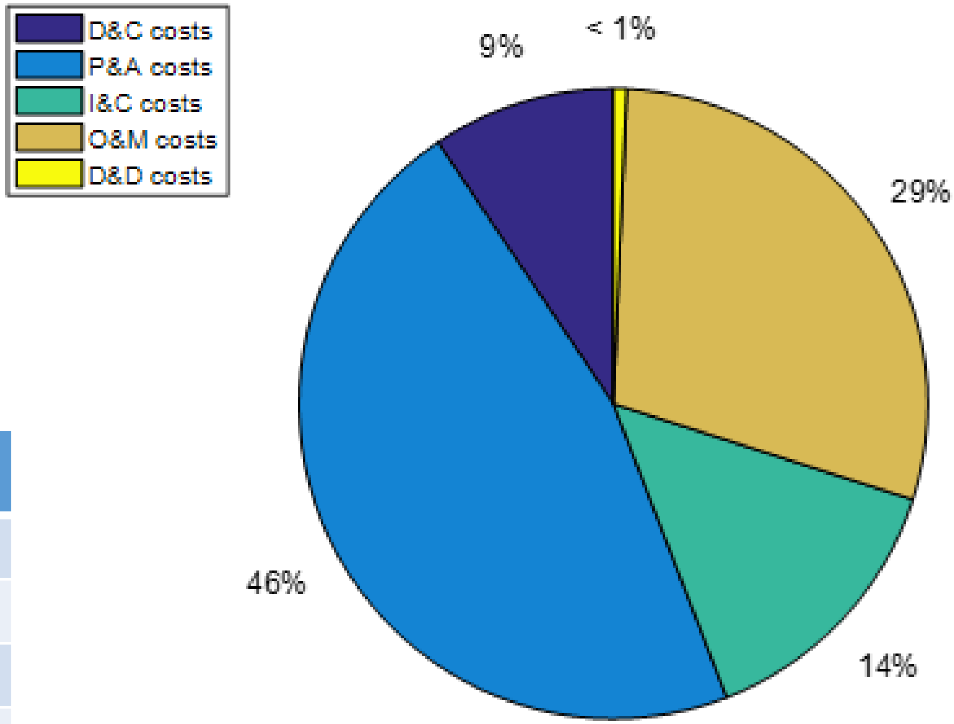
Wind turbine

- Rotor diameter, d=107m
- Hub height, h=77.5m
- Pile diameter, D_{pile}=6m
- Rated power: 3.60MW
- Cut-in speed:4m/s
- Cut-out speed: 25m/s

