Ref. Ares(2020)4753561 - 11/09/2020

LiftWEC

DEVELOPMENT OF A NEW CLASS OF WAVE ENERGY CONVERTER BASED ON HYDRODYNAMIC LIFT FORCES

Deliverable D7.2

Development of Models and Operations Framework

Deliverable Lead	University College Cork
Delivery Date	9th September 2020
Dissemination Level	Public
Status	Final
Version	1.2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

Document Information

Project Acronym	LiftWEC
Project Title	Development of a new class of wave energy converter based on hydrodynamic lift forces
Grant Agreement Number	851885
Work Package	WP7
Related Task(s)	T7.2
Deliverable Number	D7.2
Deliverable Name	Development of Models and Operations Framework
Due Date	31st August 2020
Date Delivered	11th September 2020
Primary Author(s)	Brian Flannery (UCC)
Co-Author(s)	
Document Number	LW-D7-02

Version Control

Revision	Date	Description	Prepared By	Checked By
0.1	31/08/2020	Draft for consortium review	BF	JM
1.0	01/11/2020	Revised on feedback from consortium	BF	JM
1.2	09/11/2020	Release to commission	BF	JM

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

EXECUTIVE SUMMARY

This deliverable will outline the models and design frameworks, which will be developed to assess the LIFTWEC concepts. A description is given for the installation strategy design framework developed to review the concept designs and identify viable installation strategies. Similarly, a description is given for the decommissioning strategy design framework. The recently developed O&M Expert tool, created to model O&M costs is also discussed.

TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

1 INTRODUCTION

A description of the intended models to be applied to the lifecycle stages (installation, Operations and Maintenance (O&M) and decommissioning) of the LiftWEC device will be given. The installation and decommissioning models are adapted from existing ones created by UCC as part of the LEANWIND offshore wind project. The history of their development as well a description of the features and uses is described.

The O&M tool, just recently developed by UCC as part of the Eirwind project will additionally be discussed.

2 HISTORY OF MODEL DEVELOPMENT

The 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 reducing the cost of installation, operation and maintenance (O&M), and decommissioning of offshore wind farms (LEANWIND 2017.). 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 the impact on all phases of an offshore wind farm lifecycle.

Separately, University College Cork developed installation and decommissioning models and SINTEF Research developed an O&M model, while both institutions together, developed the full lifecycle financial analysis model to be able 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 (at the time) of the Financial model was the use of a detailed time-series Monte Carlo simulation methodology for the analysis of all three lifecycle phases. Advantages of this approach are that it allows for 1) accurately assessing the impact of metocean conditions and other stochastic elements on offshore logistics, and thus on key cost and time result parameters for each phase; and 2) a probabilistic analysis of the variability in these result parameters.

The LEANWIND model performs time-series simulations of the installation, O&M, and decommissioning phases of an offshore wind farm lifecycle using time-series simulation modules for each lifecycle phase. These modules are all probabilistic models, employing Monte Carlo simulation to consider stochastic elements such metocean data and component failures. Using a single scenario predefined by the user, these variables are perturbed over multiple instances of a project lifecycle to model the potential impact on time and costs.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

