A lifecycle financial analysis model for offshore wind farms

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ABSTRACT

Simulation and modelling allow a range of offshore wind farm stakeholders to test and improve a project's viability in a cost-effective and safe manner. This paper presents a model developed to conduct detailed financial analysis of an offshore wind farm. It extends the current state of the art by employing stochastic time-series simulation modules performing in-depth analysis of the technologies, strategies and procedures applied during the installation, operation and maintenance, and decommissioning phases of a wind farm lifecycle. The model was designed for versatility and can consider both fixed and floating technologies, a wide variety of strategies, and any site specified by the user. Results include energy production, costs and the duration of activities at each stage. These populate financial spreadsheets, which calculate key performance indicators including the Levelised Cost of Energy. The model has been successfully validated against real-life case-studies where possible; published data; and uses sensitivity analysis to ensure the model is working as expected. Through a case-study, the paper demonstrates how 1) the model enables the identification of key cost and time drivers, facilitating scenario optimisation; 2) the stochastic nature of the model considers the impact of uncertain variables on results such as weather conditions and wind turbine failure rates; 3) the model can be used to assess different business models and financing structures. This comprehensive range of abilities means that the model is suited to a variety of end-users and meets the demands of a growing industry, striving to achieve further cost-reductions across a range of site conditions, technologies and markets.

Keywords: Offshore wind, financial analysis, lifecycle cost, offshore logistics

1. INTRODUCTION

In 2010, the European wind energy sector set ambitious targets of 20% wind energy penetration by 2020 and 33% by 2030 [1]. Grid-connected capacity is at almost 16 GW in 2017 and Wind Europe predict an installed capacity of 24.6 GW by 2020 [2]. As the offshore wind industry develops, turbine capacity will increase beyond 10 MW and wind farms will move further offshore. These developments will bring new challenges to the industry in terms of foundation solutions, site accessibility and suitable vessels.

The recently completed EU FP7 LEANWIND project (December 2013-November 2017) aimed to specifically address the logistical challenges of deploying, installing and operating large-scale wind turbines in transitional and deep water with a view to reduce the cost of installation, Operation and Maintenance (O&M), and decommissioning of offshore wind farms. The project looked at both fixed and floating foundation solutions for 5-10 MW turbines, and the associated transport, logistical and maintenance operations. Novel approaches to vessel design and O&M strategies were also investigated in the project. In order to determine the cost-benefits of the project innovations, a comprehensive financial model was developed to assess their impact on all phases of an offshore wind farm lifecycle.

1.1 State of the art for financial analysis and lifecycle cost modelling of offshore wind farms

Prior to the LEANWIND project, existing financial models lacked the capability to assess the installation, O&M and decommissioning phases of a project in the detail required in LEANWIND and many were protected in-house tools. This prompted the need to create a lifecycle financial analysis model, which extends

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the current state-of-the-art. An overview of models existing prior to 2011 is given by Hofmann [3] who concluded that while there are a number of models that can estimate costs for different phases of an offshore wind farm, few cover the entire lifecycle. Those that do address the total costs (e.g. TU Delft's Opti-OWEC cost model, ECN's DOWEC and OWECOP models, DNV's Extend simulation model and OWFIC models) do not consider each phase in detail [3]. Several applied detailed modelling of the O&M phase in isolation, and a number of detailed O&M cost models have also been developed in the years following this article. These are included in an updated review in 2018 [4]. However, there are still relatively few models for the installation or decommissioning phase. Examples are separate installation and decommissioning cost models created and used by Kaiser and Snyder in [5] and [6].

A number of high-level Levelised Cost of Energy (LCoE) models were created to assess specific technologies. The DELPHOS model [7] uses a number of baseline scenarios representing a range of technologies with different Final Investment Decision (FID) dates to calculate the LCoE and other economic parameters. Castro-Santos and Diaz-Casas [8] developed a general methodology for evaluating the cost breakdown of a floating offshore wind or wave energy farm. Myhr et al. [9] calculate and compare the LCoE for floating concepts and fixed monopile solutions. Open access cost tools exist that are essentially cash flow sheets, and while these are very useful for high-level LCoE calculations, they did not meet the need for detailed assessment of all lifecycle phases in LEANWIND. Such tools include the Megavind open source methodology for calculating LCoE [10], and the DECC simple levelised cost of energy model [11]. In addition, a cash flow model combined with detailed bottom-up modelling of the O&M phase was used for calculating the LCoE breakdown for a baseline offshore wind farm in the IEA Wind Task 26 [12].

More recently, the parametric model presented by Shafiee et al. [13] applies a multivariate regression/neural network approach to identify the key drivers of cost in all phases of a fixed offshore wind farm lifecycle. Ioannou et al. [14] combine parametric equations with the ECN O&M tool [15] to develop an integrated techno-economic model.

None of the above models apply detailed stochastic time-series simulation modelling to all three lifecycle phases. In addition, most models also only focus on the LCoE, Net Present Value (NPV), Internal Rate of Return (IRR), neglecting the inclusion of more detailed financial parameters that enable users to consider different financing structures. Therefore, the model presented in this paper extends the current state-of-the-art.

1.2 The Financial model

University College Cork (UCC) and SINTEF Research developed the full lifecycle financial analysis model (herein referred to as the Financial model) to assess project innovations in terms of technologies as well as novel strategies and procedures. The aim is to examine scenarios in detail from a financial perspective at each project stage (installation, O&M and decommissioning) to support decision-making and planning. The main novelty of the Financial model compared to the state-of-the-art models presented above, lies in the use of a detailed discrete-event time-series Monte Carlo simulation methodology for the analysis of all three lifecycle phases. Advantages of this approach are that it allows 1) accurate assessment of the impact of metocean conditions and other stochastic elements on offshore logistics, and thus on cost and time; and 2) a probabilistic analysis of results. In addition, it should be noted that the model was designed to be able to consider any technology and site input by the user including fixed or floating turbines in near, transitional or deep water.

Furthermore, a broad range of financial parameters can be input to the model to define the business case under consideration. This enables the user to determine the required financial support for the offshore wind farm project. The model breaks down the Capital expenditures (CAPEX, which includes dry CAPEX, i.e. the purchase of assets and wet CAPEX i.e. installation activities); Operational expenditures (OPEX); and Decommissioning expenditure (DECEX), which feed into an annual cash flow sheet that facilitates analysis of project finances on a yearly basis. In this way, the model combines detailed bottom-up modelling of the individual lifecycle phase cost contributions with the financial capabilities of a detailed cash flow model. The model calculates key financial indicators including LCoE, NPV, IRR and the Payback period, which help validate the potential cost savings of different strategies and technical innovations.

Beyond the LEANWIND project, the anticipated end users of the financial model are primarily developers of offshore wind farm projects and technologies. Other potential end users include farm operators, investors, manufacturers, policy makers, researchers, students and port authorities. A brief overview of the Financial model has been presented by Devoy McAuliffe et al. in [16] focusing on use cases for this model together with the other (logistics optimisation) models developed in the project. The present paper aims to build on [16] by describing the Financial model and the underlying methodology in more detail (Section 2) as well as describing model validation activities (Section 3), including the application of the model to a real-life case-study and comparing the results to published data. Section 4 describes financial analysis performed on the case-study data, which demonstrates the capabilities of the model. Concluding remarks are provided in Section 5.

2. FINANCIAL MODEL DESCRIPTION

2.1 Model overview

This section provides a detailed description of the user interface as well as the overall scope and capabilities. A schematic of the main components of the model is presented in Figure 1.

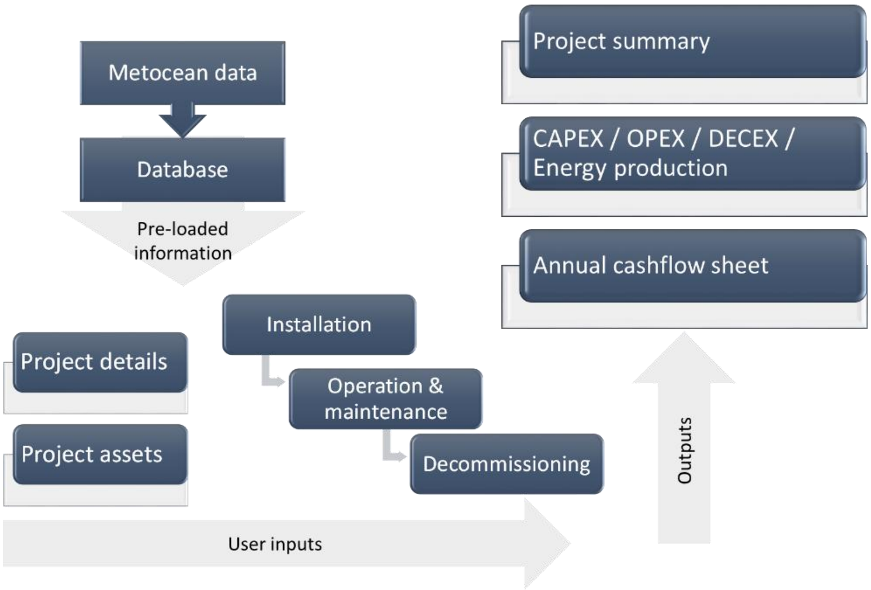

Figure 1 Financial model schematic

The model consists of an Excel interface with a number of input and output sheets as well as a database for commonly used information, which can be easily accessed via the input sheets. To run a scenario, the core information required includes the farm assets (e.g. details of the turbines, foundations, substation); details of the strategy and resources (e.g. vessels, technicians, equipment) available during installation, O&M and decommissioning; the wind farm lifetime; and the financial parameters to apply to the results (e.g. the Discount Rate (DR)).