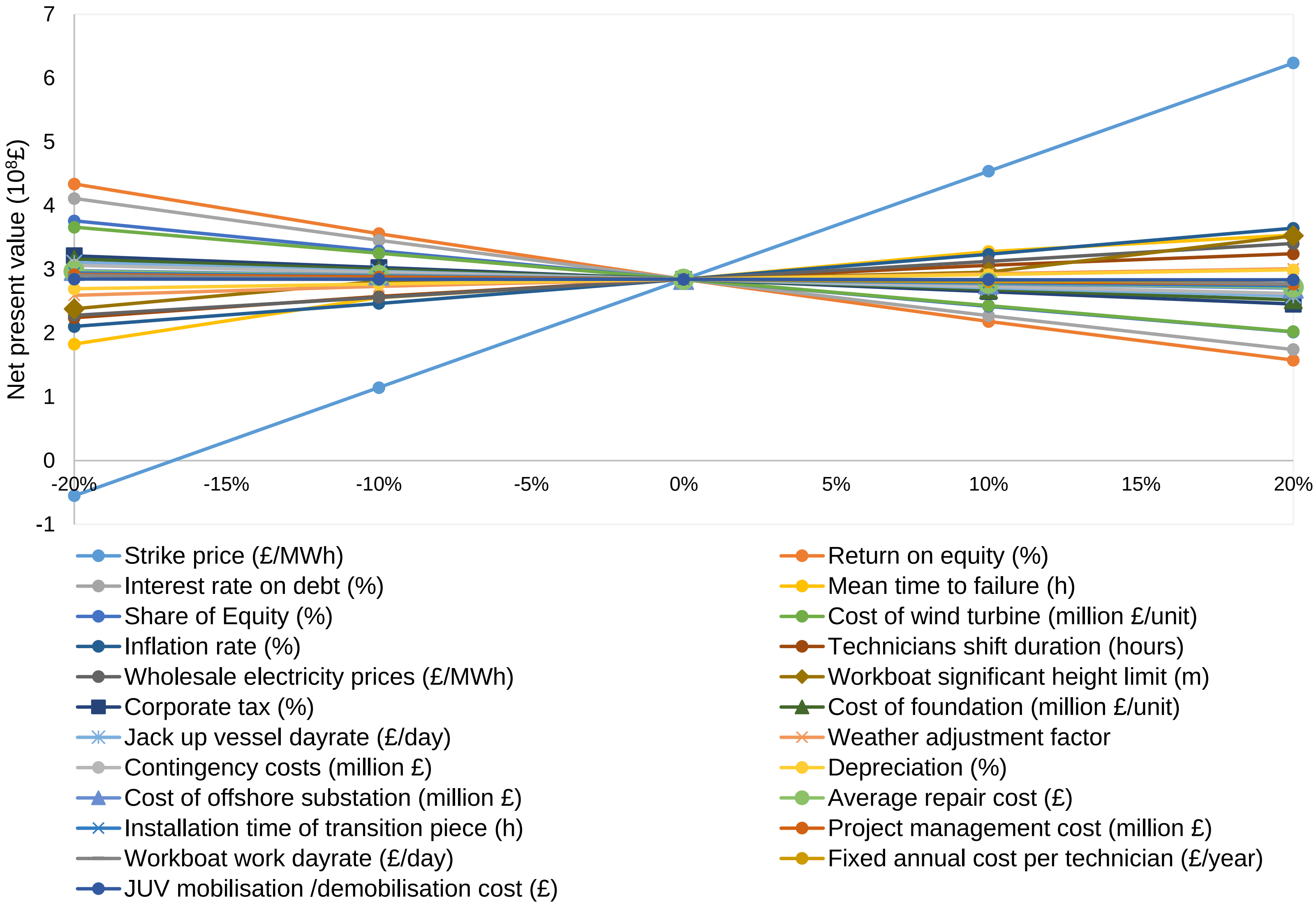
Case study: Life cycle cost breakdown

- CAPEX = £1.674 billion (Total undiscounted)
- Annual OPEX = £56.597 million
- NPV = £284 million at a real discount rate of 6.15% with an IRR= 10.3%
- LCOE= 109 £/MWh

Lifecycle costs	Value
CAPEX in k£	
Total P&C costs, $C_{P\&C}$	205,750
Total P&A costs, $C_{P\&A}$	1,040,230
Total I&C costs, $C_{I\&C}$	305,742
Total D&D costs, $C_{D\&D}$	122,860
OPEX in k£/year	
Total O&M costs, $C_{O\&M}$	56,597



Case study: Sensitivity analysis



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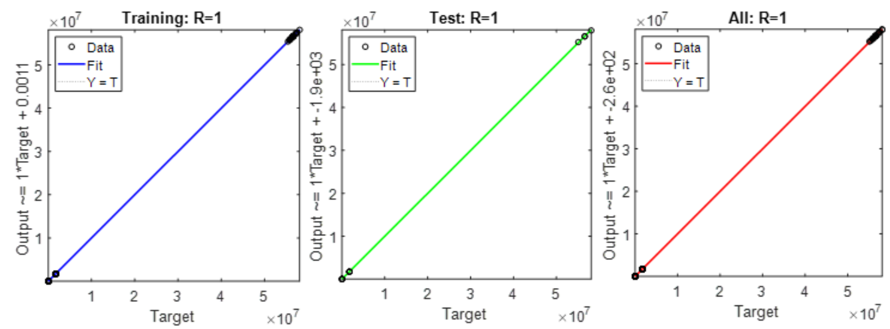
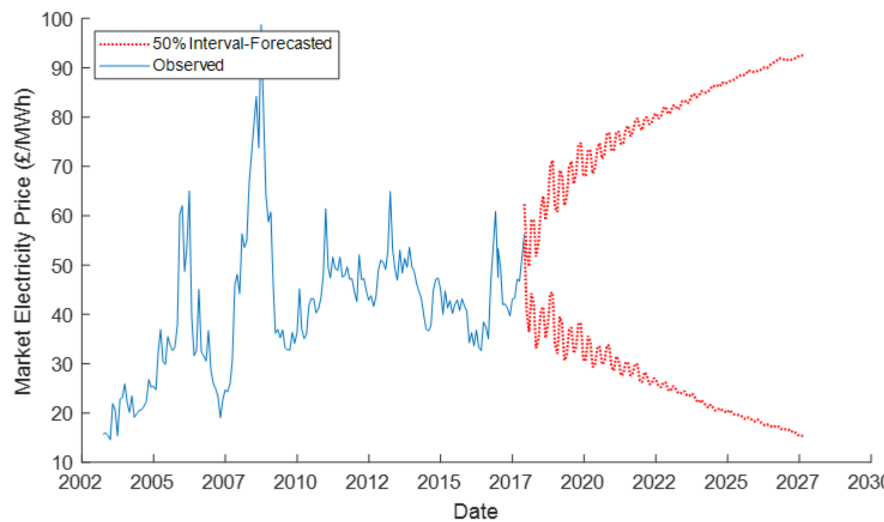
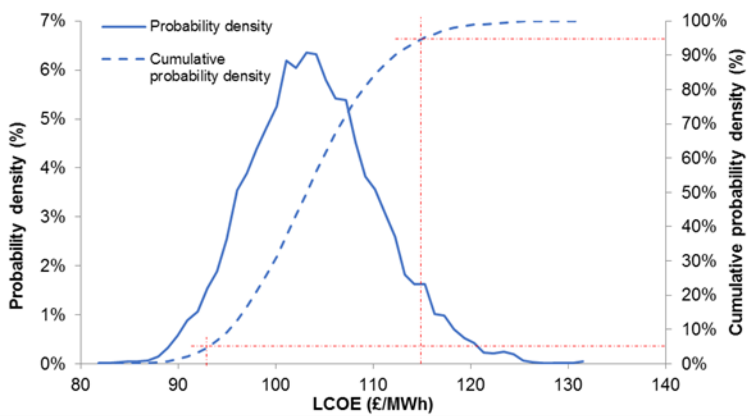
Stochastic inputs/Approximation models