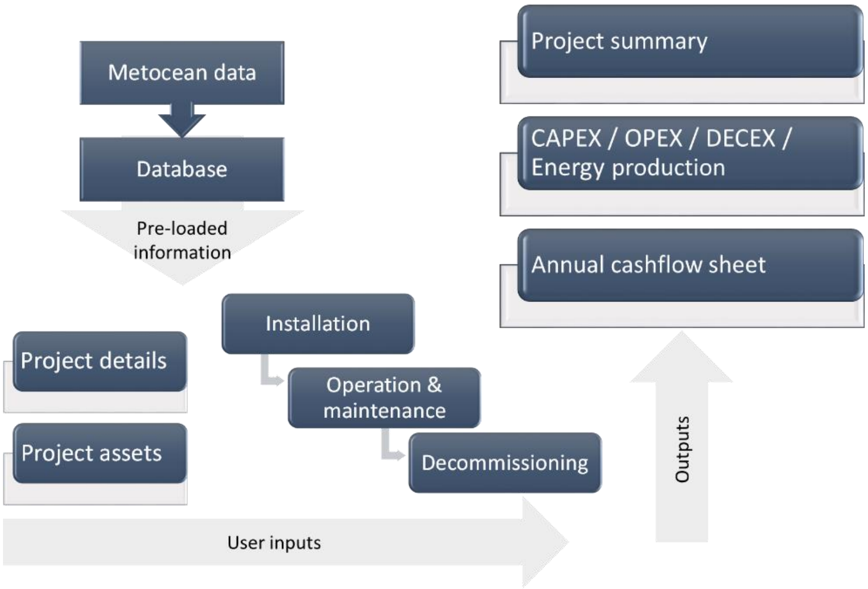


Figure 2-1:LEANWIND Model Schematic (Frances Judge et al., 2019)

The LEANWIND 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, i.e. details of the turbines, foundations, substation etc. In addition, required inputs include details of the strategy and resources (e.g. vessels, technicians, equipment) available during installation, O&M and decommissioning. The user also specifies the wind farm life expectancy, and the financial parameters to apply to the results such as the discount rate.

The Excel interface of the financial model contains a database of information on

- The resources available for installation, 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.
- Project assets such as foundations, devices and their respective power curves, associated installation strategy options etc.
- Metocean data files with links to time series of wind speeds and significant wave heights at the site in question (options of Atlantic, North Sea and Mediterranean Sea locations) with an hourly resolution. Longer time-series allow the time-series simulation modules to better capture the variability in weather that may be experienced by the wind farm project. Using the same input metocean time series for the simulation of all lifecycle phases ensures consistency in the assessment of the impact of the weather conditions at the site.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

2.1 USE OF THE INSTALLATION MODEL FOR THE LIFTWEC PROJECT

The Installation model will be used for the LiftWEC project, to inform the research group as to the expected costs of the various proposed configurations. Take for example a simple categorisation of LiftWEC devices as either fixed or floating. The model would estimate the overall installation costs of the both the fixed and floating LiftWEC configurations: calculating expected operational durations as well as expenses (technicians, vessel costs etc.) revealing which of the two categories has a higher expected installation cost. This is obviously a coarse approximation as there are several different protentional fixed (as well as floating) configurations and each configuration will need to be examined on its individual merits.

It could be the case that a relative cheaper installation strategy, incurs higher O&M costs or the reverse, that an initially expensive configuration (from an installation perspective) incurs lower O&M costs. Additionally it could be the case, that a configuration with both high CAPEX and OPEX produces such exceptional energy yield, as to offset the costs: or that a relatively simple device (with low OPEX and CAPEX) produces a relatively lower energy yield, would however in the long run turn out to be more efficient due to lower associated costs.

It is apparent therefore, that the decision of which configuration is “better” can not be made by looking at any lifecycle stage in isolation, rather, an informed decision can only be made when taking all aspects of the device into account throughout its entire lifespan. This is the overall goal of the LiftWEC project.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

3 INSTALLATION MODEL

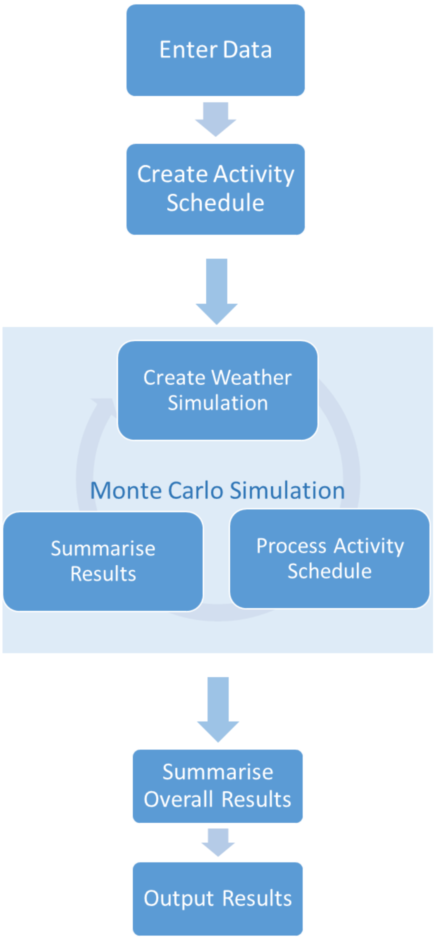


Figure 3-1: Installation Module Process Diagram (Lynch et al 2016)