The model performs time-series simulations of the installation, O&M, and decommissioning phases of an offshore wind farm lifecycle using individual modules for each phase. This means that discrete-event simulations of the relevant offshore operations and logistics are carried out for each phase based on a time-series of hourly significant wave height and wind speeds, which determine if/when the offshore operations can be carried out. These modules run concurrently for computational efficiency. They all employ Monte Carlo simulation, which is a technique that allows users understand the impact of uncertainty and risk in prediction models by drawing random values using probability distributions for stochastic variables, i.e. elements with inherent variability. In the Financial model, the key stochastic elements are weather conditions, component failures and costs. Using a single scenario predefined by the user, the corresponding variables fluctuate over multiple simulations of a project lifecycle to model the potential impact of uncertainty on time and costs. The model outputs the estimated mean result as well individual results per simulation. The latter can be analysed by the user to determine the standard deviation and standard error of the mean, providing a measure of confidence in the estimated mean result. These principles are further explained in Section 2.2.4 and demonstrated in Section 3.4.4.4.

The modules are implemented as MATLAB executables, which are activated via the central Excel interface. A key capability is that the modules can be used as stand-alone models. This means that the user can either examine just one stage; the full project lifecycle; or having run a full scenario, edit and re-run a single model to further analyse aspects of one specific phase to determine the impact on the overall LCoE. This feature facilitates rapid sensitivity analyses by avoiding repeated simulations of the full lifecycle.

Results from the modules are used to populate the financial model annual cash flow sheet: the Installation module generates the installation costs of the total CAPEX, which are included for the year(s) prior to commissioning; the O&M module generates OPEX and annual energy production outputs for each year of the O&M phase; and the Decommissioning module generates DECEX output for the year(s) of the decommissioning phase, as well as the expected salvage income from this phase. The following section describes the different model components in more detail.

2.2 Model components

2.2.1 Database

The Excel interface of the financial model contains a database of information, which can be selected to reduce the amount of inputs required for each scenario. The database can also be edited by the user to include new options. Information stored for selection includes:

- The resources available for installation, O&M and decommissioning in terms of vessels, technicians, on-land transport etc. including their capabilities. For example, the vessel data includes wave and wind limits for different vessel operations, load carrying capacity, transit speeds, fuel consumption, chartering costs, maintenance requirements, technician accommodation details etc.
- The project assets that can be selected such as foundations, turbines and their respective power curves, associated installation strategy options etc.
- A list of the metocean data files available. These must be provided by the user in a specified format and contain time-series of wind speeds and significant wave heights at the site in question with an hourly resolution. Longer time-series allow the time-series simulation modules to better capture the variability in weather.

2.2.2 Project details

The project details sheet allows the user to specify high-level project inputs such as the lifetime of the wind farm, metocean dataset, water depth and the number of simulations to be performed. A higher number of simulations increases the statistical precision of the outputs, as explained in Section 3.4.4.4. This input sheet also contains financial input parameters that define the business case of the scenario under consideration and are described in Table 1. By varying the financial parameters, the user can consider the impact of different funding, debt repayment and savings strategies; consider the impact of different subsidy models; and apply different discount rates. This can determine the appropriate financial support required for a project, from either industry investments or government incentive schemes. Further manipulation of the financial parameters can be carried out after the time-series simulation modules have run. The financial parameters are further explained and demonstrated in Section 4.

Table 1 Financial parameters

Financial Parameters	Description
Constant electricity price (€/kWh)	Average electricity price
Discount Rate (DR) (%)	Used to convert a future cash flow to the present value. The real discount rate takes inflation into account.

Equity amount (€)	The capital available to invest in the project. The balance of CAPEX must be financed by a grant and/or loan.
Grant amount (€)	The grant available to invest in the project.
Deposit interest (%)	% interest earned on bank deposits.
Depreciation rate (%)	The rate at which the capital assets depreciate during the project lifetime. Can be chosen by the user or calculated linking to the salvage value produced by the decommissioning module.
Contract for Difference (CfD) rate (€/kWh)	Anticipated rate if a CfD subsidy applied. This is further explained in Section 2.2.6.
CFD term	The number of years the rate will apply for.
Renewable Energy Feed-in Tariff (REFiT) (€/kWh)	Anticipated rate if a REFiT subsidy applied. This is further explained in Section 2.2.6.
Loan amount (€)	Amount
Interest rate (%)	Fixed for the duration of the loan.
Loan term	The number of years over which the loan will be repaid.
Loan start year	The Project Year in which loan repayments begin.
Loan administration charges (%)	Bank charges as a % of the loan amount.
Tax rate (%)	Fixed for the duration of the project.
Savings fund amount (€)	Total amount to save during project.
Savings fund term	Total number of years savings will be made.
Savings start year	Year savings begin.
Savings fund injection	Year savings fund will be injected into the cash flow.

2.2.3 Project assets

The project assets sheet includes details of the:

- Turbine e.g. rating, hub height, cost
- Foundations (turbine and substation) e.g. type, fixed/floating, cost
- Substation e.g. rating, cost
- Inter-array cabling e.g. length, cost
- Export cabling e.g. length, cost
- Balance of plant costs e.g. onshore works

This sheet performs an initial calculation of the dry CAPEX costs.

2.2.4 Time-series simulation modules

Each of the lifecycle modules (installation, O&M and decommissioning) were developed separately with a focus on the aspects most significant to each respective lifecycle stage. Therefore, they vary somewhat in input requirements as well as methodology. Figure 2 provides a high-level illustration of the inputs for each module. The outputs of all modules are averaged over all simulations and reported for each year of the lifecycle phase, but the modules also produce more detailed individual phase reports including cost breakdown charts and outputs for each simulation etc. These can be used for visualisation purposes, to help identify key cost drivers, and to perform further analysis as demonstrated in Section 3.

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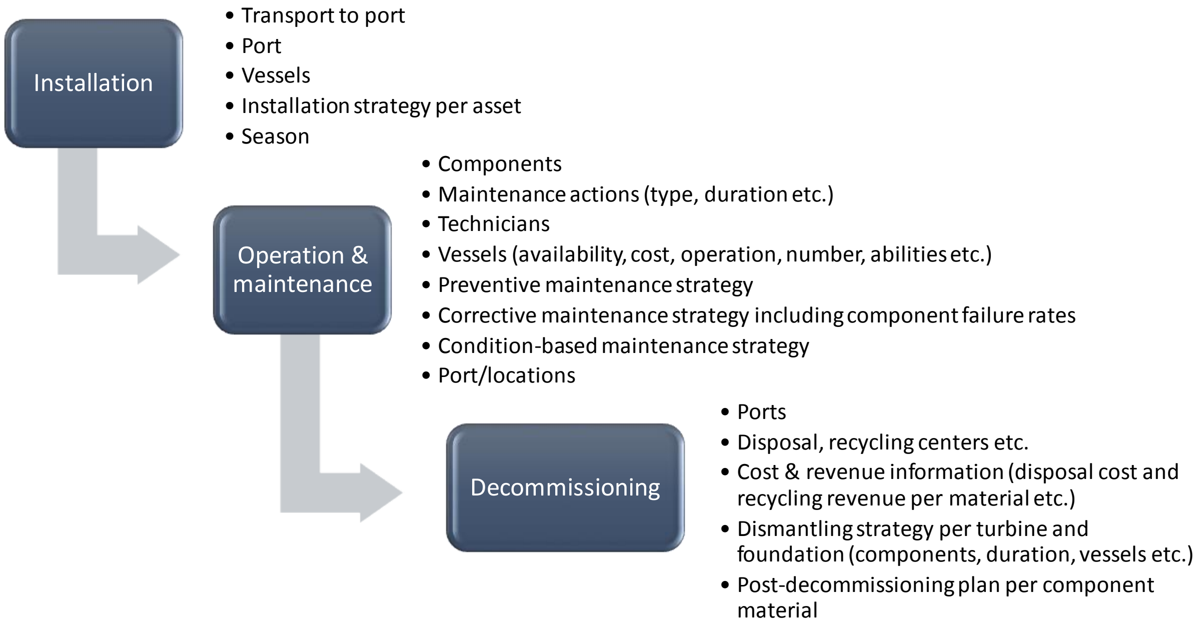

Figure 2 Financial model - time-series simulation module inputs

2.2.4.1 Installation module

The Installation module calculates the cost contribution of installation activities to the CAPEX of the wind farm project and was developed by UCC. Currently the scope includes the turbine, foundation, substation, substation foundation, export and inter-array cabling. The installation method for each element is specified from a list of options. For example, the methods for cabling include plough burial or separate trench and lay; there are a range of options for turbines e.g. pre-assembled, all components installed individually etc.; and the foundations may be floated-out or craned (lifted). The wide range of installation options ensures the model is extremely flexible and can simulate activities associated with either fixed or floating turbines in near or deep water sites.

The resources required for each activity are also specified, e.g. the vessels and the number of turbines or foundations each vessel can transport with the selected installation method. The transport distances from manufacturing centre to the staging port by road and sea for all project assets (e.g. turbines, foundations, export cable etc.) as well as the distance from port to offshore site are required inputs. Additional project costs such as project management, port costs, and survey and monitoring costs are also specified on the installation input sheet.