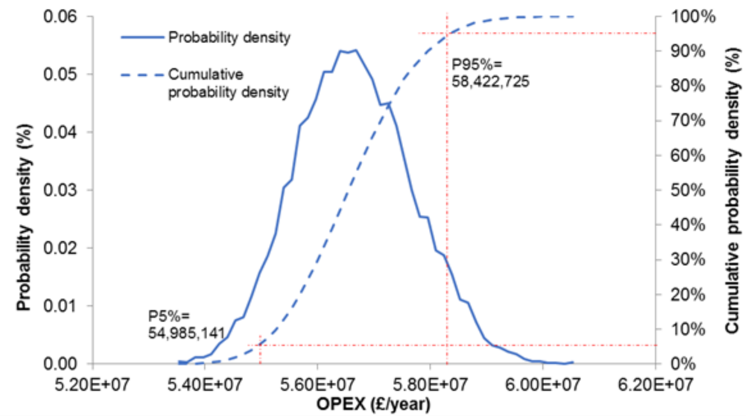
Variable	Type of distribution	Characteristic values
CAPEX parameters		
Cost of wind turbine (million £/unit)	Uniform	Min: 2.85, Max: 3.37
Cost of foundation (million £/unit)	Uniform	Min: 1.14, Max: 2.77
Technicians shift duration (hours)	Normal	μ= 11, σ=1.1
Weather adjustment factor	Normal	μ= 0.85, σ=0.085
Contingency costs (million £)	Normal	μ=126.4, σ=12.6
Cost of offshore substation (million £)	Normal	μ= 29.5, σ=2.95
OPEX parameters		
Average repair cost (£)	Normal	μ= 1, σ=0.1
Mean time to failure (h)	Normal	μ= 1, σ=0.1
Revenue parameters		
Strike price (£/MWh)	3 Scenarios	
Wholesale electricity prices (£/MWh)	ARIMA	
FINEX parameters		
Share of Equity (%)	Normal	μ= 30.00%, σ=3.00%
Inflation rate (%)	Normal	μ= 2.50%, σ=0.25%
Corporate tax (%)	Normal	μ= 17.00%, σ=1.70%
Depreciation (%)	Normal	μ=18.00%, σ=1.80%
Return on equity (%)	Normal	μ= 15.80%, σ=1.58%
Interest rate on debt (%)	Normal	μ= 7.00%, σ=0.70%
General parameters		
Workboat significant height limit (m)	Normal	μ= 1.8, σ=0.18
Workboat work dayrate (£/day)	Normal	μ= 3,250, σ=325
Jack up vessel dayrate (£/day)	Normal	μ= 112,600, σ=11,260
JUV mobilisation /demobilisation cost (£)	Normal	μ= 405,000, σ=40,500
Fixed annual cost per technician (£/year)	Normal	μ=95,000, σ=9,500

