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

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List of abbreviations

Abbreviation	Description
ARIMA	Auto-Regressive Integrated Moving Average
BOP	Balance of Plant
CAPEX	Capital Expenditures
CFD	Contract For Different
CLV	Cable Laying Vessel
CREST	Cost of Renewable Energy Spreadsheet Tool
DECC	Energy and Climate Change
D&C	Development and consenting
FINEX	Financial Expenditures
GUI	Graphical User Interface
KPIs	Key Performance Indicator
HV	High Voltage
ICC	Initial Capital Cost
ICM	Internal Cutting Manipulator
LCCC	Low Carbon Contracts Company
LCOE	Levelized Cost of Electricity
MTTF	Mean Time to Failure
MV	Mean Voltage
OPEX	Operational Expenditure
O&M	Operation and Maintenance
OWECOP	Offshore Wind Energy Costs and Potential
P&A	Production and Acquisition Phase
POF	Probability of Failure
ROV	Remotely Operated Underwater Vehicle
SAM	System Advisor Model
SOVs	Special Operations Vessels
WACC	Weighted Average Cost of Capital

1. Executive Summary

This report links with Task 8.1 of WP8 and documents the review of existing life cycle costing and O&M tools and the stage of conceptual development of a high fidelity cost/revenue model for the purpose of impact assessment of the outcomes of the ROMEO research project. This deliverable is the 1st output within the development of this task and will be the starting point for the future research (D8.2 and D8.3).

The model that is proposed differs from those currently available in a number of aspects: (i) it considers both the costs and the revenues throughout the life cycle of the assets, allowing for alternative key performance indicators (KPIs) to be considered; (ii) the real value of cash-flows is taken into account for a more accurate financial appraisal; (iii) stochasticity of certain inputs are taken into account through Monte-Carlo sampling to assign confidence levels in the assessment; (iv) a flexible O&M evaluation model is incorporated for a fully integrated, robust analysis.

The report is organised as follows; after an introduction highlighting the requirement for an innovative, high-fidelity financial appraisal model, a review of commercial and research O&M tools is presented, together with the structure of a previously built customised O&M tool that will be further expanded for the purposes of this project. Following, the structure of the life cycle cost/revenue model is presented covering aspects of all stages of an offshore wind investment. Next a stochastic expansion of the model is discussed towards a systematic consideration of uncertainties in the analysis. Finally, indicative outcomes of the final model are presented through a series of KPIs that could be evaluated.

During the next stages of the project, the model will be translated into an integrated numerical tool, with input from the consortium partners and industry networks who will offer their insights on the particularities of the financial appraisal of offshore wind farms. For those aspects for which information will not become available due to confidentiality reasons, data from literature will be adopted through references included in this report. Building the expertise within the industry avoids having to import costly and/or not fit for purpose approaches such as from onshore wind or the Oil & Gas sector.

2. Introduction

Offshore wind levelized cost of electricity (LCOE), which is the net present value of the unit-cost of electricity over the lifetime of a generating asset, can be estimated by calculating the following components:

i. Capital expenditures (CAPEX),
ii. Operating expenditures (OPEX),
iii. Financial expenditures (FINEX) and
iv. The amount of energy production.

Reviewing data from past projects, based on historical data of installed projects and surveys of project developers ([1]–[5]), significant variation in cost components can be observed, as illustrated in Figure 1 and Figure 2 . This scatter denotes a high degree of uncertainty across the industry due to a number of reasons including the ongoing development of the supply chain, upscaling of new generation offshore wind farms, increased demand of new assets pushing upwards the CAPEX and reduced confidence in the assessment of Operation and Maintenance (O&M) costs of aging assets.

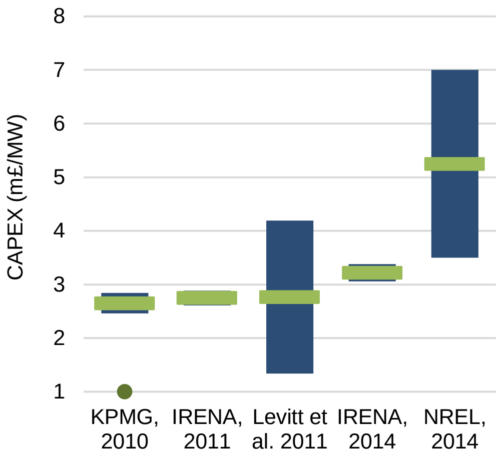

Figure 1 Range and average values of capital costs (£m/MW) in existing literature compiled and converted to 2015 £ currency (Sources: [1]–[5])

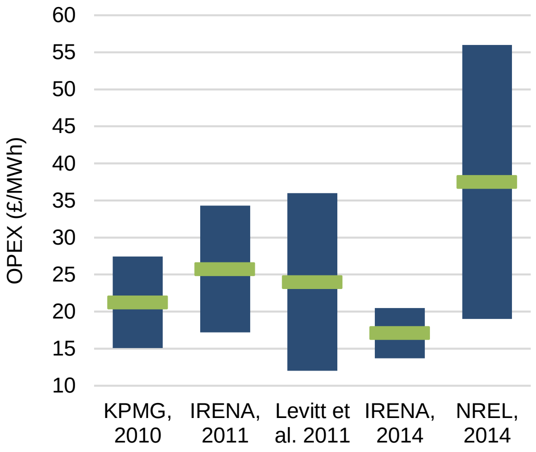

Figure 2 Range values of operating costs (£/MWh) in existing literature compiled and converted to 2015 £ currency (Sources: [1]–[5])

A review in the technical and economic feasibility of OW farms has been performed in [6], identifying a number of interesting works [7]–[12], related innovative concepts [13], [14], and the development of cost models for offshore wind (OW) farms [15]–[18]. In [7], a feasibility study was performed for the development of an OW farm installed in the Northern Adriatic Sea, in order to test the suitability of the region for the development of the technology, while [12] refers to a feasibility study off the Turkish coast. Another study determining the profitability of an OW energy investment across different areas of Chile was performed in [11]. Kaiser and Snyder (2012) have developed models for the installation and decommissioning costs of offshore wind farms, based on existing data in European wind farms [16], [19]. Myhr et al.

(2014) developed a lifecycle cost model with the aim to predict the LCOE of a number of offshore floating wind turbine concepts and compare them with their fixed monopile counterparts [8]. One of their conclusion was that LCOE is particularly sensitive to the distance from shore, load factor and availability. Authors in [10] develop a methodology for the life-cycle costing of a floating OW farm and apply it to analyse a location in the North-West of Spain and indicate the best platform option. Dicorato et al. (2011) formulated a general model to evaluate the costs in pre-investment and investment stages of OW farms and then employed this method to indicate the most suitable wind farm layout [15]. A review of offshore wind cost components was performed by [20], summarising parametric expressions and data available in literature including the acquisition and installation of wind turbines and foundations, the electrical system, the predevelopment costs, etc. Shaffie et al. (2016) have also developed a parametric whole life cost model of offshore wind farms, which requires less input data in relation to other tools available [17], aiming to provide a simple framework for estimating the LCOE of the investment. Data were also trained in order to provide expressions for the estimation of the cost of materials used in a wind turbine, as well as the cost of the offshore substation. Finally, sensitivity analysis was performed in order to indicate the most impactful parameters of the model on LCOE.

Several tools have been developed to date to predict costs of offshore wind energy. A basic LCOE prediction tool has been developed by BVGA [21] in the context of the Department of Energy and Climate Change (DECC) Offshore Wind Programme to enable identification of high-impact (in terms of LCOE reduction) technological developments in offshore wind farm reaching financial investment decision (FID) in 2020. The tool incorporates a number of benchmark base case scenarios with a few predetermined design parameters: nameplate capacity, water depth, foundation style, currency year. It can be used for evaluating the impact of change in OPEX, CAPEX, decommissioning costs, energy generation and WACC (weighted average cost of capital) on the final cost of energy. A stochastic expansion of the last model through the employment of Monte Carlo simulations was performed in [22]. Another model widely available is the **Cost of Renewable Energy Spreadsheet Tool** (CREST) provided by the **National Renewable Energy Laboratory** (NREL), which calculates the cost of energy (COE) and the LCOE for a range of solar, wind and geothermal electricity generation projects [23]. **System Advisor Model** (SAM) is a performance and financial model designed to facilitate decision making in the renewable energy industry. SAM includes several libraries of performance data and coefficients that describe the characteristics of system components such as photovoltaic modules and inverters, parabolic trough receivers and collectors, wind turbines, and biopower combustion systems. For those components, the user can simply choose an option from a list, and SAM applies values from online databases [24]. ECN has developed an offshore wind energy costs and potential (OWECOP) model, evaluating the cost of energy for offshore wind energy using a GIS database. A probabilistic analysis was implemented into the OWECOP cost model to form OWECOP-Prob [25].

Although deterministic models can support decisions pertinent to the development and operation of an offshore wind farm, they lack the ability to systematically account for the inherent uncertainty of input parameters when predicting the economic feasibility of a wind power project. To this end, a probabilistic/stochastic approach can significantly increase value of the outputs of the analysis, assigning confidence levels to the predictions towards better informed decisions. Stochastic cost modelling of power generation technologies has been applied in numerous studies focusing on fossil fuel [26], nuclear [27] as well as renewable power plants [28]. A probabilistic cost model for a solar power plant in USA was developed in [29]. Pereira et al. [30] presented a methodology based on Monte Carlo simulation to estimate the behaviour of economic parameters and applied it in a rooftop photovoltaic system in Brazil. Arnold et al. [31] and Amigun et al. [32] focused on analysing economic uncertainties regarding renewable energy technologies with a case study on bio-energy infrastructure. The profitability of wind energy investments was investigated by Caralis et al. [33] for different regions in China. Wind intermittency related to long-term cost analysis that compares the wind power to non-renewable generating technologies was studied by Li et al. [34].

Findings from the review of literature yields a need for the development of a lifecycle techno-economic assessment framework for the prediction of lifecycle costs of OW farms, which incorporates up-to-date models for the estimation of key cost components, taking into consideration technical aspects associated with the installation and maintenance of the asset. Such 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 uncertainty of key variables in a systematic way and assigning confidence levels on the expressions of estimated KPIs.