The stochastic variable in this module is the weather time-series (both wind speeds and wave heights), which is created taking a random selection of the years of data input by the user per simulation. The random year generated is drawn from a discrete uniform probability distribution of the years available. A matrix of available weather windows is then generated for all operations considering their duration and weather restrictions. This is consulted during the simulation to determine if/when an activity was able to be carried out, recording the actual time taken to consider the impact of delays on time and costs.

Using the scenario inputs and the hourly metocean data, the module generates a schedule of activities, recording the sequence of events, the time spent carrying out each activity, and any delays. It calculates the overall time taken and the cost of activities broken down as follows: the dry CAPEX of assets; pre-installation transport costs from the manufacturer to the supply port (not included in the time-series); the charter and fuel costs for vessels; costs for survey and monitoring, port activities, other balance of plant (e.g. onshore works) and project management. These are averaged over the number of simulations and fed into the Annual Cash Flow Sheet (Section 2.2.5) as annual figures. A separate output file contains more detailed cost and time breakdowns for individual activities; results per simulation; and details on travel distances and fuel consumption per vessel to facilitate environmental impact assessment or Lifecycle Assessment (LCA).

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2.2.4.2 O&M module

The O&M module calculates the OPEX and the energy production of the wind farm project. It is based on the NOWIcob model [17,18] developed by SINTEF Energy Research within different research projects including LEANWIND. A brief summary of the O&M module is given below with a more detailed description available in [17].

The module analyses a given O&M strategy for a wind farm considering preventive, corrective, and condition-based maintenance, the resources available, including vessels, personnel (including shift patterns), spare parts, and the maintenance base location. Maintenance tasks can be specified to require vessels with special abilities, e.g. jack-up ability for replacements of large components. Such vessels may be specified as chartered on demand, with associated charter cost, charter duration and mobilisation time. Vessels that are not chartered on demand but are available on long-term charters or owned by the wind farm owner, have an associated fixed cost per day.

Maintenance operations at offshore wind farms and the wind turbines' downtime and energy production are all highly weather dependent. Therefore, the discrete-event Monte Carlo simulation approach considers the variability and uncertainty in weather by using Markov chain modelling techniques [17]. The input weather time-series are used to generate monthly weather state transition matrices, which are then used to generate new, representative weather time-series for each simulation of the O&M phase. The other key stochastic variables are the time of occurrence of unplanned outages. Occasionally, turbine downtime is caused by component failures, alarms or pre-warnings that require repair or replacement of components or resetting the turbine. These outage occurrences are collectively referred to as failures in the following, and the failure times are modelled based on a homogeneous Poisson process and annual failure rates. In addition, the user can specify probability distributions to model the following variables as being stochastic: the mobilisation time of chartered vessels; the lead time for spare parts; the direct repair time of maintenance tasks; and the pre-warning time for condition-based maintenance tasks.

Annual results are averaged across simulations and fed into the Annual Cash Flow Sheet including the annual energy production and the total annual O&M costs considering personnel; vessel (fixed costs, on-demand charter costs and fuel costs); and spare parts. Energy production is calculated by combining a wind turbine power curve and with the simulated wind speed time-series to calculate power production. Downtime losses are explicitly accounted for during the simulations as described above, while user-defined loss factors have to be specified to account for wake effects, electrical power losses, and losses due to outages in the electrical infrastructure. Loss of revenue from grid operator curtailment is not considered. This module also produces a more detailed breakdown of costs and energy production; results per simulation; a summary of downtime and availability (time-based and energy); vessel and technician utilization.

2.2.4.3 Decommissioning module

The Decommissioning module calculates the DECEX and salvage revenues. It was developed by UCC and the current scope is limited to modelling the decommissioning of the turbine and foundations. Inputs include the mass, dismantling duration and port destination for materials; whether they are intended for recycling, disposal, re-conditioning or re-sale (considering depreciation on the parts sold); the distance to disposal and recycling centres on-land; disposal costs and recycling revenues per tonne of material; and decommissioning vessels, technicians and on-land transport available.

The stochastic variables considered are the weather time-series, costs and revenues. Based on the metocean time-series and a forecast time specified by the user (e.g. 12-72 hours), the model will check a randomly selected year of data (using the same method as the installation model) considering the most stringent operational weather limitation for a given task before commencing operations. Prior to the first simulation, the model also generates a matrix of the probability of weather windows being available for all operations based on the average annual conditions at the site. The user can specify a minimum probability requirement of a weather window being available for each operation in a task (e.g. transit, positioning, offshore operation etc.) before a vessel is deployed to a new activity. This minimises the risk of weather changing during an operation as the module currently does not model the impact of weather delays if a task takes longer than the forecast

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time specified. Future work will update this technique to match the installation model, which is computationally faster and a more accurate simulation of events. Ultimately the intention is also to update both modules to generate a new time-series per simulation using Markov chain modelling like the O&M module or a similar method.

Cost and revenue figures can vary significantly (e.g. the price of steel, survey and monitoring, port costs) and are particular risks when simulating this project phase as there is very little experience of decommissioning offshore wind farms to date. To account for this uncertainty, the costs and expected revenues are varied per simulation by generating random values from a beta distribution similar in shape to a normal distribution curve, using specific lower and upper domain limits [x_0, x_1]. Where the user input value is a, the standard deviation is b, $x_0 = a(a - ab)$ and $x_1 = a(a + ab)$. Currently a standard deviation of 10% is assumed but future work could consider allowing the user specify this and to choose the probability distribution curve to apply.

The module derives an annual estimation of DECEX including project management, contingency, planning, surveys and monitoring, ports, vessels, technicians, on-land transport, and disposal (e.g. landfill charges) costs. It also calculates the salvage revenue; the time taken to complete activities; energy produced or O&M costs if the user has chosen to decommission in stages. Results per year are fed into the Annual Cash Flow Sheet while a more detailed individual output file is created including a detailed breakdown of costs and time per activities; results per simulation; and details of distance travelled per vessel or vehicle used.

2.2.5 Annual Cash Flow sheet

The Annual Cash Flow Sheet presents the financial results on a yearly basis using the data collated in each time-series module and applying the financial parameters input by the user (Table 1). Table 2 summarises the cash flow sheet calculations while Table 3 describes the financial Key Performance Indicators (KPIs) produced. They are further explained and demonstrated in Section 4. **Error! Reference source not found.**

Table 2 Annual cash flow sheet calculations

Parameter	Description	Calculation
Discount factor	Converts a future cash flow to the present value applicable for a given Project Year	$\frac{1}{(1+DR)^{Year}}$
	Energy Production	
Energy Production	Delivered Energy for the current Project Year	Imported from the O&M module and the Decommissioning module (where staged decommissioning is selected)
Discounted energy	Value of energy for the current Project Year	$Energy \times DF$
	Cash Inflows	
Salvage income	Income from Salvage for the current year	Imported from the Decommissioning module
Revenues	Total revenue from all sources for this year.	$(Grid\ sales\ revenue + subsidies) \times Energy\ production$
Deposit interest	The interest earned on cash in the bank	*Interest rate* × ((*Revenues* + *Salvage income*) - (*OP*
Savings fund injection	The year when any savings put aside for future farm costs (see Cash Outflows) are injected into the cash flow e.g. if saving for decommissioning costs.	User input
	Cash Outflows	
CAPEX	Total capital expenditure for this year including installation costs.	Imported from Installation module
OPEX	Operational Expenditure for the	Imported from the O&M module

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	current year	
DECEX	Cost of decommissioning in the current year	Imported from the Decommissioning module
Interest repayments	Repayments on loan interest during the project year	Calculated within Financial model
Principal repayments	Total Principal Payment made during this year that goes towards paying the principal balance of a loan	Calculated within Financial model
Debt repayments	Principal and Interest payments made during this year	*Interest + Principal repayment*
Bank charges	Administration charges on loan applied in first year of borrowing	*Loan amount × Administration Charge %*
Savings fund	Cash put aside during course of the project	User input
Tax	Tax paid	Calculated within Financial model: Profit & Loss sheet
	Profit & Loss sheet (income statement)	
Profit	Nominal Profit made during the current project year. Note: Only the interest payment on a loan is included as the repayment of the principal loan is not considered an expense	*Revenues + Deposit interest - OPEX - Interest repayments - DECEX - Bank charges*
Depreciation	Annual depreciation of assets: 1) Straight line depreciation method subtracting a set amount each year or 2) using a yearly % reduction in value determine by the salvage value output by the Decommissioning module.	*1)* $\text{Fixed annual expense} = \frac{asset\ value}{project\ lifetime}$ *2)* $\text{Annual \% reduction} = \frac{(100\% - \left(\frac{Salvage\ inc}{asset\ val}\right.}{project\ lifetime}$
Taxable profits	Portion of profit which is liable to Corporation Tax	*Profit - Depreciation*
Taxable profit after losses	Taxable Profit after losses: profit remaining after cumulative losses	*Taxable profits - cumulative losses*
Tax	Tax paid on Taxable Profit after Losses	*Tax rate × Taxable profit after losses*
After tax profit	Profit after Tax is deducted: Nominal Profit minus Tax	*Taxable profit after losses - Tax*
	Cash Flow Sheet	
Net cash flow	The difference between cash inflows and outflows.[1]	*Cash inflows - Cash outflows*
Discounted net cash flow	Net cash flow, discounted to consider the present value	*Net cash flow × Discount factor*
	Balance sheet	
Total liabilities/Debt	Remaining debt each year	*Outstanding loan - Principle repayment + Tax + OPEX + DECEX + Bank charges*

[1] CAPEX is considered an investment and the money spent is not reported on the Cash Inflows sheet, but is treated as an asset on the balance sheet. CAPEX is deducted over the course of several years as a depreciation expense following the year of investment and is reported on the Cash Outflows sheet.