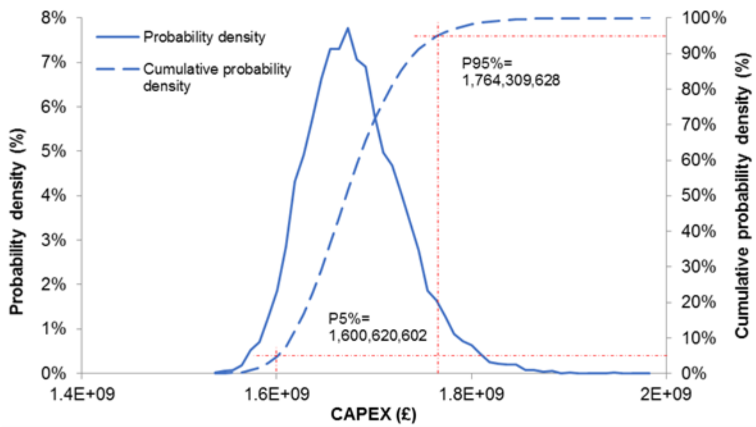


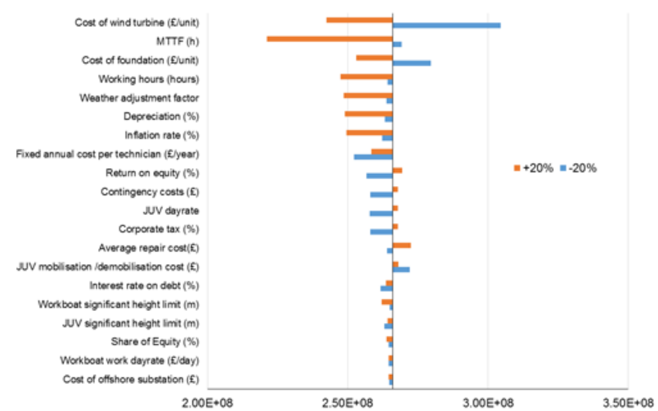


Probabilistic results

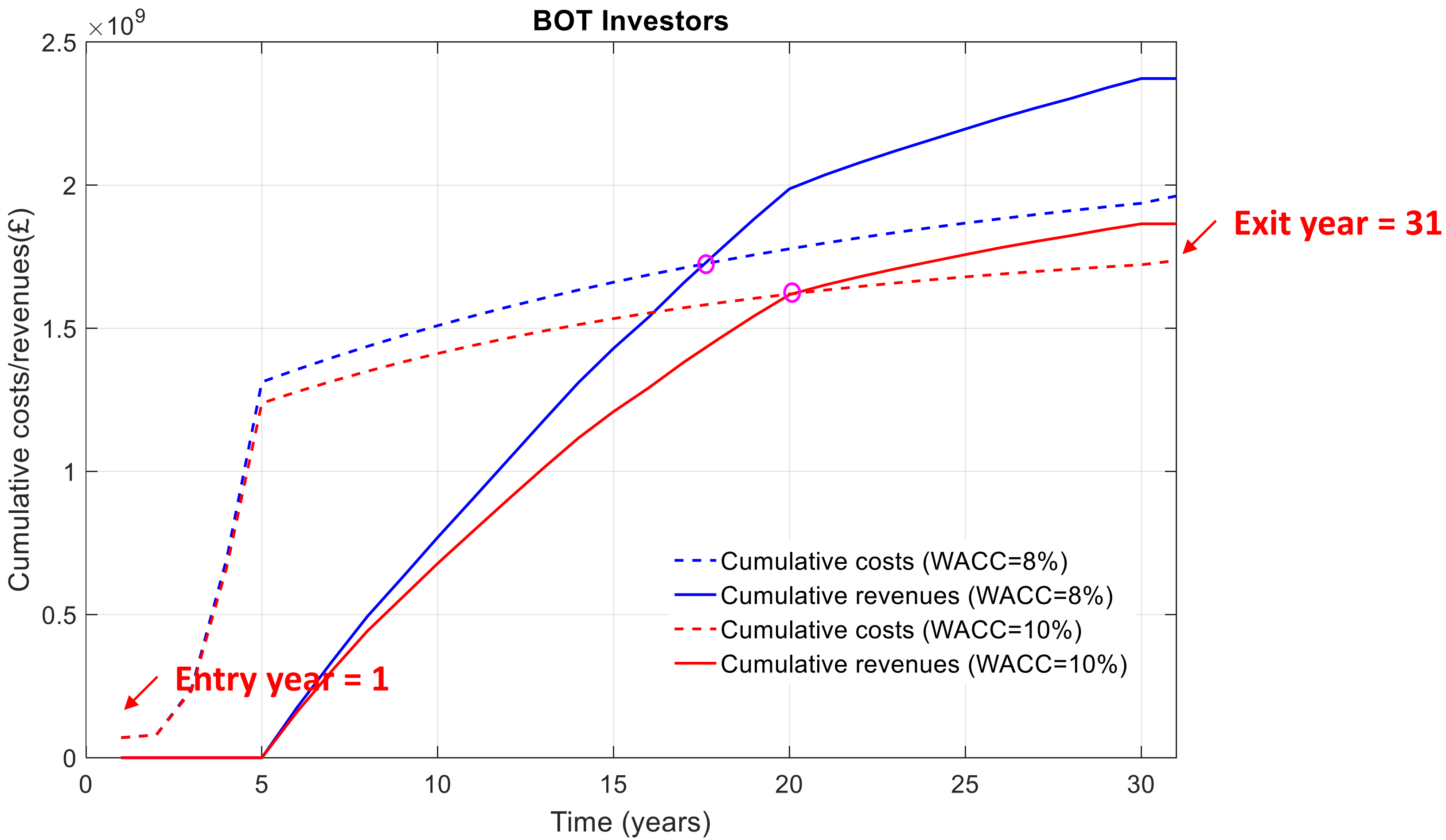