3. Development of a flexible O&M module

One of the most important components of an integrated cost model is the O&M module, which predicts the costs associated with the operational period of the asset. For the purpose of the ROMEO project, an O&M tool originally developed by the WP leads will be further advanced and customised in order to address the requirements of the project. In this section, after a brief review of available commercial and research O&M models/tools, a presentation of the basic aspects of them proposed tool is included highlighting its interfaces (inputs/outputs) with other elements of the analysis.

Review of existing O&M tools

During the past two decades, a number of operation and maintenance (O&M) models and computational tools for offshore wind farms have been developed.

It should be noted that the development of decisions for the different steps of the model have taken into consideration not only the accuracy of the calculation but also the computational efficiency required so as to allow a serial execution of simulations which is relevant to the comparative analysis which is the aim of this study. An important aspect in the development of such tools is that of validation, as complete data from operations of offshore wind farms are difficult to obtain; it is planned however to perform a high-level validation based on the results of published cases, while further calibration of the model for more accurate results will take place through consultations with experts from different parts of the supply chain.

Table **1** below provides an overview of the state-of-the-art in the literature for these models focusing on offshore wind farms. Most models are variants of risk-based methods grounded on reliability engineering and uncertainty quantification methods to model the relationship between availability, maintenance and cost, considering the variability of the sea climate. Of the reviewed models, only one third of them are commercially available computational tools (the most relevant being ECN O&M [35], NOWIcob [36] and O2M [37]), while the rest of them are authored models not publicly available as computational tools. In general, the revised models and tools allow the modelling and simulation at a whole-system wind-farm level, considering various failure types for each wind turbine. The input for the models typically consists of a description of the failure rates of the various subsystems, maintenance and repair policies, and weather conditions. Then, stochastic simulations (e.g., Monte Carlo) are run in the time domain and failures are simulated based on the failure rates. Each failure type belongs to a certain maintenance category, which determines the weather limitations and vessel, crew, and time needed for the repair. The repair is performed when the simulated weather conditions allow for it so that the faulty turbines do not produce power until the repair is finished. The models also keep track of availability of vessels, crews, and spare parts, such that the influence of the availability vessels and crews on the availability and maintenance costs of the overall plant can be assessed.

Table 1 lists the reviewed models and tools providing relevant information and particularities about these such as the output produced by the model, or the programming language or software used, among others.

Overview of the proposed model

An overview of the O&M analysis framework is illustrated in Figure 3. The main modules are: (1) the failure modelling module, (2) the weather modelling module, and (3) the cost modelling module.

The failure modelling module is further divided into the mean time to failure estimation (namely the uptime of the asset) and the mean time to repair estimation throughout the planned and unplanned maintenance operations (namely the downtime of the asset). The mean time to repair calculation is based on the annual failure rates, while the planned and unplanned maintenance operations require data related to the resources required for the repairs. Resulting downtime depends on the availability of the required vessels, technicians, weather window, spare parts, mission organisation time, duration of navigation and repair, as well as the required number of technicians' shifts.

The weather modelling module enables the forecasting of the future sea states, namely future significant wave heights and wind speeds. Weather conditions play an important role in the total downtime of the wind farm, as when the related parameters surpass the set wave height and wind speed limits of the vessels, travelling to wind turbines and accessing them becomes impossible. Therefore, unfavourable weather conditions will delay repairs, thus increasing downtime and decreasing the wind farm's availability.

The cost modelling module takes into account the actual duration of all stages required to perform the repair and maintenance operations and uses vessel and crew day-rates, along with material costs to predict the total O&M cost. Other outputs of the model are the time-based and production-based availability, and the power production losses.

The model is currently been developed in Matlab, taking advantage of the multiple available toolboxes that can be employed, however a translation into python in a later stage will be considered to also enable an efficient GUI and potentially standalone execution.

It should be noted that the development of decisions for the different steps of the model have taken into consideration not only the accuracy of the calculation but also the computational efficiency required so as to allow a serial execution of simulations which is relevant to the comparative analysis which is the aim of this study. An important aspect in the development of such tools is that of validation, as complete data from operations of offshore wind farms are difficult to obtain; it is planned however to perform a high-level validation based on the results of published cases, while further calibration of the model for more accurate results will take place through consultations with experts from different parts of the supply chain.

Table 1 Overview of existing O&M models for offshore wind farms

Tool/Model	Institution/Owner	Year	Commercial	Software	Model output	Ref
Santos *et al*	CENTEC, Univ. of Lisbon (Portugal)	2018	No	GRIF (Petri Net)	Costs, Availability	[38]
ECN O&M Access	ECN	2017	Yes	Not specified	Accessibility	[39], [40]
Rinaldi *et al*	Univ. of Exeter (UK)	2017	No	Not specified	Costs, Availability	[41]
Ambühl and Sørensen	Alborg Univ. (Denmark)	2017	No	Not specified	Cost, Availability RCM	[42]
Li *et al*	Universities of Playmouth, Stirling, Liverpool (UK), and Le Havre (France)	2016	No	Xpress IVE	Costs, Optimal maintenance	[43]
Joschko *et al*	Univ. of Hamburg, Bremen Univ. of Applied Sciences (Germany)	2015	No	BPMN 2.0, DESMO-J (Java)	Costs	[44], [45]
Endrerud *et al*	Univ. of Stavanger (Norway)	2014	No	AnyLogic (Java)	Costs Availability	[46]
NOWIcob	NOWITECH	2013		Not specified	Costs Availability	[36]
Dinwoodie *et al*	Univ. of Strathclyde (UK)	2013	No	MATLAB	Costs Availability	[47]
Byon *et al*	Univ. of Michigan (USA)	2010	No	DESJAVA	Costs Availability	[48]
Maros	DNV	2010	Yes	Not specified	Net present value	[49]
SIMLOX	Systecon	2010	Yes	Not specified	Costs Optimal maintenance	[50]
Iberdrola tool	Iberdrola	2010	Yes	Not specified	CAPEX/OPEX Power	[51]
MWCOST	BMT	2009	Yes	Not specified	Net present value	[51]
OMCE	ECN	2009	Yes	MATLAB	Costs	[52], [53]
Besnard *et al*	KTH Chalmers (Sweden)	2009	No	GAMS, MATLAB	Costs	[54], [55]
Rangel-Ramirez and Sørensen	Alborg Univ. (Denmark)	2008	No	Not specified	Costs	[56], [57]
O2M	GL Garrad Hassan (DNV)	2007	Yes	Not specified	Costs Lost production	[37]
ECN O&M	ECN	2007	Yes	Excel @Risk	Costs	[35], [58], [59]
Bharadwaj *et al*	Loughborough Univ. TWI Ltd (UK)	2007	No	Excel @Risk	Net present value	[60]
Andrawus *et al*	Robert Gordon Univ. (UK)	2006	No	Excel, Cristal Ball	Net present value	[61]
RECOFF-model	ECN	2004	No	Excel @Risk	Costs	[62]
Maddens *et al*	Universite Libre de Bruxelles (Belgium)	2004	No	GRIF (Petri Net)	Costs Availability	[63]
CONTOFAX	TU Delft (Netherlands)	1997	No	Excel	Costs Availability Power	[35]

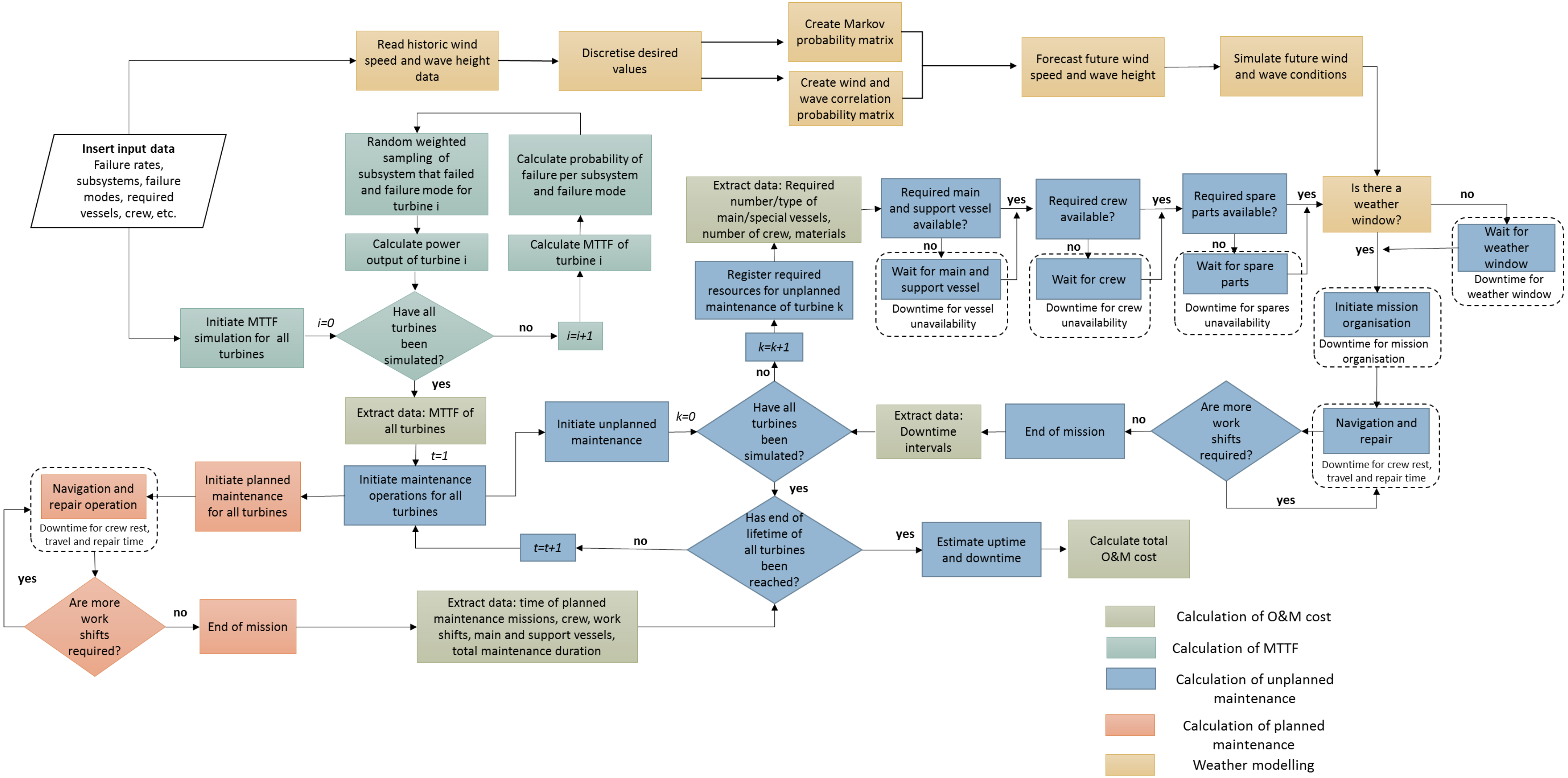

Figure 3 Flowchart of O&M cost model

Failure modelling module

Estimation of Mean time to repair (MTTR)