The Installation module will be used to calculate the installation cost contribution to the CAPEX of the LiftWEC wave farm project. It is a time-series simulation model of the installation phase of a project developed by University College Cork (UCC). Currently the scope includes relevant input data (the first block in the schematic above) such as number of devices, foundation, substation, substation foundation, export and inter-array cabling. The installation method for each component 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 devices e.g. pre-assembled, all components installed individually etc.; and the foundations may be floated-out or craned (lifted). Additional inputs are resources required for each activity, e.g. the vessels and the number of devices or foundations each vessel can transport with the selected installation method. The distance of the wave farm to the primary staging port, and the transport distances by road and sea for the devices, foundations, substation, substation foundation and both the inter-array and export cable are required inputs. 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.

Using the scenario inputs and the hourly metocean data, the module generates a schedule of activities. The model then essentially assumes the role of a project manager, (as depicted by the "Process Activity Schedule" block in Figure 3-1) whereby a list of all activities yet to be completed is compiled and the appropriate resources (vessels & crew) are assigned.

The model records the sequence of events, the time spent carrying out each activity, any delays encountered as well as the cost of all 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 are reported as total costs as well as the costs incurred per year.

The impact of weather changeability while operating offshore on installation activities (particularly the impact of having to return to port without completing the installation activity) is handled by the model having an internal "weather forecast": using statistical data of the likelihood of a weather window occurring. The model will then go offshore to carry this activity and check the weather while offshore. Should the time series weather data show inclement weather, the vessel will either stay offshore or return to port. This will be reflected in the project finances and time for installation activities.