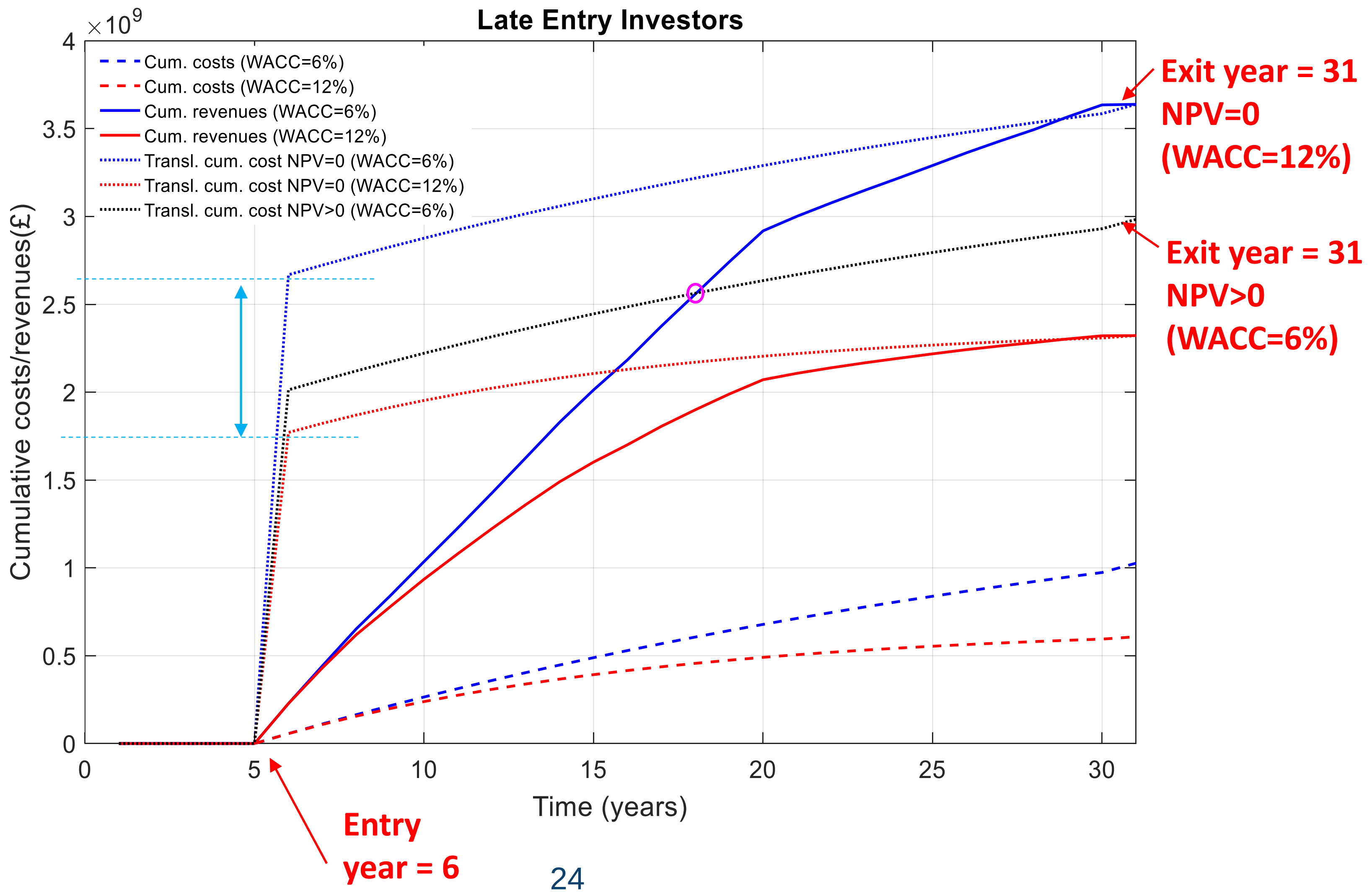


Cost/revenue profiles of different investor strategies – BOT investors