The repair categorisation of Reliawind project [64] can be adopted which classifies repair classes of subsystems into minor repairs, major repairs and major replacements. A total of 19 subsystems of the wind turbine will be considered, while data used for the application of the model on failure rates, average repair times, average material costs and number of required personnel can be retrieved from [65]. Assuming that the reliability of the turbine follows an exponential distribution (other distributions such as Weibull can also be taken into account), the probability of failure (PoF) can be expressed as:

$$PoF = 1 - Reliability = 1 - e^{-\lambda_{turb}\cdot t}$$

$$t = MTTF = -\frac{1}{\lambda_{turb}} ln(1 - PoF)$$

Where, λ_{turb}=$\sum_{i=1}^{Subsyst}\lambda_i$, is the sum of the failure rates of each turbine's subsystems in series. Monte Carlo simulation is then performed to generate numerous random PoFs and subsequently returns an average MTTF value for each wind turbine. Once MTTFs are calculated, the probability of occurrence of each subsystem's failure can be calculated as:

$$PoF_{subsyst} = 1 - e^{-\lambda_{subsyst}\cdot MTTF_{subsyst}}$$

where, $\lambda_{subsyst} = \sum_{k=1}^{Repair\ class}\lambda_i$ is the sum of the failure rates of the different repair classes of the subsystems. It should be noted that MTTF values of the different components of the wind turbine are inputs to the system so that the most updated values can be used from literature or operators' experience. Once the probabilities of each subsystem's failure is known, the model performs random weighted sampling to determine which subsystem will fail once the MTTF has elapsed along with the repair class, which is also randomly selected following the same logical process. Along with the MTTF calculation, the model calculates the absolute time set of the simulation, which is interpreted as the actual time from the beginning to the end of life of the wind farm. The duration of the individual activities are added to the absolute time set, enabling the calculation of the uptime and downtime of the turbine and registering the time when a certain failure happens.

Planned and unplanned maintenance

Unplanned (corrective) maintenance is carried out following the occurrence of a failure on the turbine or the BOP (balance of plant), which may affect several turbines. The procedure after the occurrence of a new failure is illustrated in Figure 3. Once a failure has occurred on the first turbine, the required resources - namely, the number and type of main and special vessels, number of crew and materials, depending on the subsystem and the repair class - are registered. In the simple case, if a major repair, or a major replacement is needed, the turbine instantaneously shuts down, however a functionality will be included to account for PF intervals for each failure mode based on data from literature and findings from other WPs of the project such as Task 1.4. The process begins with the availability check of the required main and support vessels. It is assumed that a predetermined number of vessels will be continuously operating in the wind farm, hence they will be available to access the wind turbine that failed if the weather conditions allow so and the same applies for a predetermined number of personnel and the spare parts needed for the repair. If, however, all available vessels are occupied, the failure remains unresolved and the check is repeated once the required number of vessels are released from the previous mission. Vessels in the analysis are modelled parametrically so that different types and numbers of vessels could be accounted for. All required resources can also be inserted by the user as per each subsystem and repair class. Once the required vessels, crew and spare parts are available, the weather conditions are checked. The weather window is sufficient as long as the significant wave height and the wind speed conditions at the wind farm site are below the operational threshold limits of the vessels commissioned throughout the whole intended time offshore. Subsequently, the organisation of the mission, including the mobilisation of the vessel(s) (if required), take place. Once the crew accesses the subsystem that failed, the repair is carried out; it is assumed that one work shift lasts for up to 12 hours, which includes the total repair time, transitioning from harbour to the site and vice versa, as well as a mid-shift break. In case that more than one shifts are required, the crew returns to harbour and the mission restarts 12 hours later. When the damage is restored, the wind turbine starts producing power again, and the MTTF of the subsystem is reset to its original value. Finally, the transit back to the harbour and the demobilisation time are added to the total downtime of the wind farm. The durations of all unplanned maintenance activities are registered and added to the absolute total time set. Once the absolute total time set equals the service life of the wind farm, the simulation stops.

Planned maintenance (else calendar-based maintenance) operations are carried out periodically and deal not only with one subsystem of the wind turbine, but with groups of subsystems or the entire wind turbine. Planned maintenance can be scheduled ahead of time, during periods of favourable weather conditions when delays to missions due to exceedance of vessels' safety limits (weather window downtime) are not likely to occur, so that the availability of the wind turbine and amount of generated electricity is affected the least possible. The same applies for vessels, crew and spare parts unavailability downtimes. In this analysis, calendar based maintenance is assumed to take place every one year with a deviation of ±1 month, to simulate the real life operations. Downtime due to planned maintenance is assumed to originate exclusively from the navigation and repair time, together with the potential downtime due to crew rest. In this analysis, it is assumed that planned maintenance can only restore minor repairs, i.e. once each mission terminates the mean time to failure of minor repairs is reset. It is expected that unplanned maintenance will incur higher downtimes in relation to planned maintenance considering the longer expected downtimes and types of maintenance activities.

Weather modelling

As described earlier, predicting weather conditions for the operational lifetime of an offshore wind farm is crucial to predict its availability. If wave height and wind speed conditions exceed vessels' safety thresholds, transit from harbour to the wind farm is not possible leading to delays in performing repairs, thus increasing downtime and decreasing the wind farm's availability [66].

Commonly used methods for generating sea state time series comprise Gaussian and Langanian approaches for short term wave modelling, Autoregressive Moving Average (ARMA) methods and Markov-based models which work well for long term forecasting and can capture persistence of sea state parameters [67], [68].

For the purpose of this study, the discrete time Markov chains will be chosen as the weather forecasting method. To this end, historic weather datasets from 1992 to 2017 with a 3-hour time step need to be retrieved from BTM ARGOSS database [69]. Discrete time Markov chains method is based on having a finite number of states in a system and estimating the probability, *pij* of state *i* to evolve into state *j*. Markov probability matrices are generated for each month, to account for seasonality, as shown below:

$$P(sea\ state\ parameter)_{month} = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{pmatrix}_{month}$$

Where, $p_{i,j}$ equals the number of transitions of sea state parameter *i* to *j*, divided by the total number of times, state *i* appears. As such, initially, the weather data is discretised with a resolution of 0.2 for wave height and 1 m/s for wind speed data, resulting in a finite number of possible values, namely 23 and 25 values, respectively. A time step of 3 hours is also considered for the forecast, during which wind speed and wave height are assumed to remain constant. Based on the probabilities of each transition matrix, the wave height for the starting month is randomly selected, successively all sea state conditions are predicted as a function of the previous state and the transition probability.

Cost modelling

The cost modelling module gathers the data recorded during each iteration, which are required to estimate the O&M cost. For unplanned maintenance of wind turbines, the time that a failure occurs is registered with reference starting point the beginning of operation of the wind farm. Further, the subsystem that failed and the type of failure will define the required main and support vessels (to match the correct day rates) and the number of crew members required for the repair. Downtimes of crew unavailability, spare parts unavailability, weather window, navigation time and demobilisation time are taken into account and assigned to the respective day rates of vessels, crew, cost of materials, mobilisation and demobilisation costs, to estimate the total O&M cost.

Interfaces of the model

Figure 4 highlights the interfaces of the O&M module with other parts of the LCC analysis of the asset, including data requirements for each stage of the algorithm.