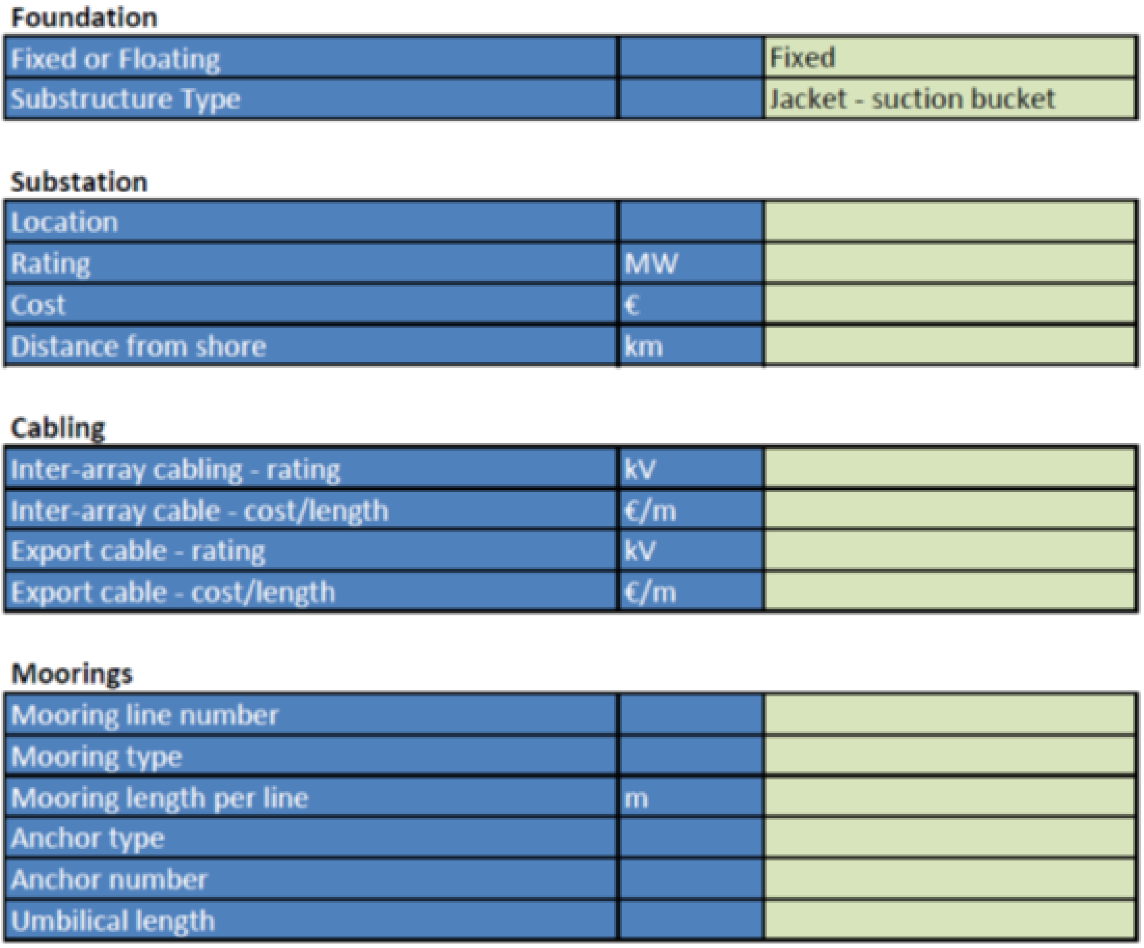
3.1 PROJECT DETAILS

The project details sheet allows the user to specify high-level (overarching) project inputs such as the lifetime of the wave farm, metocean dataset, water depth and the number of Monte Carlo simulations (i.e. Monte Carlo iterations, or instances of the lifecycle to be performed in the time-series simulation modules. A higher number of simulations increases the statistical precision of the outputs of the probabilistic simulation models. The large assembly components that make up the wave farm are specified on the project assets sheet. These include

- Devices, (number, MW rating etc.)
- Foundations (fixed or floating),
- Substation details, (MW rating, distance from port, distance from onshore cable landing)
- Inter-array cabling
- Export cabling

The details of the above e.g. turbine rating, substructure type, export cabling length etc., are specified as shown in Figure 3-2 below.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.



Foundation

Fixed or Floating		Fixed
Substructure Type		Jacket - suction bucket

Substation

Location		
Rating	MW	
Cost	€	
Distance from shore	km	

Cabling

Inter-array cabling - rating	kV	
Inter-array cable - cost/length	€/m	
Export cable - rating	kV	
Export cable - cost/length	€/m	

Moorings

Mooring line number		
Mooring type		
Mooring length per line	m	
Anchor type		
Anchor number		
Umbilical length		

Figure 3-2: Project Details (main components)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

3.2 PRIOR TO INSTALLATION MODEL (LOGISTICS MODEL)

The user inputs values used to calculate the CAPEX cost component related to transport of the project assets from the manufacturer to the installation staging port. If the manufacturer location of the major project assets (e.g. Siemens, etc.) is known and the farm site is known then free online software such as google maps, or similar, could be used to provide an estimate of travel distances to input into these cells. There is capability in the model to include delays in the vessel lead-in times or the arrival of some or all components. These are optional inputs and can be simply ignored in which case no delays will be assumed by the model.