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amount		
Equity amount	Shareholder funds each year	*(Investment – depreciation) + (cash available – savings)*
Equity	Capital investment	User input
Grant	Any grants	User input
Borrowing	Any borrowing	User input
Cash reserves	Cash available	*After tax profit + last year's cash reserves*

Table 3 Description of financial performance indicators

Term	Description	
NPV	The net present value of future cash flows.	$\sum$ *annual discounted net cash flow*)
Payback period	The number of years required to recover the initial investment.	
IRR	The expected rate of return on an investment. It is calculated considering the DR required to bring the NPV to zero.	
LCoE	The net present value of the cost of electricity of a project lifetime. It can be used to determine the price required for a project to breakeven.	$\frac{(CAPEX + \mathrm{NPV}(Total\ costs))}{\mathrm{NPV}(Total\ energy\ production)}$

2.2.6 Revenue and debt-equity summary

To allow the user to quickly identify and review key information, the model also contains two additional summary sheets, namely 'Revenue' and 'Debt-equity'. The revenue sheet provides annual figures for capital grants in addition to electricity sales income, taking into account REFiT or CfD subsidies if relevant (Table 1), and the user specified electricity sale price. REFiT is a mechanism for compensating renewable energy providers by providing price-certainty in the form of long-term contracts that help finance renewable energy projects. CfD refers to a long-term contract where the provider is paid (or pays) the difference between the agreed strike price for generating low-carbon electricity and the reference price, or average market price for electricity. The purpose of both mechanisms is to incentivise investment in low-carbon electricity generation. The debt-equity sheet summarises the debt-equity ratio, the debt term and amount, the equity amount, the borrowing rate, and monthly/annual repayments.

2.2.7 Project summary sheet

This provides an overview of the project scenario and results including:

- Wind farm energy outputs including total production and average annual production.
- Lifecycle cost components including total CAPEX, OPEX and DECEX as well as any salvage revenue.
- Financial KPIs: debt-equity ratio, NPV, payback period, IRR and LCoE.

3. MODEL VALIDATION

Multiple paradigms and techniques for validation of computer models exist. For instance, operational validation [19] could be achieved by comparing model outputs with real, historic data for the system the model is meant to represent, using as input to the model real data for the same system. However, this is challenging for offshore wind farms due to the limited availability of such data as 1) it is often commercially sensitive, and thus not readily available to the research community; and 2) it is scarce due to limited operational experience. Historic data is almost non-existent for the decommissioning phase [20] [21], whereas data is available for the installation phase of a number of offshore wind farms currently operational [22]. Therefore, validation of the financial model was initially carried out by considering each module separately, considering the information available for each phase, and undertaking sensitivity analysis as an additional form of validation to ensure each model is working as expected. Sections 3.1-3.3 present a summary of the validation exercises undertaken for each module. The model was also validated as a whole using a case-study based on an actual wind farm (Crown Estate Phase 1), as presented in Section 3.4.

3.1 Installation module validation and sensitivity analysis

The LEANWIND project validated the Installation module using published data from three different wind farms: C-Power Phase 1 (30 MW), C-Power Phase 2 & 3 (288 MW), and Teesside (62 MW). These case-studies were chosen as they represent a range of different technologies, installation methods and farm sizes. In all three cases, it was found that the modelled installation time was consistently less than the published figures. This in turn impacted the predictions for installation costs, particularly for the larger wind farms, with the model generally under predicting CAPEX. For a small wind farm (C-Power Phase 1), it was found that the model produced accurate predictions of the project costs (within 1% of the documented costs). C-Power Phase 1 is considered in more detail in Section 3.4. Discrepancies between the model predictions and published data were attributed to the following factors:

- The installation module may not be able to exactly represent the vessel logistics employed in the wind farm installation. For example, a feeder vessel was used during the turbine installation on the C-Power farms. One vessel loaded the turbine from port and delivered the turbine to site, while the other installed the turbine. The model does not yet cater for this type of workflow.
- Tug vessels are needed when using a jack-up platform (i.e. a non-self-propelled installation vessel). The model does not yet have the capability to include tugs when using this type of installation vessel.
- The model assumes that all components of a turbine are manufactured in the same location. It is not possible at present to add in transport for blades, towers, nacelles etc. separately.

Figure 3 summarises the results of the sensitivity analysis for the CAPEX. The variation of all variables considered in the sensitivity analysis caused the financial model to behave as expected. For example, increases in dry CAPEX and the number of turbines have the most severe effect on the total installation cost. While other factors have less of an influence, they roughly show a linear increase or decrease as expected. The exception to this trend are the operational thresholds (wind speeds and wave heights) where analysis could only check the impact of up to a 40% reduction in limits before the model was not able to find enough weather windows to complete installation. In addition, the impact of increased thresholds ultimately tapers as it exceeds the most common and maximum conditions at a given site.

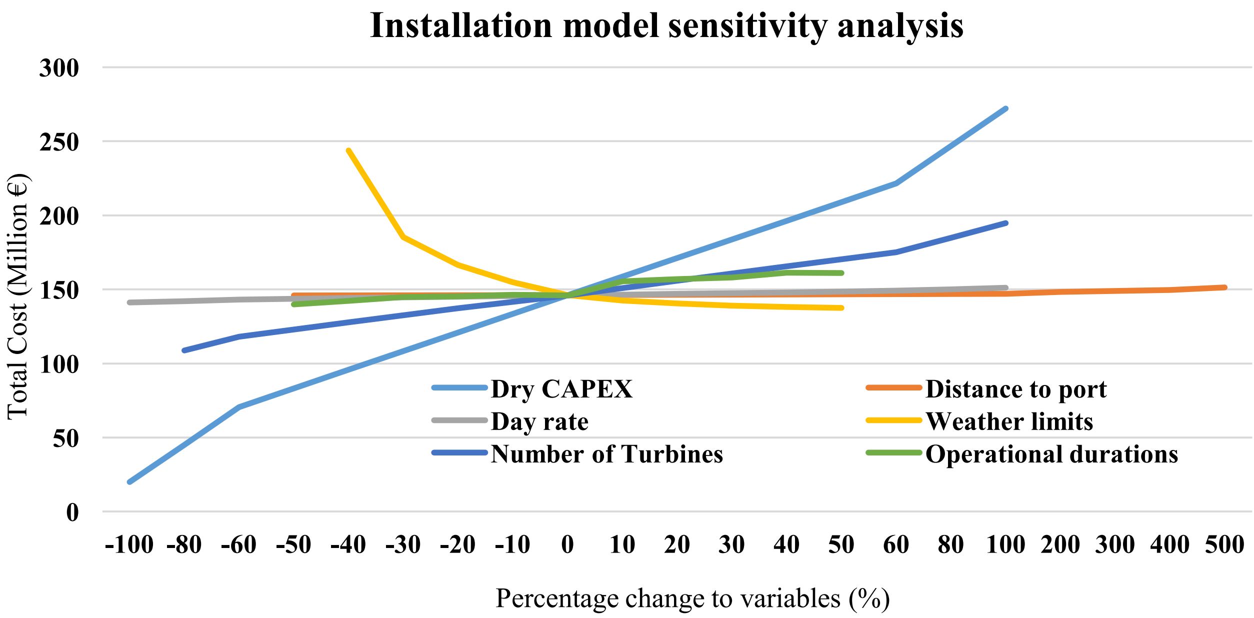

Figure 3 Installation module sensitivity analysis: Change in total costs versus changes to individual variables

3.2 O&M module validation and sensitivity analysis

The O&M module has undergone a series of verification and validation activities both before and after its integration in the lifecycle financial model, as discussed in more detail in [23]. These activities include code-to-code comparison of four different O&M simulation models (NOWIcob, the ECUME model of EDF and models from University of Strathclyde and University of Stavanger), which were used to conduct a sensitivity analysis for a reference case developed to benchmark such models [24]. A comparison between the O&M module and the ECN O&M Tool is documented in [12] in the context of LCoE estimation, and a comparison with yet more O&M models in the context of O&M strategy decision support is documented in [25]. During the LEANWIND project, the O&M module was benchmarked against the industry-grade O&M tool used by an offshore wind farm developer/owner/operator affiliated with the project. In this study, results were compared to data from a real but undisclosed offshore wind farm project, but cannot be published due to their commercially sensitive nature. These studies have demonstrated that the results from the O&M module are as reasonable as those produced by the other models considered.

Some key findings from the above validation activities for the O&M module can be summarised as follows:

- While there are some differences in the absolute values predicted for result parameters by different models, they broadly agree on sensitivities.
- Differences in modelling a jack-up vessel charter strategy have been identified as the likely reason behind a large part of discrepancies between the models.
- Results for wind turbine availability is strongly sensitive to the assumed limiting significant wave height for accessing the turbines as well as assumptions for how crew transfer vessels utilize weather windows where access is possible.
- For detailed validation and unambiguous one-to-one comparison between models it is essential that models have consistent and clearly defined output parameters.
- Furthermore, O&M models can capture different features of an offshore wind farm project with varying accuracy and may include different modelling capabilities. As they have different strengths and weaknesses, it is useful to use multiple models to assess the expected availability of an offshore wind farm project and understand sensitivities. [23,25].