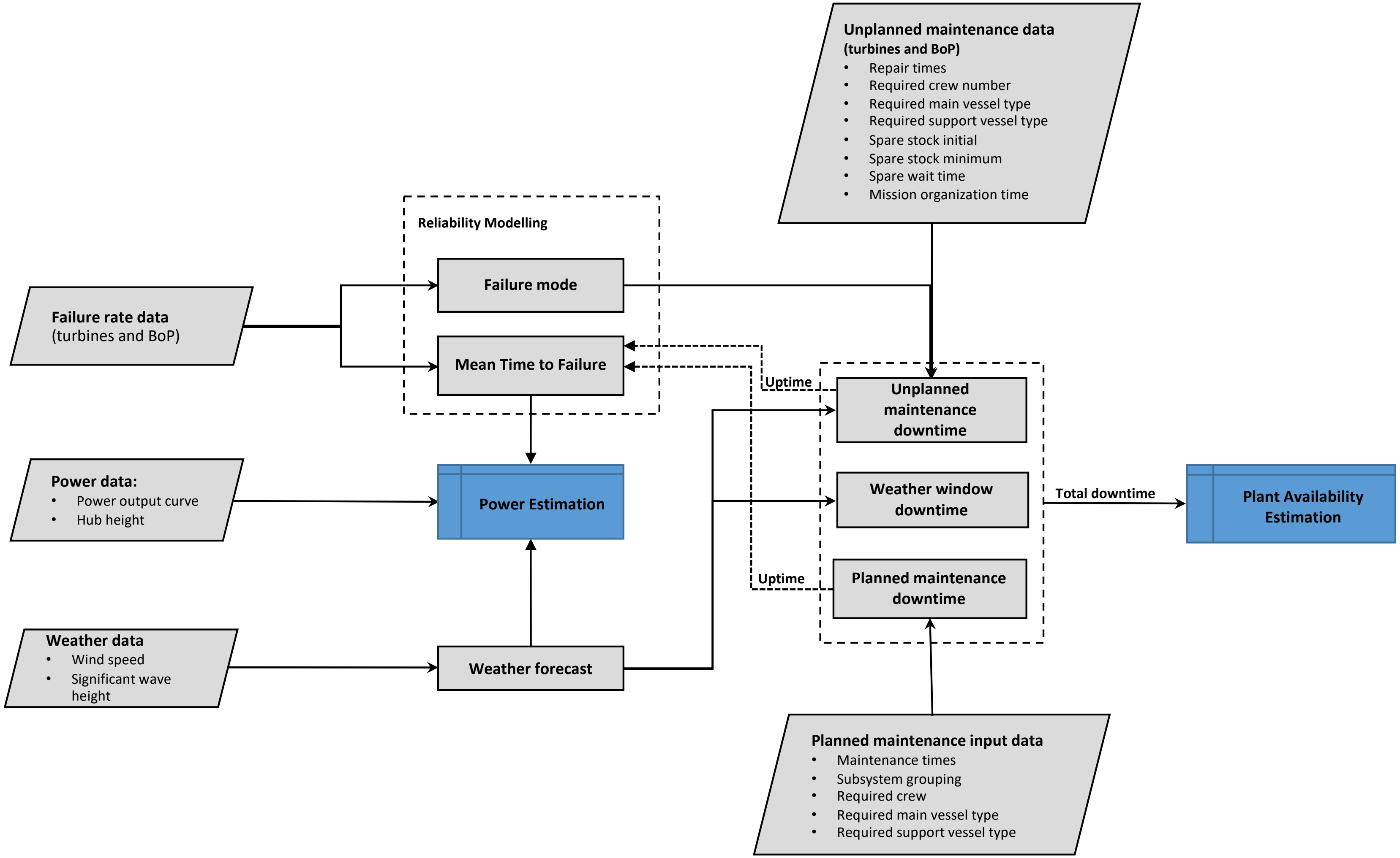

Figure 4: Interfaces of the O&M tool

5. Integration to a Life Cycle Cost/Revenue model

The integrated Life/cycle cost/revenue model consists of the following, as illustrated in Figure 5:

(i) CAPEX module, consisting of the D&C, P&A, I&C and D&D phases of the OW farm;
(ii) General site characteristics module detailing the weather conditions, site water depth, distance from port, vessels, cost of personnel etc.;
(iii) FinEx module with parameters on financing expenditures, such as WACC, inflation rate, equity and debt ratio, etc.,
(iv) OPEX module incorporating data from the O&M module presented earlier;
(v) Revenue module, which considers the net power generation, the energy policy scheme in place for supporting the technology, namely the Contracts for difference (CfD) scheme, and the market electricity price to derive the revenues relevant to the investment.

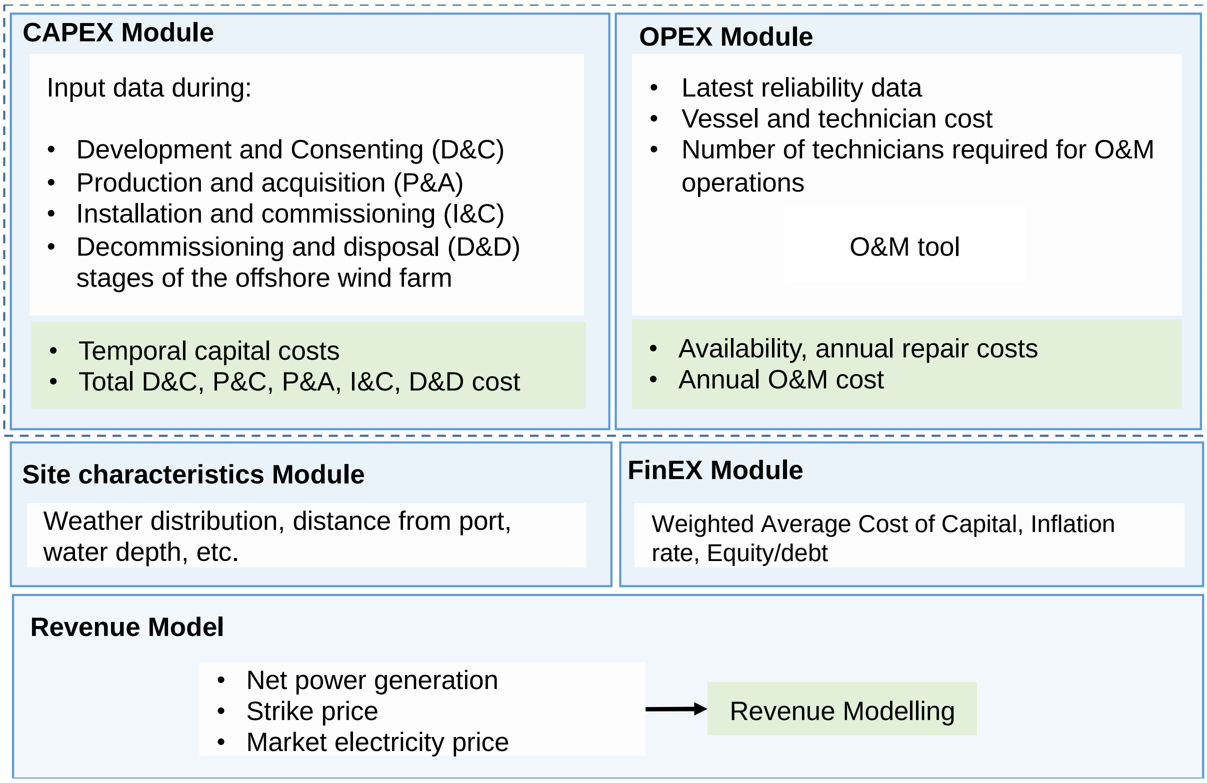

Figure 5: Methodological framework

In this section, each of the key modules will be presented briefly, forming the basis for the integrated tool that will be subsequently developed.

CAPEX module

The CAPEX module includes costs during the D&C, P&A, I&C and D&D phases of the OW farm, as presented in detail in [6].

Development and consenting (D&C)

This category relates to all costs prior to the point of financial close including project management, surveys, legal authorisation, front-end engineering and design and contingency costs [17], [70]. Costs during D&C of the wind farm vary significantly across different sites; thus, different values of costs can be obtained from literature. Indicatively, in [70] a total of £60 million for a 500MW wind farm is reported, while in [17] costs were estimated £202.8 million for a wind farm of the same capacity. Myhr et al. [8] assumed a cost of £89.9 million/500MW, while in [71] a total cost of £156.5 million/500MW was estimated, when adjusted to the respective currency and inflation rate.

Production and acquisition phase (P&A)

Wind turbines

The acquisition of a fully equipped turbine is one of the most expensive cost components of the P&A phase of the wind farm. Cost is usually expressed as a function of the turbine capacity and different parametric models have been developed to predict the cost of different sizes of turbines [14], [15], [18], [20]. A typical expression for this cost can be obtained as [17]:

$$c_{T,pa} = 3 \cdot 10^6 \, ln(P_{WT}) \; - \; 662{,}400, \text{ in £/turbine}$$

where, P_{WT} is the capacity of the wind turbine (MW). For a wind turbine of 3.6MW, the equation above results to £3.1804 million/turbine, while by adding the tower cost into the total turbine costs (which according to [70] is of the order of £1 million for a 5MW turbine), total cost for the acquisition of the turbine and the tower accounts for approximately £3.90 million/turbine

Foundations

Considering a monopile configuration, as it remains the most popular substructure up to date with a cumulative amount of 87% of all installed foundations in 2017 [72], the cost depends largely on the type of foundation, the depth of the site, the seabed characteristics as well as, to a lesser extent, the turbine capacity, the wave and wind conditions [20]. The cost of foundation, $c_{F,pa}$, can be obtained by the following parametric equation (hub height, h and rotor diameter, d) according to [73]:

$$c_{F,pa} = 320{,}000 \cdot P_{WT} \cdot \big(1 + 0.02 \cdot (WD - 8)\big) \cdot (1 + 8 \cdot 10^{-7} \cdot (h \cdot ((d/2)^2 - 100000)))$$

Other parametric expressions, found in the literature, link foundation cost with water depth, turbine capacity, as well as cost of material usage and fabrication [8], [15], [20]. Since the project also considers jacket foundations, relevant parametric studies will be considered for this type of support structure linking key deployment parameters to the overall cost of acquisition.

Transmission system

The transmission system of the wind farm consists of: the collection system of the generated power by means of array cables, the integration of the power through an offshore substation, the transmission of the electricity from the offshore substation to shore through the export cables. Two kinds of export cables are distinguished: the offshore export cables transmit the electricity from the offshore substation to the onshore substation, and the onshore export cable which transport the power to the grid connection point.

Array cables organise turbines in clusters adopting various different grid schemes, such as the radial design according to which, turbines of each cluster are interconnected in a ‘string’ ending at an offshore substation. Mean Voltage (MV) submarine cables are most frequently used as array cables, while High Voltage (HV) export cables carry the stepped up voltage from the offshore substation to the grid connection point. MV cable unit costs, similarly to HV cable unit costs vary according to the cable section and nominal voltage (as shown in [15]).

Export cables can be either high-voltage alternating current (HVAC) or high-voltage direct current (HVDC) depending on a number of factors and especially the distance from shore. Generally, if the distance from shore is less than 50km, AC cables would be preferred while for longer distances and in more remote wind farms, DC cables are used since HVDC cabling has no reactive power requirements resulting in lower power losses [71], [74].

In general, the total cost of the cables, $C_{cables,pa}$, is calculated by the product of the unit-length price of the cable, c_i (£/m), with the number of cables, N_i, and the average length of each cable, L_i (km). Protective equipment (such as J-tube seals, passive seals, bend restrictors etc.) is required to protect the cables [17].

$$C_{cables,pa} = \sum_{i=1}^{3} (c_i \cdot L_i \cdot N_i) + C_{protection} \quad \text{, in £}$$

where, i denotes the cable type of the wind farm, namely: the MV array cables (i=1), the HV subsea export cables (i=2) and the HV onshore export cables (i=3).