LOGISTICS

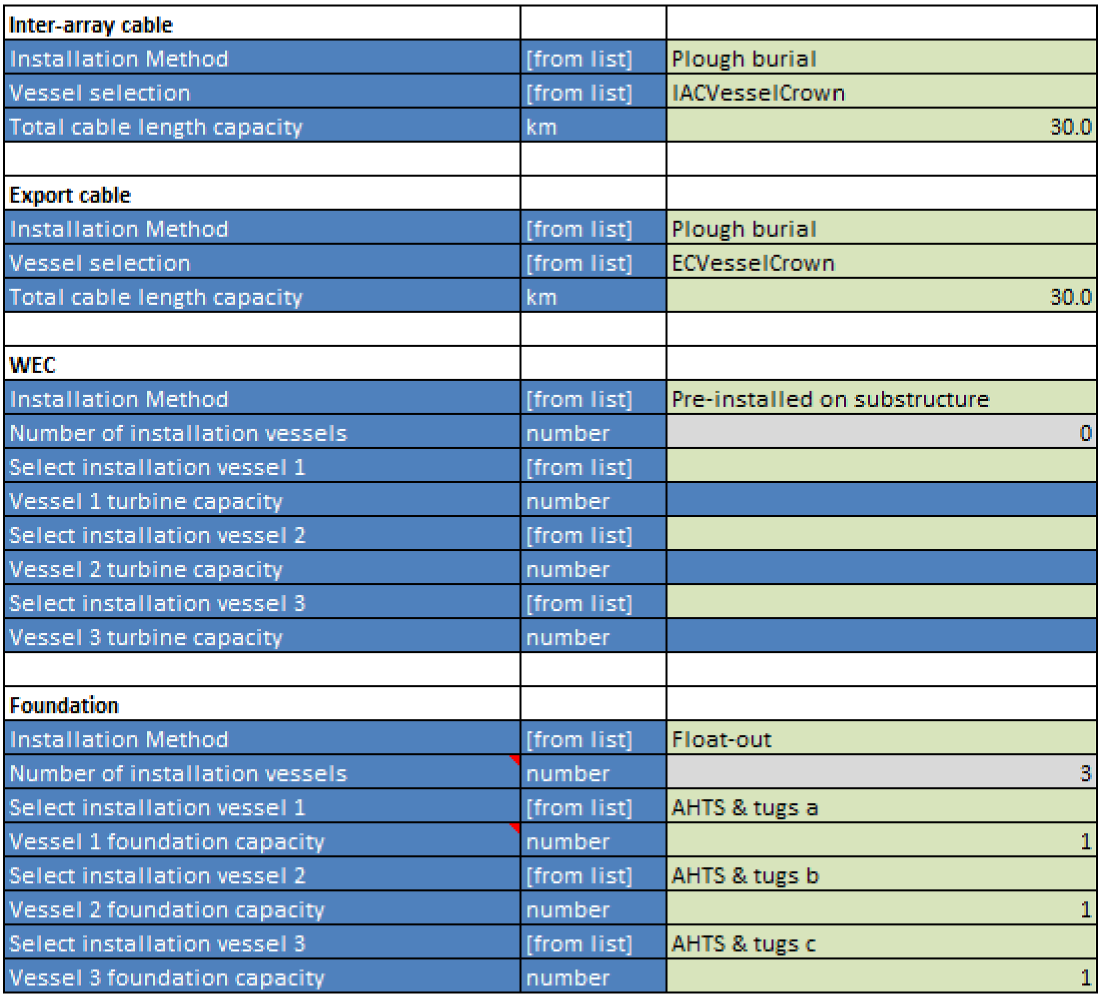
Ports		
Primary staging port	[name]	
Distance to primary staging port	km	
Use of secondary staging port	yes/no	
Secondary staging port	[name]	
Distance to secondary component supply port	km	
Component coming from secondary port	[from list]	

Transport		
Turbine		
Road transport distance	km	
Sea transport distance	km	
Foundation		
Road transport distance	km	
Sea transport distance	km	
Substation		
Road transport distance	km	
Sea transport distance	km	
Cable		
Road transport distance	km	
Sea transport distance	km	