3.3 Decommissioning module validation and sensitivity analysis

Due to the relatively immature stage of development of the offshore wind industry, there is a limited knowledge of how decommissioning will be undertaken. Options include the reverse of installation or using new methods, demolition or leaving in-situ; the length of time for different tasks; and the post-processing strategies (whether to dispose of, recycle or re-sell blades etc.). It is also difficult to get accurate costs and expected revenues for example, for disposing of or recycling different materials, port costs, vessel day rates etc. This is partially because only two wind farms have been decommissioned so far (Yttre Stengrund [26] and Vindeby offshore wind farms[21]) but also because this information is commercially sensitive. The expected costs are generally not included in decommissioning plans, a requirement to achieve planning for a project. Revenues for salvage etc. are also highly dependent on the market.

Therefore, validation of the Decommissioning module in LEANWIND involved developing a generic base case scenario and comparing results with figures in the current literature. In summary, it was found that decommissioning a scenario comprising a hundred 8 MW turbines with monopile foundations cost €214,896/MW. This is within the €200,000-€600,000/MW range estimated by a 2015 DNV GL study cited by [27]. This indicates that the outputs from the present model are reasonable, although at the lower end of the DNV GL estimates. The BVG estimate for a similar 800 MW wind farm is €333,252/MW [28]. However, it is important to remember that the BVG figures are for projects with FID 2020 and are based on the output of a cost model. The structure and scope of the BVG model are not available, so it is not possible to identify where potential differences in the assumptions and functionality of the models could account for the variance in results. It is anticipated that as empirical data become available from the future decommissioning of actual wind farms, the Decommissioning module can be further validated and calibrated based these data.

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Given the difficulties validating costs, sensitivity analysis was also conducted to confirm that the impact of variations are as expected. Parameters varied in the model included the number of vessels and technicians available; vessel, technician and vehicle cost; maximum wave height and wind speed; operation durations; distance to port; the number of turbines and turbine size. The expected increases and decreases were found, validating that the model is working as intended. For example, Figure 4 illustrates the expected rise and fall in cost and decommissioning time when the number of resources (e.g. vessels and technicians) increases and decreases.

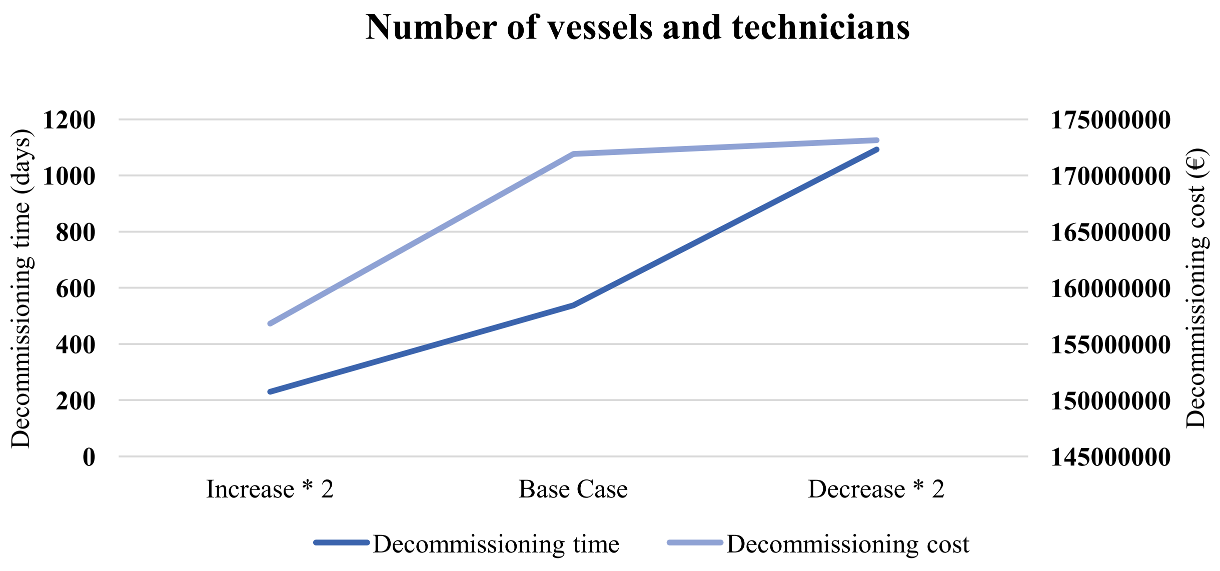

Figure 4 Decommissioning module sensitivity analysis: Impact of resources (numbers of vessels and technicians)

3.4 Validation case-study for financial model

Validation of the full financial model is achieved by applying the financial model to a scenario based on the C-Power or Thornton Bank Phase 1 wind farm, and comparing the model results to published data from C-Power and various reference datasets. Input data for the Installation module were obtained from online sources describing the construction of C-Power Phase 1 (2007-2008), whereas the inputs for the O&M and Decommissioning modules were chosen using reference datasets and industry experience as real data from the C-Power wind farm was not available. It should be noted that an exchange rate for 2017 has been used (unless otherwise specified) to convert figures from sterling or US dollars to euro where relevant as this is when data was first accessed. C-Power Phase 1 is a relatively small wind farm (30 MW) and thus not necessarily well suited to testing the capabilities of the time-series modules for simulating logistical complexities of larger wind farms. However, it provides a useful example for validating the integrated financial model.

C-Power Phase 1 consists of six Senvion 5 MW turbines and is located 30 km off the coast of Belgium. Details of the project assets including the foundations, turbine details, cabling details, onshore works, survey and monitoring and port costs, were estimated using a variety of sources and are summarised in Table 4. The metocean data for the case-study is taken from the West Gabbard site in the North Sea. This site is 30 km off the Suffolk coast and is representative of conditions at Thornton bank, being in close proximity to the latter site. The dataset consists of 10 years of wind data obtained from a mesoscale wind model (WRF) and 10 years of wave data calculated using the WaveWatch III model, calibrated using buoy data. The resolution of the wind speed and wave height data is 1.0 m/s and 0.1 m respectively. The lifetime of the wind farm was assumed to be 25 years.

Table 4 C-Power Phase 1: project asset details and costs installation phase

Project assets	Details	Cost
Foundations	Gravity base foundation (GBF) (3000t) [29]	€2.2million/foundation [30]

Turbines	Six 5 MW Senvion turbines installed in a single line [31]	€6.4 million/turbine [32]
Substation	None offshore	
Inter array cables	33kV cable network with total length 4km, supplied by ABB [33]	€0.45million/km [34]
Export cables	One 150kV export cable connects each turbine to the shore. The total cable length is 36-40km, buried in the sea bed [33]	€0.7million/km [34]
Balance of plant costs	Connection to 'Sas Slijkens' substation	€45million [35]
Other costs	Port costs of £29378/MW [13] Pre-project survey and monitoring	€1million €1.5million [35]

3.4.1 Installation phase

Details of the installation process, including the vessels used are taken from [29], [31], and [36]. The primary staging port for the construction of C-Power was Oostende, ~30 km from site. The foundations were manufactured at the staging port, and the hubs and nacelles of the turbines were manufactured in Bremerhaven Germany, and shipped to Cruxhaven where the towers are loaded. A cost of €162/km is assumed for all sea transport operations. This is based on a barge cost of €10k/d, and a tug cost of €25,000/d, travelling at a speed of 9 km/h (5 kn). It is assumed that jack-up vessels have a mobilisation cost of €500,000 and a day rate of €125,000/d.

The turbine installation strategy was pre-assembled rotor and a two-part tower. Turbines were loaded from Oostende and transported to site by the DEME jack-up vessel, Vagrant, whereas installation was carried out by the DEME vessel, Buzzard, also a jack-up platform. As the model does not currently cater for the use of a feeder vessel in this way, it is assumed that both vessels are used for the installation, and that the vessels have a turbine capacity of one. The inter-array and export cables were laid by the Eide Barge 28. The foundations were lifted from the quay by the heavy lift vessel Rambiz, and individually transported to site for installation. To account for dredging and backfilling activities, it is assumed that 60 hours of seabed preparation is required per foundation.

3.4.2 O&M phase

Energy production: An estimated power curve for the Senvion 5 MW wind turbine [37] was used to calculate energy production. Furthermore, electrical losses corresponding to 2% of the power production were assumed in the electrical infrastructure of the wind farm. A general wake loss percentage is assumed which does not consider wind direction (3.5%).

Technicians: It is assumed that 6 personnel are available per shift at the primary O&M port (Oostende). This value has been determined by considering health and safety regulations and interpolating from the number of personnel that are available for larger offshore wind farms [12,24]. It has been assumed that each technician works 12 hours per shift and one shift a day in accordance with generic industry standards [24,38]. Due to the relatively small size of the C-Power wind farm, short distance to port and lower transit times, a minimum working duration of 3 hours was assumed. Based on current literature and discussions with LEANWIND partners, a fixed annual cost per personnel of €100,000 is assumed.

Maintenance tasks: The maintenance tasks have been separated into five categories based on similar studies carried out by [24] and [12] as specified in Table 5. The values in Table 5 were taken from [24] and adapted in accordance with expert opinion documented in more detail in [12]. Substation maintenance is not considered since the substation is onshore. Furthermore, no cable maintenance has been taken into consideration, but it is assumed that on average 1% of the electricity production is lost due to outages in the electrical infrastructure.