The length of the subsea export cable, L_2, is assumed equal to the distance between the centre of the OW farm (where the offshore substation is located) and the shore (where an onshore substation is located), an assumption also taken in [75]. Finally, the length of the onshore export cable, L_3, is equal to the distance from the onshore substation to the grid connection point. The electrical system is typically comprised of 33kV array cables and two offshore substations of 336MW HVAC transmission system. Further, the transmission assets are considered connected to the onshore substation by three 800mm^2 132kV subsea export cables.

The most cost efficient electric power transmission method to reduce cable losses is by means of an offshore substation, which is considered appropriate for projects located at a distance of more than 20km offshore [71]. The total offshore substation cost has been estimated by a number of authors [17], [20] who derived parametric expressions linking the offshore substation cost to the total installed capacity of the wind farm. A realistic expression for the offshore substation cost, $C_{offSubst,pa}$, can be estimated based on [15], which breaks down the cost of offshore substation to: 1) the MV/HV transformer cost, C_{TR}, 2) MV switchgear cost, $C_{SG,MV}$, 3) HV switchgear cost, $C_{SG,HV}$, 4) HV busbar cost, c_{BB}, 5) Diesel generator cost, C_{DG} to supply essential equipment when the OW farm is off, and 6) substation platform cost, $C_{offSubst,pa_f}$. The expressions of the individual cost components are the following:

$$C_{TR} = n_{TR} \cdot (42.688 \cdot A_{TR}^{0.7513})$$

$$C_{SG,MV} = 40.543 + 0.76 \cdot V_n$$

$$C_{DG} = 21.242 + 2.069 \cdot P_{WF}$$

$$C_{offSubst,pa_f} = 2534 + 88.7 \cdot P_{WF}$$

$$C_{offSubst,pa} = C_{TR} + C_{SG,MV} + n_{TR} \cdot \left(2 \cdot c_{SG,HV} + c_{BB}\right) + (C_{DG} + C_{offSubst,pa_f})$$

where, n_{TR} is the number of transformers, V_n is the nominal voltage and A_{TR} is the rated power of the transformers. The export cables connect the offshore substations with an onshore substation which further transforms power to grid voltage (e.g. 400MW). Onshore substation cost was assumed to be half the cost of the offshore substation according to [17], [70].

More recent wind farms have integrated supervisory control (including health monitoring) and data acquisition (SCADA) systems, with the view to optimise wind turbine life and revenue generation [70]. Health monitoring of wind turbines is performed by means of sensors and control devices, gathering data that can be used for optimising operation and maintenance operations. Cost of monitoring was estimated $C_{SCADA,pa}$ = 75 k£/turbine [15].

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.

Foundation and wind turbine installation

Installation costs are a function of the vessel day rates, the usage duration and the personnel costs required for carrying out the operations. Vital components of both the wind turbine and the foundation installation cost are the vessel day rates and the duration of the installation processes. The total time per trip of an installation vessel is broken down to: the travel time, the loading time, the installation time and the intra-field movement time.

For the installation of monopiles a jack-up vessel can be employed with an assumed deck capacity of $VC_{F,JU} = 4$ foundations. After foundations are secured, the transition pieces are lifted and placed on the top of the foundation pile and are then grouted. In the context of the present case research, it can be assumed that the installation of monopiles and the placement of transition piece can be realised by the same vessel. Appropriate provisions will be considered for that case of jacket type support structures.

Turbines are installed after foundations have been placed. The vessel used, both transports turbines in the installation site and performs installation. Turbines typically consist of seven components, namely nacelle, hub, 3 blades, and 2 tower sections. Onshore assembly of some of the parts of the OWT is usually performed in order to reduce lifts offshore, which can be considered risky and prone to cause delays due to wind speeds. The installation process of OW turbines is composed by the following time steps: 1. Travel/transportation time, 2. Lifting operation time, 3. Assembly operation time (onshore and offshore), and 4. Jacking up operation time. The pre-assembly (i.e. onshore assembly) strategy followed determines the total time of turbine installation, along with the distance from the port, the number of turbines, the nameplate capacity, etc.

Scour protection installation

The scour phenomenon takes place around structures undergoing steady current conditions, and is associated with the increase in the sediment transport capacity and erosion [76]. To ensure structural stability of the wind turbine foundation (as well as protection of cables), scour protection is usually applied. Available options to protect from scour are: placement of geotextile containers/sandbags, concrete armour units/block mattresses, grout bags/mattresses and rock armour (among others), which cover a particular area of the seabed [77]. The scour protection option employed is site-specific, i.e. at some locations the amount of protection varies with sediment and current conditions, while in others scour protection may not be needed. The input data used for the estimated mass of scour protection [78], the vessel leased for installation and the total installation time can be adopted from [16], [79], [80].

Cables installation

A dedicated Cable Laying Vessel (CLV) needs to be leased for the installation of the inner array and export cables. Average installation rates of inner-array and export cables can be calculated by taking into account historic data from past projects on the total length (in km) of the cables and total installation time (in days) [16]. Average installation rates can be estimated approximately at 1.6 and 0.6km/day for export and inner array cables, respectively. For the installation of the subsea cables, a trenching ROV (Remotely Operated underwater Vehicle) is often employed for the post–lay burial of the cables with a typical daily charter rate of 82.5k£ [70]. The installation cost of export and array cables is estimated based on the total duration of the installation operation, and the day rates of the

CLV and the trenching ROC. As such, the installation cost of array and export cables are calculated by the following expressions:

$$C_{C-array,ic} = T_{C-array,Inst} \cdot (V_{DR,CLV-array} + V_{DR,Trench}) + V_{Mobil,CLV}$$

$$C_{C-export,ic} = T_{C-export,Inst} \cdot (V_{DR,CLV-export} + V_{DR,Trench}) + V_{Mobil,CLV}$$

Substation installation

Substation is assumed to be barged on site and get installed by a Heavy-Lift vessel (HL). The installation time is comprised of the jacket foundation installation time, the grout application (if applicable) and, the installation of the substation topside.

The weight of the topside substation will determine the vessel that will be required with the appropriate crane capacity. The estimation of the installation cost of the substation is based on the total effective duration of the installation operation, $\boldsymbol{T_{Subst,Inst}}$, and the HL vessel day rate, $V_{DR,HLV}$, and mobilisation cost, $V_{Mobil,HLV}$, as expressed below:

$$C_{OffSubst,ic} = T_{Subst,Inst} \cdot V_{DR,HLV} + V_{Mobil,HLV}$$

Decommissioning and disposal phase (D&D)

Energy companies are obliged to remove all structures and verify the clearance of the area upon the termination of the lease. Decommissioning activities relate to the removal of the wind turbine (i.e. nacelle, tower and transition piece) as well as the balance of the plant (substation, cables and scour protection). Removal of the wind turbine and tower is done using a reversed installation method while the removal of foundation is carried out by the use of a cutting tool that removes the transition piece, while an ICM (Internal Cutting Manipulator) is used to cut the monopile or the jacket piles at 2 meters below the mud-line [81]. Cranes are used to lift the cut pieces of the turbine. Removal of mud and internal cutting can be realised by means of a workboat, while the lifting of the structure is performed by a jack up vessel. Two jack up vessels with deck space to load 5 complete WTGs with foundations is a realistic assumption for monopile foundations while relevant provisions will be considered for jacket foundations. For the removal of the substation topside a heavy lift vessel is required while the jacket support structure of the substation also needs to be cut (the 4 piles) in order to get removed. As far as cables are concerned, they can be partially or wholly removed, depending on whether they are buried or not [82]. Cables can be cut in several sections while they are removed, hence, less expensive vessels can be employed, such as Special Operations Vessels (SOVs) or barges. The scour protection may also be left in situ in order to conserve the marine life that would have grown on it. Site clearance is the final stage during decommissioning and it encompasses the removal of the debris accumulated in a specified radius of the structure throughout the 25 years of life of the wind farm. Vessels employed for the decommissioning of the structures are assumed to have similar characteristics to the ones used for installation.

Further to the removal of the wind turbine components, the balance of the plant and the clearance of the area, removed items need to be transported and disposed. Cost of transportation is a function of the total mass of the wind farm components, $W_{components}$, the cost per ton-mile of the transportation truck, $C_{truckperton-mile}$, the capacity of truck, W_{truck}, and the distance of port from the waste facility, $D_{port-facility}$, as follows [17]:

$$C_{transp,dd} = \frac{\sum W_{components}}{W_{truck}} \cdot D_{port-facility}$$

Revenue module

Levelized cost of electricity (LCOE) models consider the costs throughout the whole life of the asset. However, investors emerging in different phases of the OW farm are interested in the profitability profile of the investment from the purchasing instance until their potential exit point from the investment

As far as the policy instruments supporting the OW industry are concerned, the Contract for Difference (CfD) scheme is currently in effect in the United Kingdom, which is a private law contract between a low carbon power producer and the Low Carbon Contracts Company (LCCC), a government-owned company. According to the CfD scheme, the low carbon power producer sells the produced electricity, as usual, through a Power Purchase Agreement (PPA), to a licenced supplier or trader at an agreed reference market price. However, in order to reduce investors' exposure to variations in electricity market prices, the CfD states that the power producer is paid the difference between a pre-determined "strike price" and the reference market price. If the reference price is lower than the strike price, the power generator receives the difference from LCCC; reversely, if the reference price is higher, the power producer has to pay back the difference. The bottom line is that the power producer always gets the strike price for the electricity generated. CfDs are awarded to power producers in allocation rounds and the amount of the strike price is determined through an allocation process, which is either based on administrative strike prices set by the Government (provided there are sufficient funds) or by means of a competitive auction run by the National Grid. The auctions ensure that the least expensive projects are awarded, reducing, thus, the cost passed to consumers. The scheme lasts for 15 years (while the average lifetime of an OW energy asset is 25 years), after which the electricity output is sold on the average UK electricity market price, hence imposing uncertainty to the revenues yielded by the investment after the 15th year of operation [83]. To this end, appropriate modelling of the cash inflows, along with the taxation imposed to the income needs to be conducted.