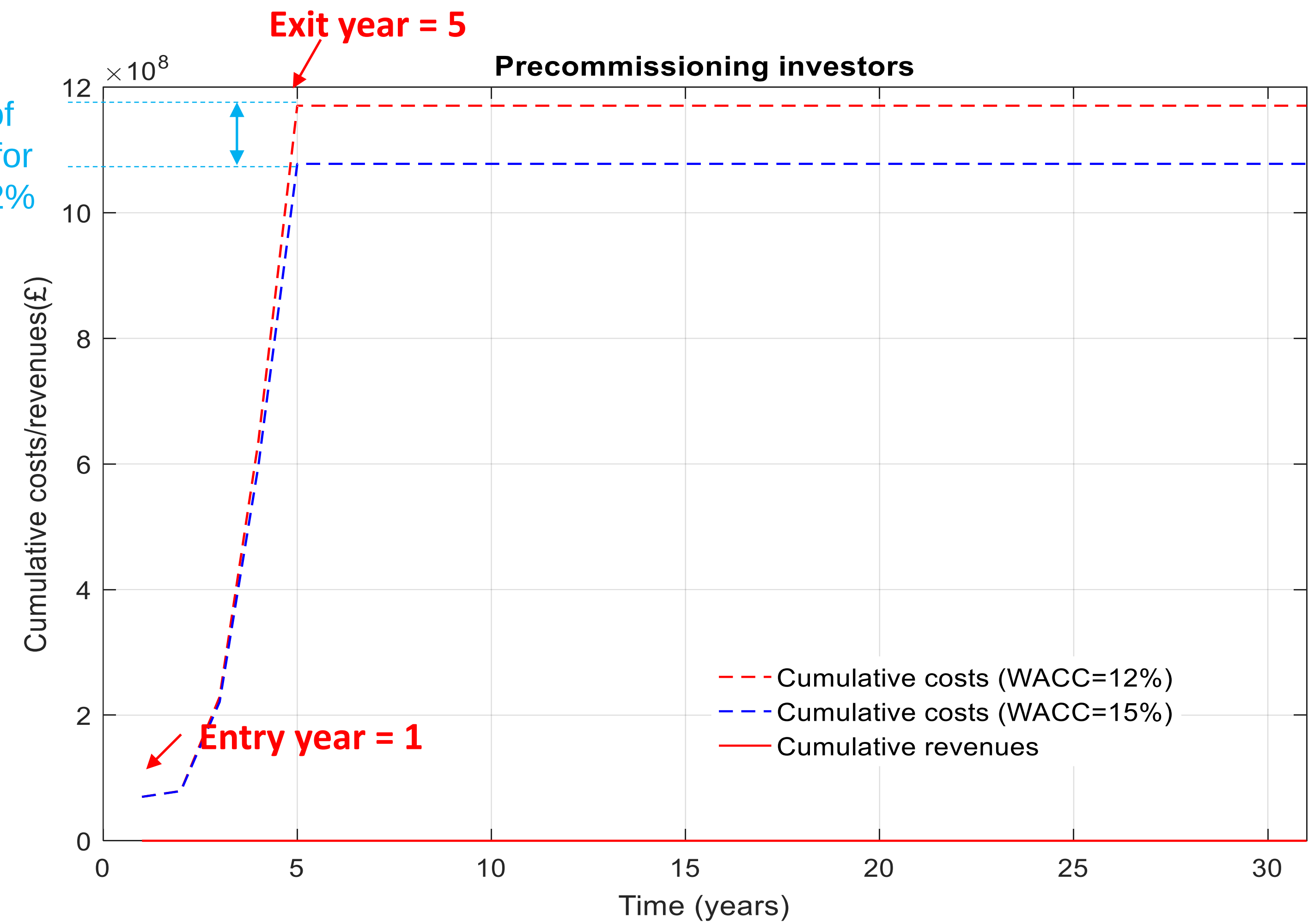
Cost/revenue profiles of different investor strategies – Late entry investors