Figure 3-2: Installation Logistics inputs

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

3.3 INSTALLATION MODEL OVERVIEW



Inter-array cable		
Installation Method	[from list]	Plough burial
Vessel selection	[from list]	IACVesselCrown
Total cable length capacity	km	30.0
Export cable		
Installation Method	[from list]	Plough burial
Vessel selection	[from list]	ECVesselCrown
Total cable length capacity	km	30.0
WEC		
Installation Method	[from list]	Pre-installed on substructure
Number of installation vessels	number	0
Select installation vessel 1	[from list]	
Vessel 1 turbine capacity	number	
Select installation vessel 2	[from list]	
Vessel 2 turbine capacity	number	
Select installation vessel 3	[from list]	
Vessel 3 turbine capacity	number	
Foundation		
Installation Method	[from list]	Float-out
Number of installation vessels	number	3
Select installation vessel 1	[from list]	AHTS & tugs a
Vessel 1 foundation capacity	number	1
Select installation vessel 2	[from list]	AHTS & tugs b
Vessel 2 foundation capacity	number	1
Select installation vessel 3	[from list]	AHTS & tugs c
Vessel 3 foundation capacity	number	1

Figure 3-3: Installation methods

An overview of the main components involved in the installation is shown in Figure 3-3: Installation methods. Some of the input options for the model are elaborated in Table 1 to 5.

Inter-array cable	**Units**	**Description**
Installation Method		Select either combined plough and lay burial or separate trench and lay
Vessel selection		Select from a list of cable installation vessels

Table 1: Installation Methods Input Parameters: Inter-array cable

Export cable	**Units**	**Description**
Installation Method		Select either combined plough and lay burial or separate trench and lay

Vessel selection		Select from a list of cable installation vessels

Table 2: Installation Methods Input Parameters: Export cable

WEC	Units	Description
Installation Method		Select from a dropdown list
Number of installation vessels		Up to a total of 3
Select installation vessel 1		Select from a dropdown list
Vessel 1 WEC capacity	no.	The number of WECs that Vessel 1 can carry using this installation method
Select installation vessel 2		Select from a dropdown list
Vessel 2 WEC capacity	no.	The number of WECs that Vessel 1 can carry using this installation method
Select installation vessel 3		Select from a dropdown list
Vessel 3 WEC capacity	no.	The number of WECs that Vessel 1 can carry using this installation method

Table 3: Installation Methods Input Parameters: Turbine

Foundation	Units	Description
Installation Method		Select float-out or craned installation method
Number of installation vessels		Up to a total of 3
Select installation vessel 1		
Vessel 1 foundation capacity	no.	The number of these foundations that Vessel 1 can carry using this installation method
Select installation vessel 2		
Vessel 2 foundation capacity	no.	The number of these foundations that Vessel 1 can carry using this installation method
Select installation vessel 3		
Vessel 3 foundation capacity	no.	The number of these foundations that Vessel 1 can carry using this installation method

Table 4: Installation Methods Input Parameters: Foundation

Installation Strategy	Units	Description
Number in a batch		Number of foundations(fixed/floating) to be installed before the WECs are installed. This can be in "batches" of e.g. 6 or 20 or the entire farm if required. It is a necessary indicator to the model to ensure the installation strategy is reflected accurately.
Weather window confidence limit	%	The model uses simulated "weather forecast" to decide to go out to install. The model will check the weather window probability and if the likelihood is greater than this "weather window confidence limit" the model begin the installation task.
Use of feeder vessel		Whether a feeder vessel is used in the installation. Yes / No input

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

Select feeder vessel	Select from a dropdown list of known feeder vessels, or input own parameters

Table 5: Project Installation Strategy Input Parameters: Installation Strategy

By breaking the installation strategy down into key stages, the user can develop any number of simple or more complicated installation design trees (storyboards) as shown in the Figure 3- below. This should ensure that the installation model is robust enough to handle the multitude of different options available to all the LiftWEC preliminary configurations