FinEX module

Depreciation and tax

Tax depreciation is available through the capital allowances regime, according to which $d_{rate} = 18\%$ of qualifying expenditure on equipment is reduced [84]. Depreciation is a term used in accounting in order to spread the cost of the capital assets over the life span of the investment, so that the net profit in any year will reflect all the costs required to produce the output. The effect of depreciation is estimated by dividing the equipment cost of the wind farm, $C_{equipment}$, over the total life span of the asset and deducting the 18% of this annual cost from the tax payment. The net tax, t_{net}, can then be calculated by deducting the depreciation credit, d_{credit}, from the yearly tax payment, $t_{payment}$, as shown below:

$$d_{credit} = \frac{C_{equipment}}{n} \cdot d_{rate}$$

$$t_{net} = t_{payment} - d_{credit}$$

$$t_{payment} = t_c \cdot P_{gr}$$

where, $t_c = 17\%$ is the nominal corporate income tax rate paid every year and P_{gr} represents the gross profit. Accordingly, the Net profit, P_{net}, of the investment can be calculated as:

$$P_{net} = P_{gr} - t_{net}$$

WACC and inflation

Inflation and interest rates are used to account for the time value of money. Inflation accounts for the reduction in the purchasing power of a unit of currency between two time periods, while the interest rate is the rate earned from a capital investment. In financial analysis, the nominal interest rate is the interest rate quoted by the banks, stock brokers etc. which includes both the cost of capital and the inflation. Real discount rate (or else real WAAC) integrates the inflation adjustment and the discount of cash flows according to Fisher Equation [85]:

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

The discount rate is determined by the source of capital as well as the estimation of the financial risks associated with the investment. Projects gather their capital by raising funds through debt and equity. These sources of financing demonstrate individual risk-return profiles; hence their costs also fluctuate. The cost of capital will correspond to the weighted average of cost of its equity and debt, with weights determined by the amount of each financing source. The WACC is calculated by the following expression [86]:

$$WACC = \frac{VE}{V} \cdot RoE + \frac{VD}{V} \cdot Rd \cdot (1 - tc) \qquad \text{Eq. 2}$$

where, VE is the market Value of Equity, VD is the market Value of Debt, $V = VE + VD$, RoE denoted the Return on Equity, and Rd the interest rate on debt. The risk of the project significantly influences the amount of return on investment required by the investor. External capital is cheaper and, thus, it is often desirable to obtain the highest possible amount of debt; however, the cost of debt depends on the specific investment risk, namely the highest the investment risk, the lower the amount that banks will be willing to lend. Further, the real WACC is calculated by taking into account the inflation rate.

6. Stochastic expansion of the lifecycle techno-economic model

Having developed the integrated life-cycle cost model a non-intrusive formulation will be adopted allowing for a set of well-established discrete steps to be followed. For this to occur, variables better expressed stochastically should be identified and treated accordingly based on their classification as time dependent or independent. The sequence of steps to be followed is shown in Figure 6 and presented further below.

i. *Parametrisation of cost model:* This step accounts for the parametrisation of the high fidelity deterministic cost/revenue model to allow for iterative simulations under varying input conditions.
ii. *Identification of stochastic input variables:* Selection of the stochastic variables should be carefully selected as their number will significantly influence the computational effort required for the analysis. The selected variables should be chosen following a sensitivity analysis and setting of a cut-off point, gradually increasing/decreasing by 20% the value of each variable and comparing with a baseline case.
iii. *Identification of key output variables:* For the expression of the results of the analysis, KPIs such as the NPV, IRR, cumulative cost/revenues, break-even point, LCOE are relevant.
iv. *For time dependent stochastic variables*, methods such as the Auto-Regressive Integrated Moving Average (ARIMA) approach should be adopted to generate time series based on available historical data. This will allow for a random data set of values of electricity price to be considered, for each of the simulations that will run.
v. *For time independent stochastic variables*, appropriate probability distribution functions will be assigned. In the absence of real data, normal and uniform distributions can be chosen for the analysis, which is a common practice followed by other researchers such as in [87].
vi. *Run a number of Monte-Carlo Simulations:* Once the above steps are completed, a series of Monte Carlo simulations will be executed in order to derive the joint probability distribution of the key performance indicators determined in step (iii). Following a convergence study, the necessary number of iterations should be determined for results that converge in specific values. Transition from deterministic to stochastic expression of results, implies that instead of a set of fixed output values (i.e. LCOE) derived from a deterministic set of input values, the output is expressed as the probability that the output value lies within a set threshold.
vii. *Interpretation of results and sensitivity analysis:* Once the algorithm has been developed, a sensitivity analysis of the input variables should take place distinguishing those with the higher impact to the output variables as well as investigating the impact of statistical modelling of input variables. Results are best presented through tornado graphs.

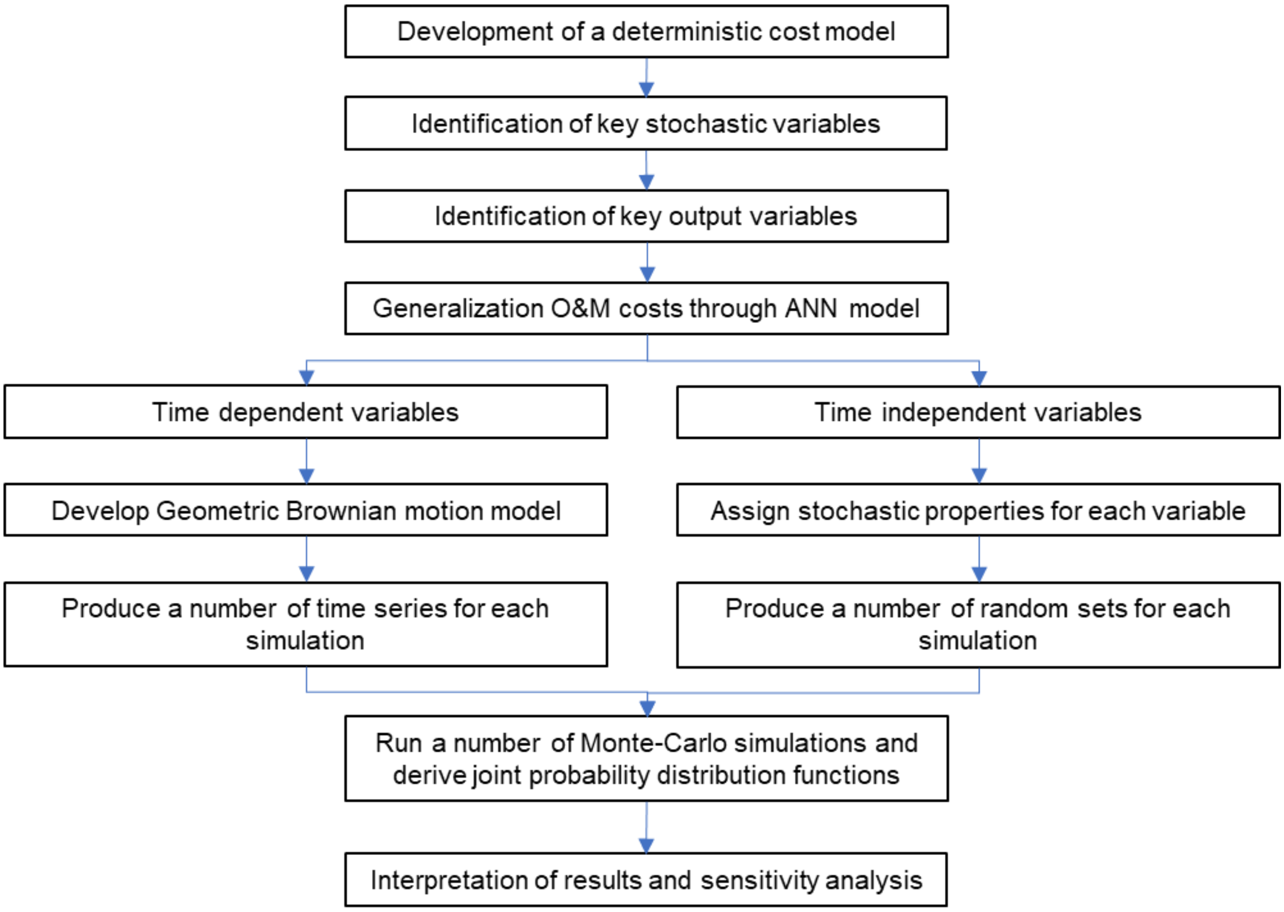

Figure 6 Methodological steps

7. Indicative model outputs

The closing section of this report aims to present indicatively expected outcomes of the discrete simulation elements that will be further developed into an integrated tool. More specifically, the form of the outputs of the deterministic model, the O&M tool and the stochastic analysis model are included. Analysis will take place throughout the project for discussion with the project partners and updated inputs will be used once relevant project outputs become available for more accurate assessment of costs.