Table 5 Maintenance tasks, associated failure rates and cost of spare parts

Maintenance	Working	Number of	Failure Rate	Material Costs relative	Cost of

Task	Duration	Technicians	(1/year)	to Turbine Investment Cost	Spare Parts
Manual Reset	3	2	5.0	0.004%	€256
Minor Repair	7.5	3	3.0	0.090%	€5,760
Major Repair	24	4	0.3	0.500%	€32,000
Major Replacement	34	-	0.11	7.550%	€483,200
Annual Service	60	3	-	0.0075%	€4,798

The major replacement task represents large components such as gear boxes and blades that occasionally have to be replaced during the O&M phase due to failures and/or degradation. It has been assumed that such a task requires a jack-up vessel, which also brings the technicians required, while all other tasks require a standard crew transfer vessel (CTV) for transferring technicians to the turbines.

It is assumed that each turbine requires an annual service every year, which is a preventive maintenance task that results in turbine downtime only during the active maintenance time. The other four maintenance tasks in Table 5 are corrective maintenance tasks carried out in response to a turbine failure and involve repairing or replacing components and/or inspecting and resetting the turbine. Corrective maintenance tasks are prioritised to minimise downtime. For simulating travel distances for multiple corrective maintenance tasks, the distance between two arbitrary turbines in the wind farm is approximated to 3.0 km. The distance between two neighbouring turbines, approximated to 1.0 km, is used to simulate preventive maintenance tasks. It has been assumed that if any component of a turbine fails, the turbine stops operating at failure and until corrective maintenance is completed. The cost of the turbine spare parts are taken as a percentage of the turbine investment costs [12] and also include the costs of consumables (e.g. oil and lubrication).

Maintenance vessels: One standard CTV is assumed to be available throughout the O&M phase of the offshore wind farm and to be based at Oostende Harbour at a fixed rate of €3,500/d. The jack-up vessel has to be chartered on demand and has a mobilisation time of 60 days. The mobilisation cost is assumed to be €500,000 [12], the day rate €125,000 and the average charter duration 6 days. In accordance with current industry conventions, the standard CTV operates for one 12-hour shift per day, whilst the jack-up vessel is always offshore once chartered and operates 24 hours a day [24,38]. Other vessel data are as specified in the reference data set available in [12]. Fuel costs are included in the fixed rates/day rates for each vessel type.

Other fixed OPEX: Based on [12], additional fixed O&M cost contributions (e.g. insurance, port costs and onshore maintenance) corresponding to 30.9 €/kW are included in the estimated OPEX.

3.4.3 Decommissioning phase

The inputs and assumptions relating to the Decommissioning module are as follows.

Survey and Port Costs: Survey and monitoring are calculated as €4,163/MW based on the original estimation in [39]. A fixed charge of €5000 is assumed for port costs.

Disposal and Recycling: Disposal and recycling revenues for different materials are presented in Table 6.

Table 6 C-Power Phase 1: Decommissioning costs and revenue rates

Survey & Monitoring costs	€125,000
Port costs	€5,000
Project Management (PM)	5% of CAPEX [28]
Contingency	10% of PM [40]
Disposal costs (landfill or recycling)	€57/t [41]
Recycling revenue – steel	€400/t [42]
Recycling revenue – copper	€4,400/t [43]
Recycling revenue – cast iron	€122/t [42]
Recycling revenue – aluminium	€1,500/t [44]

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The material and weight of each component of the turbine to be decommissioned is presented in Table 7. These were obtained from [45-50].

Table 7 Turbine component decommissioning details

Turbine component	Materials	Weight (tonne)	Task duration (hours)	Post-decommissioning strategy	Weight (%)
Blades	carbon fibre	53.22	2	Disposal	7.6
Hub	nodular cast iron	56.78	3	Recycling	8.1
Gearbox	Steel components [49]	96	3	Re-sale	13.8
Generator	65% steel 35% copper [49]	96	3	Recycling	13.8
Main shaft & bearings	Steel components [49]	9.6	1	Recycling	1.4
Transformer & power convertor		1.92	1	Re-sale	0.3
Nacelle housing	Fiberglass [49]	36.48	1	Disposal	5.2
Tower	Tubular steel	347.46	13	Recycling	49.8

The total task time to decommission the turbine is set to 27 hours. This time was obtained by extrapolating the duration estimated for a 3.6 MW turbine in [39]. The task duration for each individual component is taken as percentage of the total time by weight (Table 7). It is assumed that the carbon-fibre based blades and nacelle housing are disposed of, incurring charges; the hub, generator and tower are recycled; and the gearbox and electrical equipment are resold.

Table 8 Foundation component decommissioning details

Foundation component	Material	Weight (tonne)	Task duration (hours)	Post-decommissioning strategy	Post-processing time (hours)
GBF	Concrete	3000	36	Disposal	24
Transition piece	Steel	250	5	Recycling	-

The total task time to decommission each foundation is set to 36 hours (Table 8). This includes an estimated time to de-ballast the GBF. 24 hours of post-processing time at the port is assumed necessary for each GBF before the concrete GBF is sent for disposal, whereas the transition piece is recycled. One jack-up vessel, feeder barge and tugboat are used as a fleet for modelling purposes. The day rate for the jack-up vessel is €125,000 and a combined fee of €83,000 is used for the barge and tug. Two on-land vehicles are accessible to move materials to landfill or recycling centres.

3.4.4 Results

Each phase module was run for 100 simulations, and subsections 3.4.4.1-3.4.4.4 describe and further analyse results using outputs from the individual files created by each module. This includes cost and time breakdowns as well as analysis of the statistical precision of the predictions considering the stochastic uncertainty.

3.4.4.1 Installation results

Figure 5 presents the results predicted by the Installation module, averaged over 100 simulations. They show that the modelled and reported installation costs were in very good agreement, with the model predicting total costs of approximately €151.5 million (€5.05 million/MW), within €1.52 million (1%) of the €153 million reported by C-Power. The largest portion of the total CAPEX is attributed to the cost of assets (order costs) including the turbines and foundations.

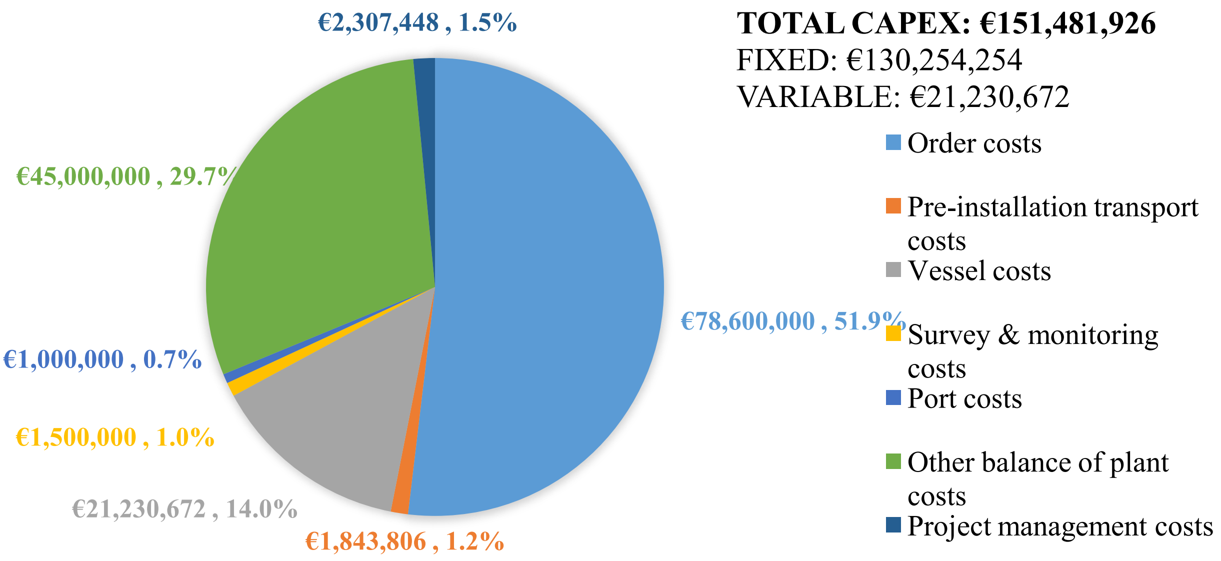

Figure 5 Installation module results for C-Power Phase 1 case-study

The predicted installation duration of 5.4 months is somewhat less however than the estimated actual duration of 10.75 months. This latter figure was calculated based on the C-Power official website timeline of effective works [31] considering individual activities to install turbines, foundations etc. The discrepancy may be due to the definition of when an installation activity began or ended and it is difficult to precisely compare the activities outlined on the C-Power website [31] with the restricted list of operations modelled. In addition, the installation of the array cable appeared to take a considerable amount of time. According to the effective works description, each turbine was started up consecutively following test procedures. These may have taken longer than generally expected as this farm was a prototype; however, the reasons for the considerable time taken cannot be verified from the description on the website. Kaiser and Snyder [5] provide an estimated time for installation of the C-Power Phase 1, which is much closer to the Financial model results. All three results are compared in Table 9 below.

Table 9 C-Power Phase 1: Activity durations in months

	C-Power effective works	Financial model results	Kaiser & Snyder study [5]
Total activity duration (months)[2]	10.75	5.40	5.15
	Individual activity durations (months)		
Turbines	2.50	0.60	2.5
Foundations (incl. seabed prep.)	2.50	2.13	1.1
Export cable	2.75	3.76	1.13
Array cable	5.50	0.63	0.42

The individual activity durations suggest that the time allocated to certain operations (e.g. turbine installation) may be under-estimated by the Financial model. This could be partially due to the learning curve required to install the first phase of Thornton Bank (2007-2008). A study carried out by Lacal-Arántegui et al. [22] shows that installation times for wind farms with monopile foundations have decreased from ~4 days per MW in

[2] Considering any overlapping activities

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2000-2003 to 1.03 days per MW in 2016-2017, despite increasing distances to shore. It should also be noted that the operations simulated by the Financial model are those identified as the main activities contributing to cost and time. They may not include all operations of an actual installation. In addition, the timings and weather restrictions applied to operations for a given scenario are based on input from industry partners where possible, but assumptions were made where data were not available. This highlights the potential uncertainty in the results and the need for more accurate input data.