Maximum prices=£1.55b - £2.52b

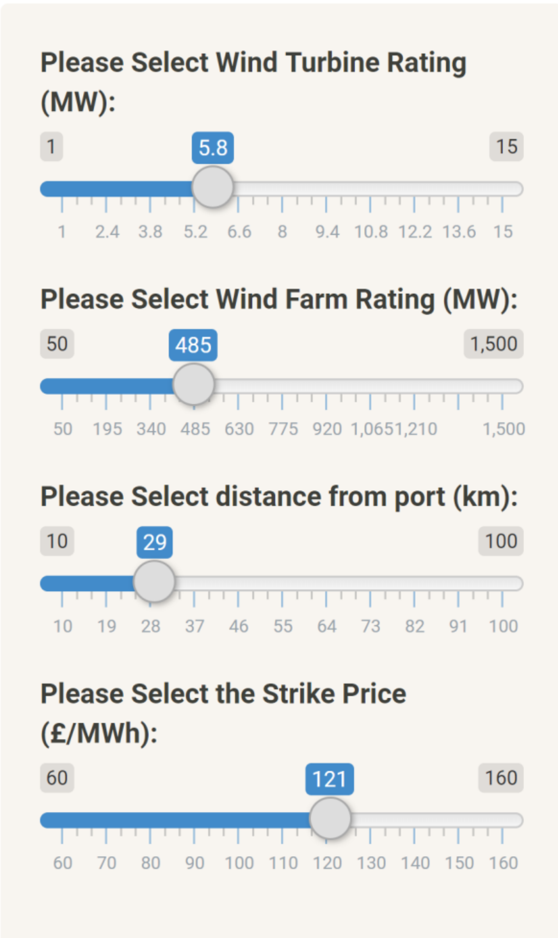


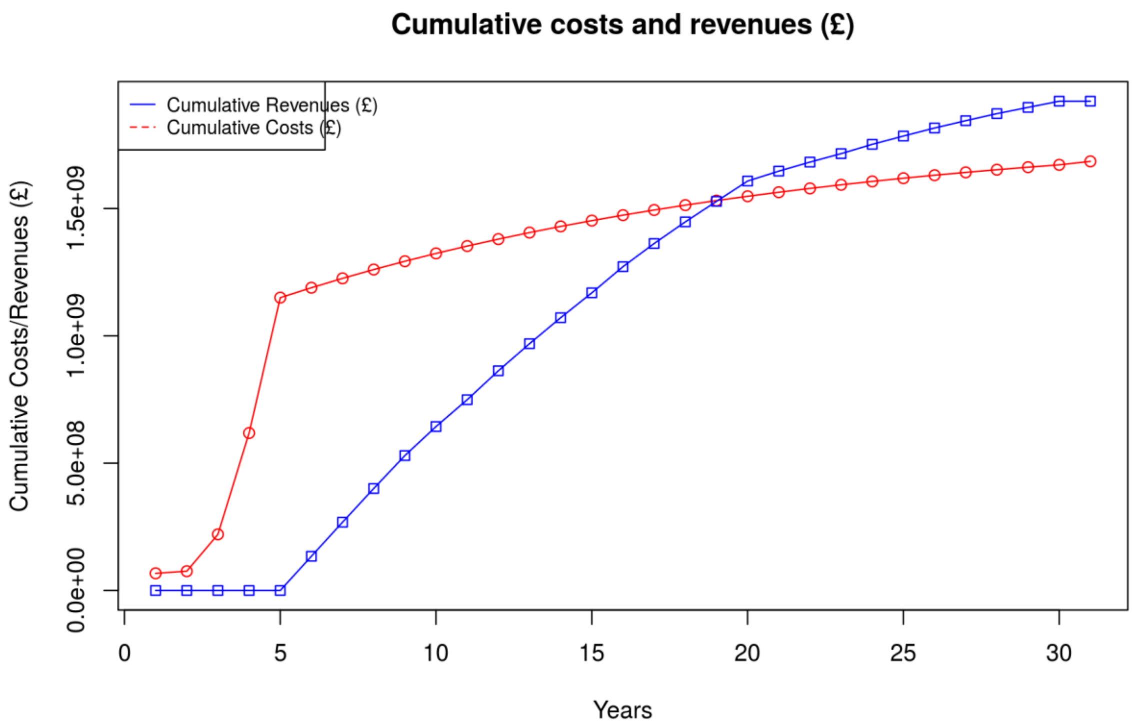
Cost/revenue profiles of different investor strategies – Precomissioning investors