Deterministic outputs

From the deterministic analysis, the following outcomes are obtained:

- LCOE
- NPV
- IRR
- Detailed cost breakdown per phase (Figure 7)
- Sensitivity analysis of key simulation variables (Figure 8)
- Life cycle cost/revenue profiles (Figure 9)

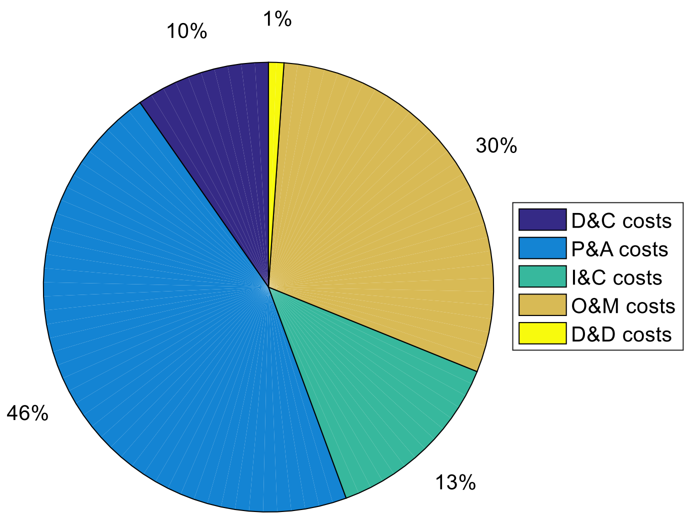

Figure 7: Life cycle cost breakdown

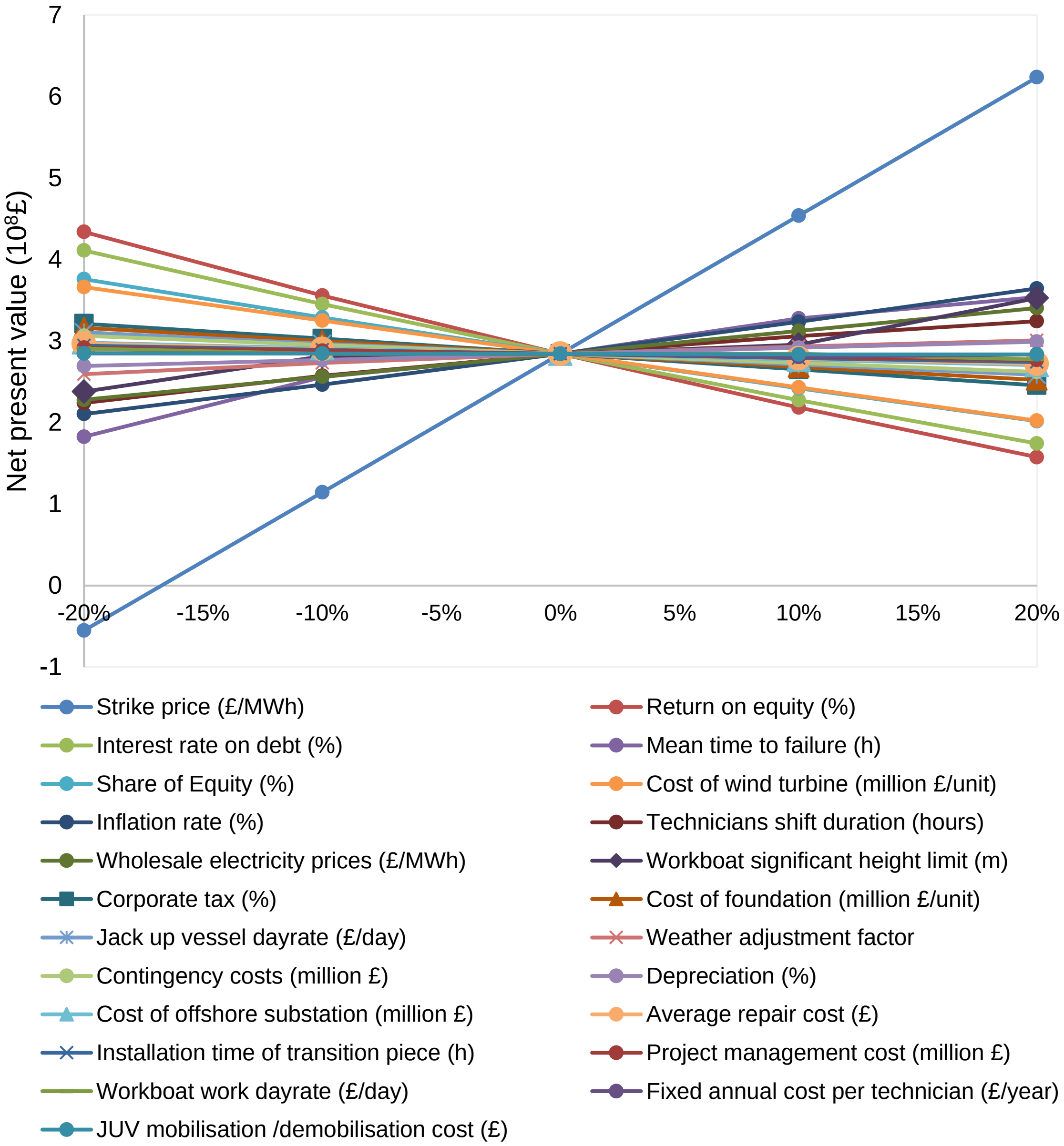

Figure 8: Sensitivity analysis of simulation parameters

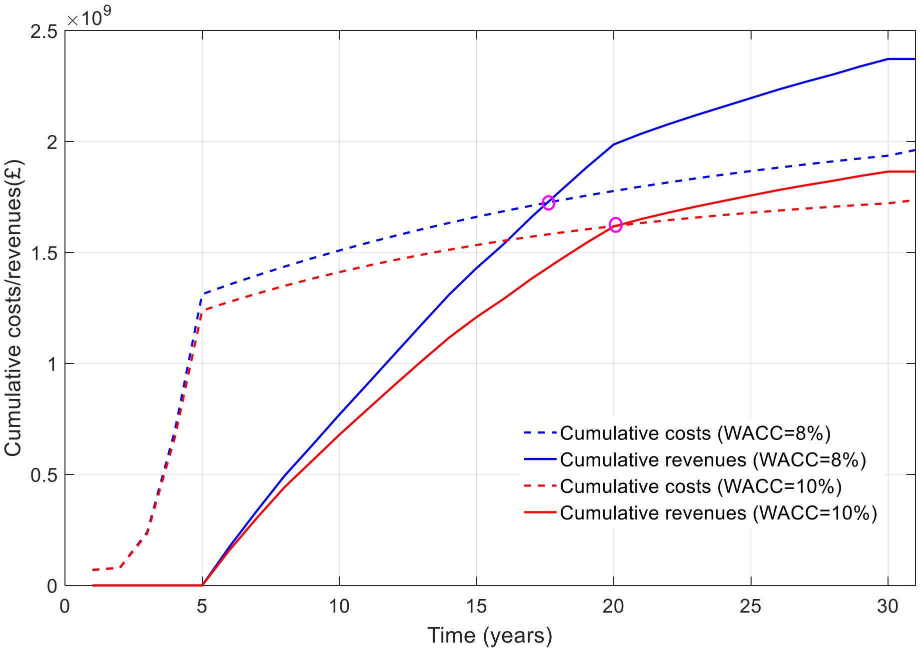

Figure 9: Life cycle cost/revenue profile

O&M outputs

The O&M module returns a number of outputs including the following:

- Production based and time based availability
- Power production losses
- Power output per each turbine
- Breakdown of downtimes
- O&M costs throughout the service life of the wind farm

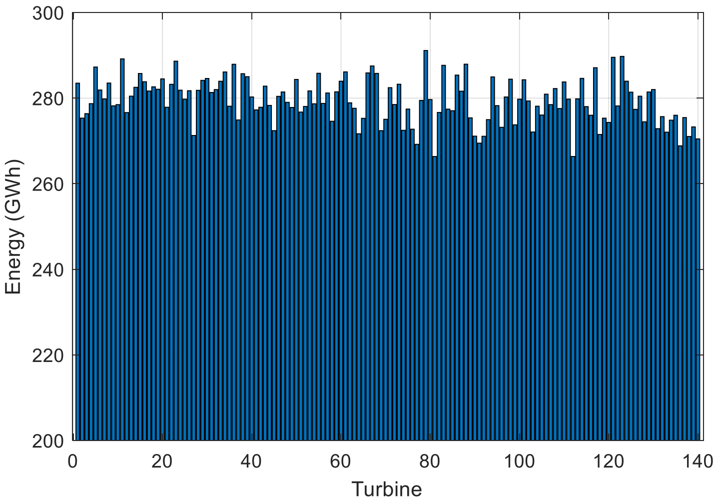

Figure 10 Power output per each turbine

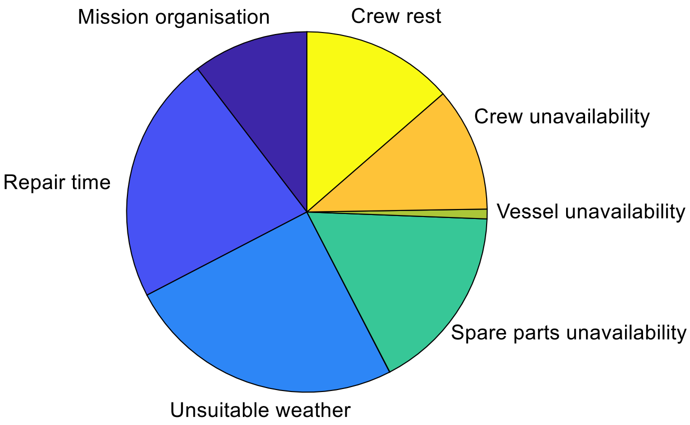

Figure 11 Breakdown of downtimes

Stochastic analysis outputs

The uncertainties included in the design and operation of offshore wind turbines requires their systematic consideration in the evaluation of assets. To this end, through a combination of the deterministic cost revenue model and Monte-carlo simulations, confidence levels can be assigned to the assessment of KPIs as illustrated below in the cases of:

- Probabilistic results of NPV under three different strike prices (100, 120 and 140 £/MWh).
- Probabilistic results of LCOE (£/MWh)
- Probabilistic results of Capital costs
- Probabilistic results of O&M costs