3.4.4.2 O&M results

The annual and total lifecycle results from the O&M module are summarised in Table 10. Figure 6 presents the O&M cost split. The cost of vessels is the most significant contributer to OPEX with 31% and 19.1% for fixed and charter costs respectively.

Table 10 O&M module results for C-Power Phase 1 case-study

		Total lifecycle	Average annual
OPEX	Euro	102,859,518	4,114,381
Energy Production	MWh	3,245,670	129,827

The modelled OPEX was on average €137,146/MW per year (€31.7/MWh per year) and approximately €3.43 million/MW over the 25-year lifecycle of C-Power offshore wind farm. Although information regarding the actual O&M costs of this wind farm is not public knowledge, sources exist which estimate typical O&M costs ranging between €60–185,000/MW per year [32, 42, 51-52] and €12–66/MWh per year [42, 53-54]. Therefore, the predicted O&M costs for the C-Power offshore wind farm fall within the range of estimates in the literature. Taking a recent reference, Ioannou et al. [14] calculate the total OPEX for a 504 MW wind farm at £112,296/MW per year, which equates to approximately €128,017/MW per year and is comparable with the results obtained using the present model.

The mean time-based availability for C-Power is calculated at 93.63%, generating approximately 3,254,670 MWh of energy over its lifecycle. This results in a net capacity factor of 49.4%. Although one should keep in mind that capacity factors are highly location dependent, this comparable with the latest rolling 12 month capacity factor for Danish offshore wind farms [55].

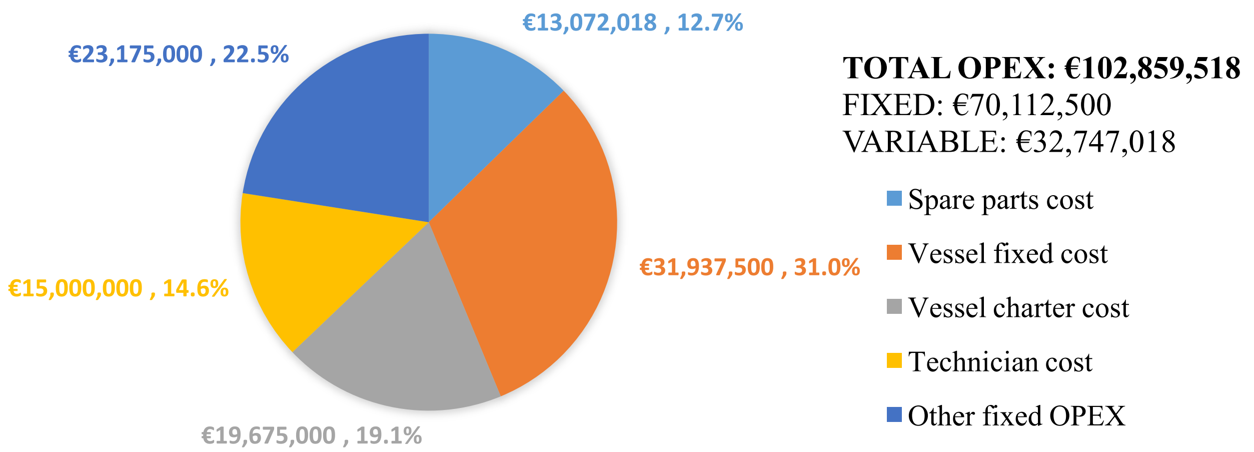

Figure 6 OPEX cost split for C-Power Phase 1 case-study

3.4.4.3 Decommissioning results

The financial model estimates a total decommissioning cost for the farm of €15.1 million. The salvage income is €3.39 million, of which €1.89 million comes from recycling and €1.5 million from resale revenue. The

DECEX predicted by the model are itemised in Figure 7. The largest portion is attributable to vessels at 79.7%, costing ~€12 million. In total, the cost is €503,242/MW, which is within the range of estimates given by [27] of €200,000-€600,000/MW. Analysis indicates that concrete GBFs are expensive to fully decommission, in comparison to other foundation types, as concrete is not widely recycled, and de-ballasting at sea and post-processing at port is required. The total time for decommissioning predicted by the financial model is 82 days, approximately half of the predicted installation time.

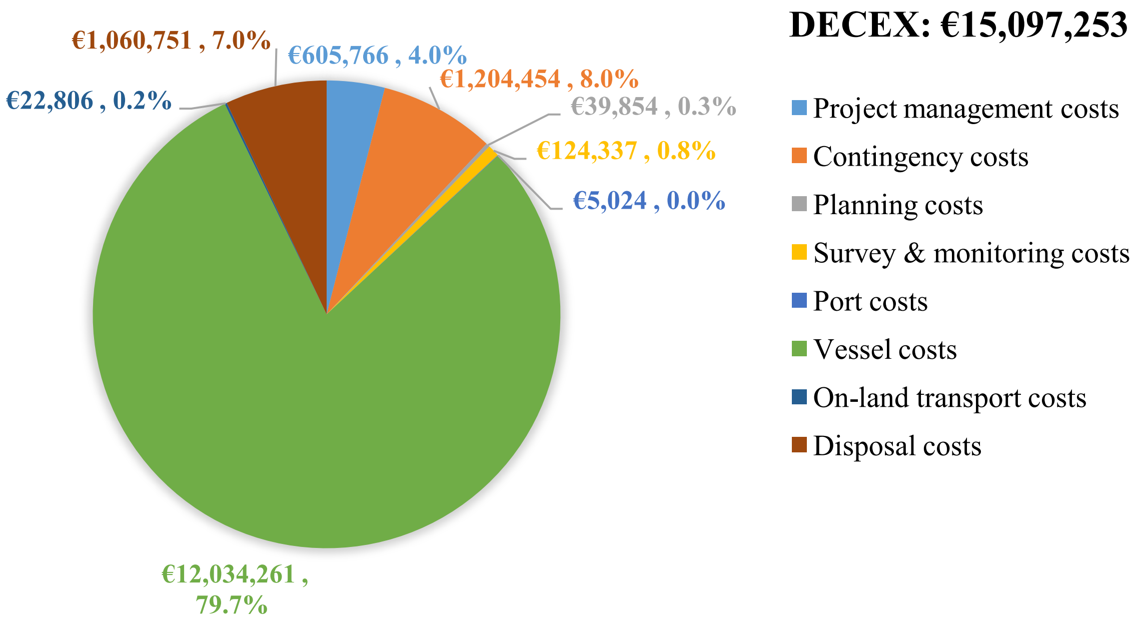

Figure 7 DECEX cost split for C-Power Phase 1 case-study

3.4.4.4 Summary and further analysis

Table 11 summarizes the results for the three lifecycle phases presented in the previous section and includes the mean value of the distribution functions estimated by the Monte Carlo simulations as well as the standard deviation. When the results are interpreted as the predictions for a given wind farm project, the standard deviation can be viewed as a measure of the stochastic uncertainty in the prediction. For instance, one could state the prediction of the installation time for C-Power Phase 1 as (5.4 ± 1.07) months, accounting for uncertainties in the weather during the installation phase.

Table 11 Summary of cost analysis

	Mean value	Standard deviation	Coefficient of variation	Standard error of the mean
Installation time	5.4 months	1.07 months	19.8%	1.98%
Energy produced	3,245,670 MWh	32,383 MWh	1.0%	0.1%
CAPEX	€ 151,481,926	€ 3,549,955	2.3%	0.23%
OPEX	€ 102,859,518	€ 6,863,175	6.7%	0.67%
DECEX	€ 15,097,253	€ 61,968	0.4%	0.04%

While the standard deviation indicates the variability in the results due to the stochastic variables accounted for in the simulations, the coefficient of variation provides more insight into the relative importance of the variation accounted for in the simulations across the lifecycle phases of an offshore wind farm. This metric is the standard deviation normalized by the mean value. Among the lifecycle phase cost contributions, the highest variability is associated with the O&M phase (6.7%) due to the stochastic nature of component failure variables involved in the calculations. The main contributor of O&M cost variability is found to be costs of relatively rare but expensive major replacement maintenance tasks, also investigated by [56]. Variability in CAPEX is only driven by variability in weather, and relative variability is lower than for OPEX because a larger part of the CAPEX costs are fixed and not dependent on offshore logistics. However, since installation logistics (vessel) costs are calculated over only one year in this case-study, compared to all 25 operational years for OPEX, this contributes to increasing the relative variability of CAPEX.

The simulated variability also influences the precision of the mean results. This precision can be measured by the coefficient of variation of the sample mean (the standard error of the mean in Table 11). To give an example of the implications, the standard error of the mean, or precision, for OPEX in the case above with 100 simulations for all lifecycle phases is 0.67%, and if one required precision better than 0.5% for all three lifecycle cost contributions, this would mean that the number of simulations should be greater for the O&M phase than for the two other phases. It is however important to note that statistical precision of the Monte Carlo simulations is only one aspect of the overall uncertainties in the results.