Minimum price of £1.08b -£1.19b for WACC=15%- 12%



Future work

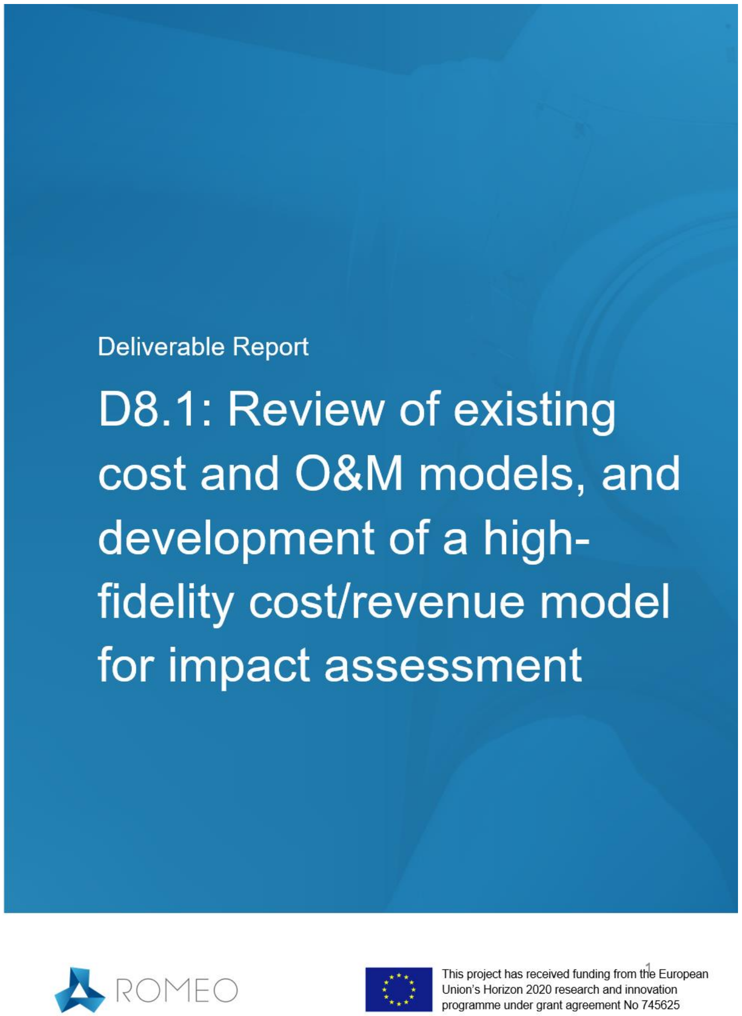

Please Select Wind Turbine Rating (MW):
1
5.8
15
1 2.4 3.8 5.2 6.6 8 9.4 10.8 12.2 13.6 15
Please Select Wind Farm Rating (MW):
50
485
1,500
50 195 340 485 630 775 920 1,0651,210 1,500
Please Select distance from port (km):
10
29
100
10 19 28 37 46 55 64 73 82 91 100
Please Select the Strike Price (£/MWh):
60
121
160
60 70 80 90 100 110 120 130 140 150 160


Cumulative costs and revenues (£)
Cumulative Revenues (£)
Cumulative Costs (£)
Cumulative Costs/Revenues (£)
0.0e+00
5.0e+08
1.0e+09
1.5e+09
0
5
10
15
20
25
30
Years

Conclusions

- This activity develops a high fidelity cost revenue model for offshore wind turbines.
- The tool will mainly include three functionalities which distinguish it from what is currently available in literature and commercial applications and allows a more well informed assessment of life cycle costs, namely:
  i. the consideration of costs and revenues and actual time that transactions occur,
  ii. a high fidelity O&M tool to allow for flexible consideration of variation of maintenance strategies and
  iii. stochastic consideration of relevant inputs to allow for confidence levels to be assigned to the various KPIs that will be considered.
- Next:
  - The tool will integrate an LCA module
  - It will be validated with real data collected from project partners
  - An online tool will be developed

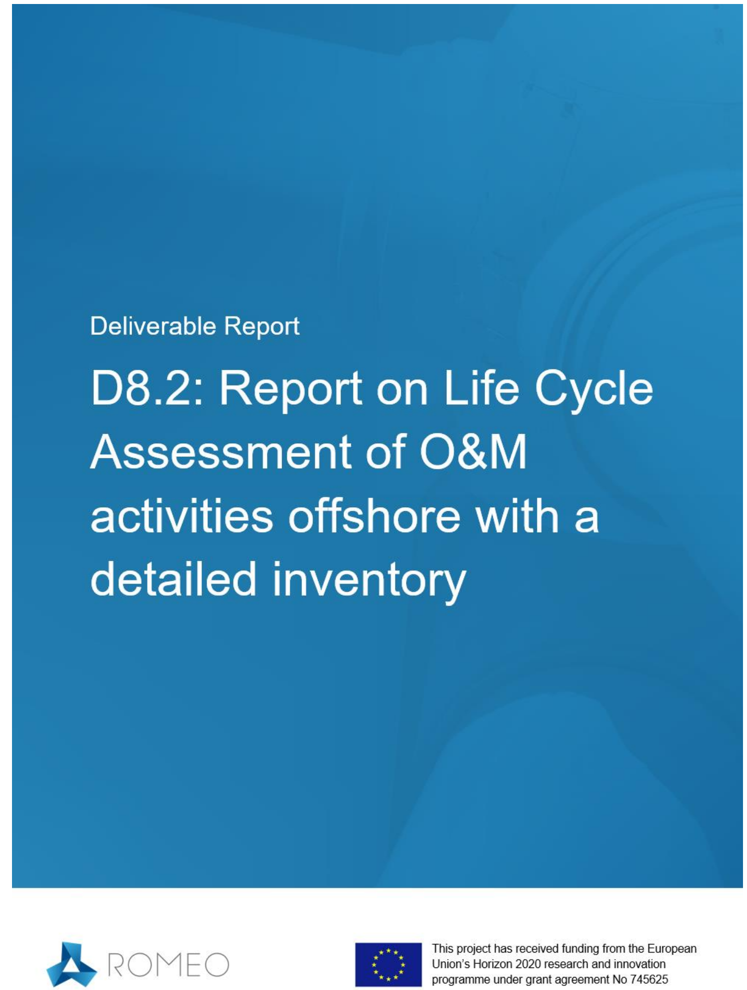
Relevant WP8 deliverables


Deliverable Report

D8.1: Review of existing cost and O&M models, and development of a high-fidelity cost/revenue model for impact assessment

ROMEO

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 745625


Deliverable Report

D8.2: Report on Life Cycle Assessment of O&M activities offshore with a detailed inventory

ROMEO

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