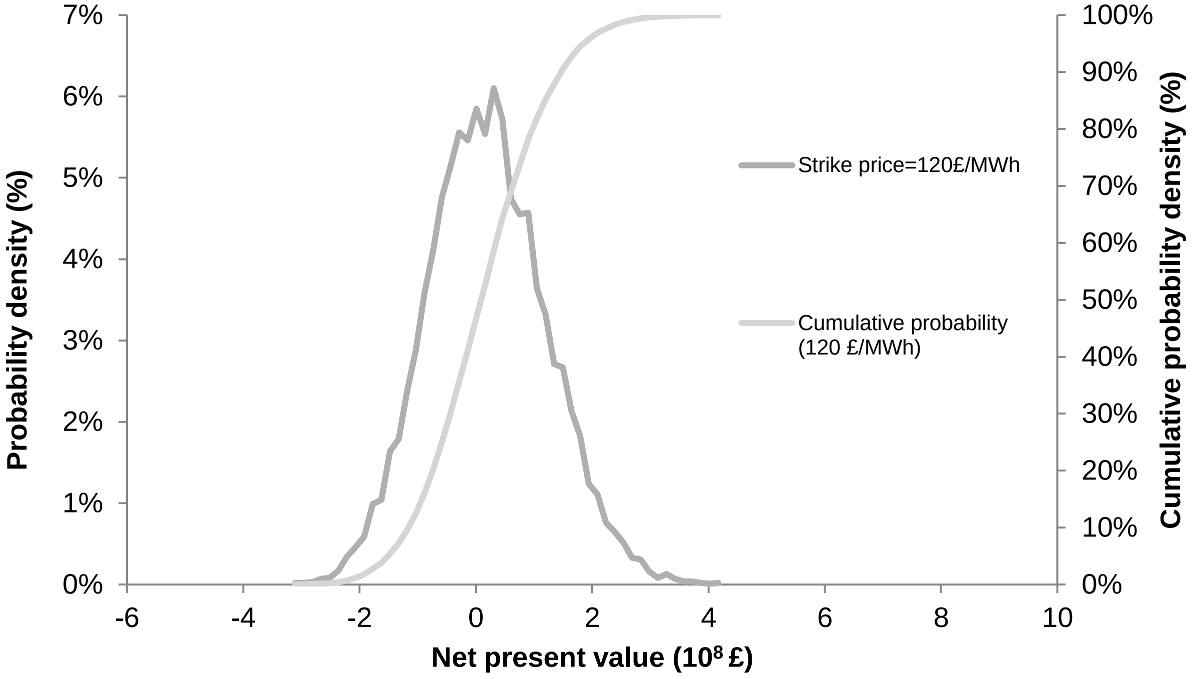

Figure 12 Probabilistic results of NPV

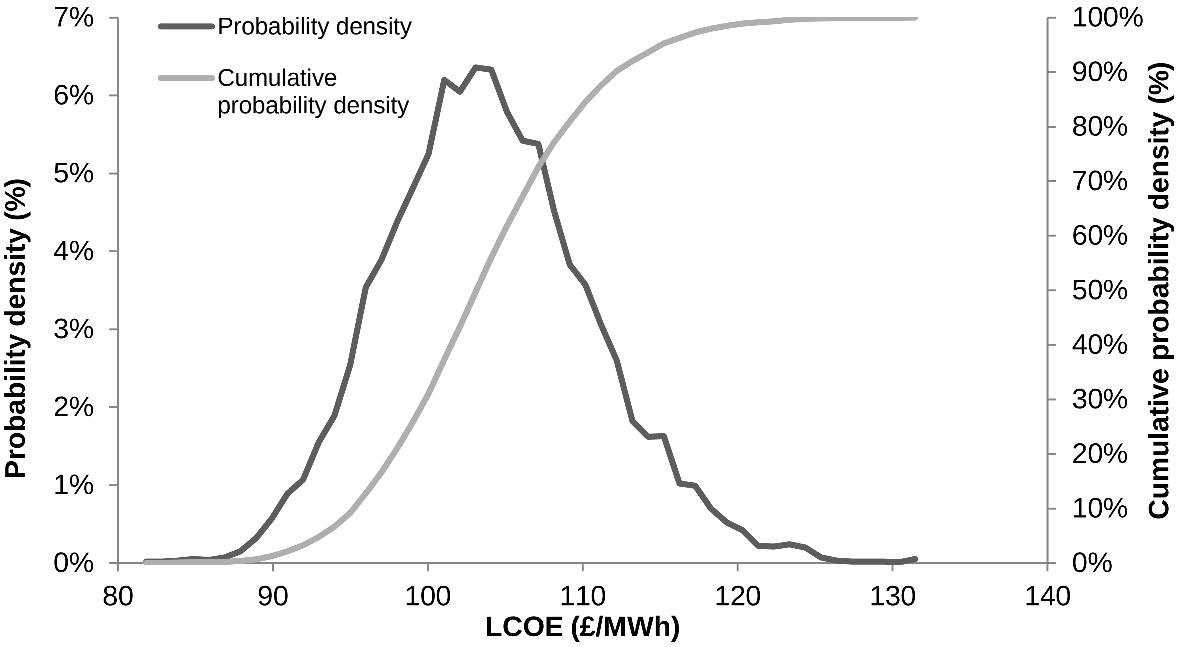

Figure 13 Probabilistic results of LCOE (£/MWh)

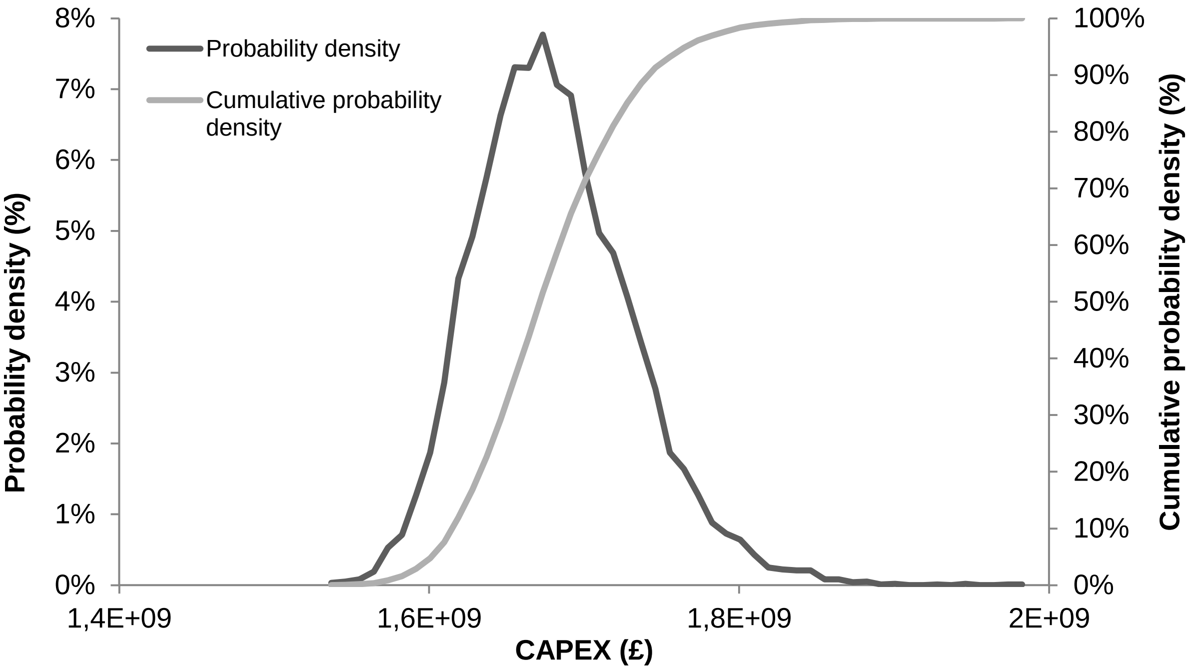

Figure 14 Probabilistic results of Capital costs

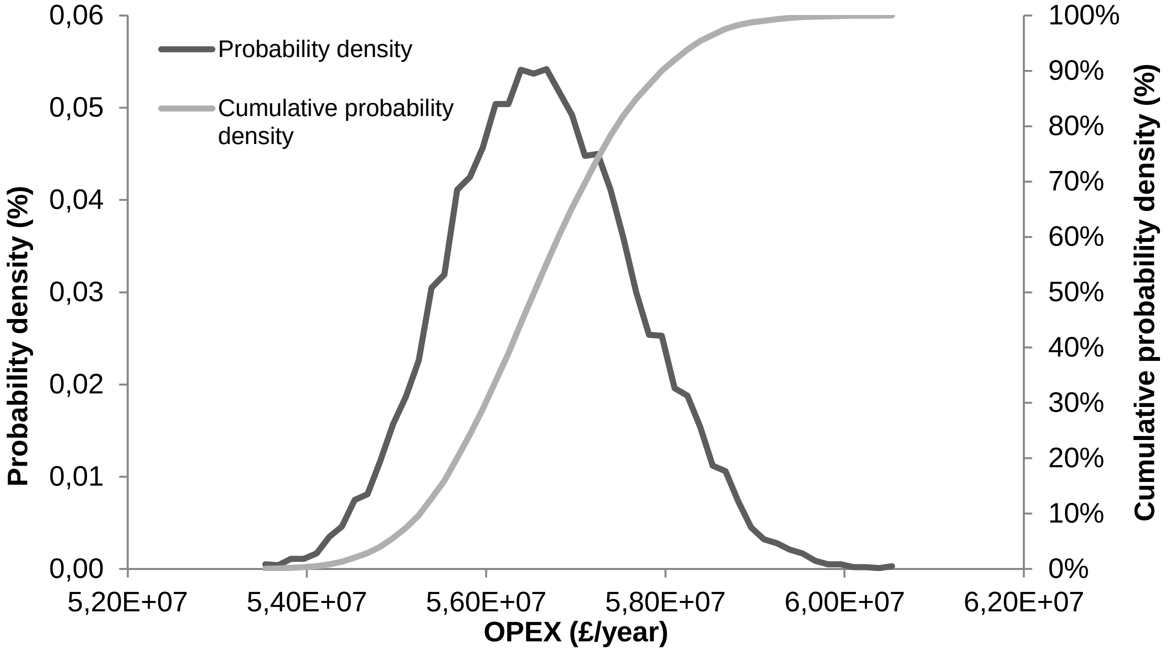

Figure 15 Probabilistic results of O&M costs

8. Conclusions

This report documents the development of the main module of the life cycle cost and impact assessment tool as documented in the tasks of WP8. 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 methodology will be fully implemented into a numerical code, with an additional environmental life cycle assessment module that will be developed and integrated for automatic calculation of the carbon footprint of the service life operation of the asset. This will be documented in the following deliverables, D8.2 and D8.3. Further input from the project partners in the next steps of the development will allow for practicalities of the O&M considerations to be fully implemented in the developed tool. Finally, various analysis will take place and documented in D8.4 for the real case studies that the project examines, quantifying the impact that the innovations of this projects will have on the life cycle costs of this project.

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