4. FINANCIAL ANALYSIS AND DISCUSSION

Outputs from the individual time-series modules are fed into the central Excel interface to determine financial KPIs and facilitate further evaluation. This section summarises the financial analysis performed on the case-study. The C-Power Phase 1 wind farm is somewhat atypical in that it is a relatively small demonstration project and given the uncertainty of many inputs, particularly for the O&M and decommissioning phases, results should not be taken to reflect financial analysis of the C-Power farm. Rather it is intended to demonstrate the capabilities of the full lifecycle financial model and illustrate how it can be applied to a real project. Please refer to Table 1, Table 2 and Table 3 for explanations of the financial parameters and calculations referenced below.

LCoE is a relatively simple and flexible method to assess the financial aspects of a project. The calculated LCoE for the case-study farm is €0.161/kWh. This meets expectations of ~ €0.16/kWh based on the ORE Catapult report that estimates an LCoE of £0.136/kWh for projects completed in 2010-2011 [57], reducing this to £0.127/kWh, assuming there was 7% inflation from 2008-2011; and converting this to euro using a 2008 exchange rate of £1/€1.126 as this was the year of project completion for C-Power Phase 1.

When reviewing results, it is important to recognise the impact of different assumptions on the LCoE calculation. The top four contributors to the LCoE for offshore wind are the CAPEX, OPEX, DR and net capacity factor. The DR is applied to estimate the present value of future cash flows. It is chosen to reflect the risk-adjusted opportunity-cost of capital and is considered the return on investment required to attract project investors [58]. For the C-Power Phase 1 scenario, a DR of 10% was assumed based on the high estimate for offshore wind in 2020 derived from a report by Oxera for the Committee on Climate Change, UK [59]. However, the DR can be difficult to determine, and varying its value to the average and lowest report estimates of 8% and 7%, the LCoE dropped to €0.142/kWh (12% reduction) and €0.133/kWh (17.4% reduction) respectively, demonstrating the impact of this assumption.

Table 12 provides a breakdown of the LCoE result (Scenario 1) and a comparison with figures reported in the IEA Wind Task 26 study for a baseline offshore wind farm [12]. The IEA study was based on existing model assumptions and high-level industry data, gathered to provide information on the cost of wind energy and transparent methodologies to facilitate more consistent analysis in this sector. O&M modelling was undertaken using the NOWIcob and ECN model using a number of the same assumptions applied in the present case study, providing inter-model comparison. Table 12 implies that the Installation, O&M and Decommissioning module results comprise a reasonable proportion of the LCoE. However, the cost of the turbine and balance of plant supply (considering dry CAPEX, balance of plant costs and supply of components to port) may be overestimated. In addition, some of the costs considered could have been applied to Other CAPEX but this depends on interpretation of the categories. However, it should be noted that the

LEANWIND case-study did not consider debt interest costs, assuming the project had 100% equity as further examined below. When the financial parameters are updated to match (Scenario 1.1 in Table 12) [12], results are considerably closer, reinforcing that results are highly dependent on input assumptions.

Table 12 LCoE breakdown and comparison with IEA Wind Task 26

	Scenario 1	IEA Wind Task 26	Scenario 1.1
Equity-loan split	100%-0%	30%-70%	30-70%
Debt term	0	15	15
Interest rate	0%	5%	5%
DR	10%	8%	8%
Loan administrative charges	0%	3%	3%
LCoE breakdown			
Turbine and balance of plant supply	69.1%	45%	43.7%
Installation	13.5%	10%	8.6%
Other CAPEX	0.8%	9%	0.5%
O&M	16.0%	17%	15.3%
Decommissioning	0.7%	3%	0.7%
Debt interest costs	0%	16%	16%

While the LCoE is the financial KPI most commonly used to compare projects, other important financial indicators include the NPV and IRR , which help determine whether a project is financially viable. The Financial model calculates these and the various input options outlined in Table 1 enable the user to explore different financing structures and undertake detailed analysis of the payback period, debt/equity ratio etc. Using this case-study as an example of how to use the Financial model, an electricity price of €0.18/kWh and a depreciation rate of 3.57% were assumed to calculate the NPV, IRR, payback period and debt-equity ratio (Scenario 1). In reality, the electricity prices may include different subsidies, and either a REFiT or CfD scenario can be modelled as these are the mechanisms in use in Europe. The depreciation rate (used to evaluate the equity) is calculated based on the salvage value determined by the Decommissioning module. However, the module is currently limited in scope to the turbine and foundation and does not consider other potential salvage revenue (e.g. cabling). Therefore, the limitations of the assumptions applied must be considered when reviewing results. With this in mind, the above scenario results are summarised in Table 13 along with two further scenarios that apply different equity-loan splits to illustrate how users can consider the impact of different financing options.

Table 13 Predicted financial indicators

	Scenario 1	Scenario 2	Scenario 3
Equity-loan split	**100%-0%**	**75%-25%**	**50%-50%**
Real LCoE	0.161 €/kWh	0.179 €/kWh	0.196 €/kWh
Discount Payback Period	17 years	24 years	-
NPV	€21.98 million	€1.38 million	-€19.22 million
IRR	11.87%	10.12%	8.31%
Debt-equity ratio	0.22	0.25	0.29

To understand these figures, the following summarises what are considered positive results for each KPI:

- The NPV should of course be a positive figure as this indicates the projected earnings exceed costs [60]
- The IRR calculates the yield on an investment and should be greater than the DR (estimated cost of capital) [61]
- The payback period should be less than the project lifetime and the shorter the better [62]

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- The debt-equity ratio compares a company's liabilities with its stakeholder equity and is used to determine their dependence on debt and ability to meet their financial obligations. Investors prefer to see a low ratio as this means less debt and risk; however, the threshold is very dependent on the company in question. As a general guideline, a ratio of less than 0.4 is desirable [63].

Thus, the scenario outlined above (Scenario 1) is positive. For a large wind farm, it is unlikely that the project owner has the equity needed to finance the project without a loan; however, as C-Power Phase 1 is a small pilot project, this is a reasonable financial structure. If it is assumed that the owner has 75% equity and takes out a loan for the remaining 25%, paid back over 25 years with an interest rate of 3% and administrative charges of 3% (Scenario 2), payback (considering discounted figures) is achieved within the project lifetime. Therefore, based on the financial indicators, this structure will lead to a viable project. When the required loan is increased to 50%, the project is no longer viable (Scenario 3).

Based on this financial analysis and having identified the key cost drivers, the user may then review and optimise strategies across the lifecycle stages e.g. technology type, the vessel fleet, installation methods etc. to reduce costs and time. As farms are beginning to come to the end of their lifetimes, another consideration for future projects is how to accurately estimate the costs of decommissioning and ways to offset these costs. For example, in addition to salvage revenue, the operator may consider a savings plan. This can be implemented in the financial model to determine the potential benefits considering the savings plan goal, term, start year and deposit interest rate applied.

5. CONCLUSIONS

This paper presents a lifecycle model for the financial analysis of an offshore wind farm. The model provides detailed bottom-up cost and time assessments for the major project phases (installation, O&M and decommissioning) through stochastic time-series simulations, calculating financial parameters that allow the business case of the modelled scenario to be assessed. Given its wide-ranging capabilities, the model would be of interest to a variety of offshore wind farm stakeholders. For example, developers/owners to calculate financial indicators to present to potential investors; operators to test and optimise a given strategy or use of resources e.g. vessel fleets; technology developers to calculate the potential cost-benefit of their innovation etc.

The individual time-series simulation modules have been validated against existing data where possible, and sensitivity analyses have been conducted to assess the impact varying certain parameters has on the model results. The full financial model has been applied to a case-study to demonstrate the model capabilities, with results compared with published data where possible to provide validation of the full financial model. In general, results are in good agreement with comparable figures in the current literature (CAPEX was only 1% less than figures reported for C-Power Phase 1; OPEX and DECEX within published estimates; and LCoE meeting expectations based on the literature). Results identify key cost drivers (e.g. dry CAPEX and vessels); the statistical precision of predictions considering uncertain factors (e.g. weather and failures); and provide detailed insight into project finances and viable business models. The model ultimately allows the user to further review and optimise a scenario, supporting planning and decision making.

Discrepancies found in results include the time taken for installation. However, it should be recognized that the quality of any validation activity is dependent on the assumptions made in the model and the input data available. In many cases, researchers are restricted in their use of wind farm data due to commercial sensitivity and/or it can be difficult to replicate a case-study exactly based on the descriptions available. It is anticipated that the financial model will undergo further validation, particularly as new data is made available for the decommissioning phase. Limitations in the scope of the model have been identified through the validation activities described in Section 3, therefore future research efforts will aim to address these. For example, while the individual modules document vessel/vehicle usage during simulations, the model could be further extended to facilitate LCA studies as environmental impact is an important consideration given global goals to reduce greenhouse gas emissions. Recent LCA studies focused on offshore wind include [64,65].

The model was developed to assess a wide range of innovative technologies, strategies and procedures at current, near-term and long-term sites for the LEANWIND project. This paper presents a case-study using a near-shore wind farm to facilitate model validation given the lack of data available for more innovative technologies, particularly floating wind where there is currently only one commercial wind farm globally. However, the model has also been applied to fixed (monopile, gravity base and jacket) and floating foundations at sites from at 40, 60 and 100 m water depth and 30 and 100 km from shore as summarised in [66]. Papers are currently in preparation based on the numerous case-studies conducted during and since the LEANWIND project assessing the cost-benefits of innovations including floating wind concepts; turbine and foundation installation methods; and vessels that are purpose-built for the offshore wind industry. Future work will also include publications specifically describing and validating the installation and decommissioning modules as these may be considered state-of-the-art in their respective fields.

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