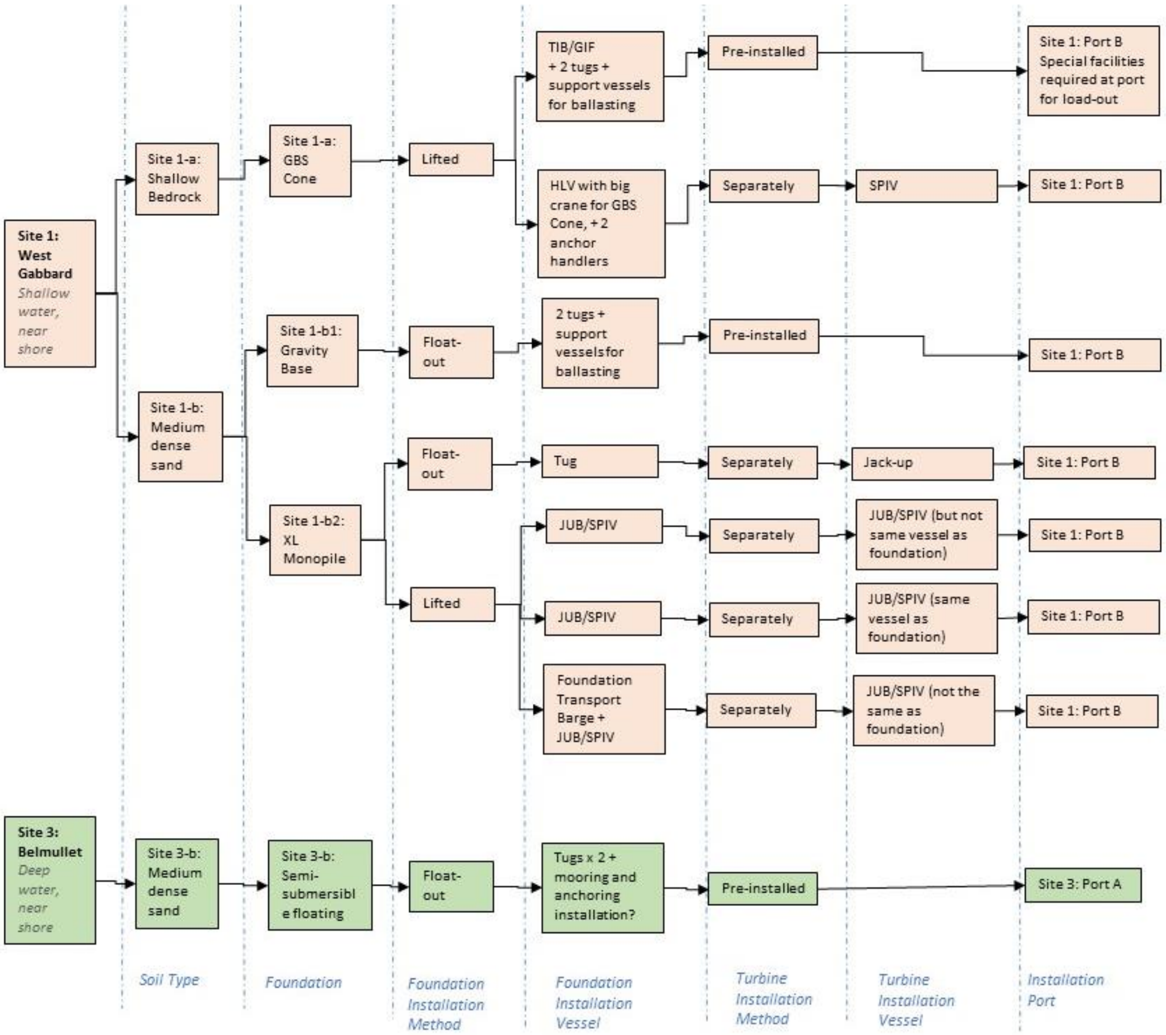


Figure 3-4:Different Installation Scenarios supported by the installation model (F Judge et al., 2017)

4 OPERATION & MAINTENANCE

O&M Expert is a time-based probabilistic operation and maintenance (O&M) modelling tool that can simulate maintenance activities for an offshore wind/wave farm over a project lifetime. The tool models an O&M strategy defined by the user and calculates operational costs, production losses and farm availability. In this way, it can be used to determine the optimal strategy for a wind/wave farm considering parameters such as distance from shore and available service vessels.

The user inputs details to describe the wave farm, vessel fleet, technician resources and port details as well as component failure rates and maintenance requirements. Metocean data (wind speeds and wave heights) representative of the wave farm site are uploaded by the user and are used to represent the weather forecast when scheduling maintenance activities. The model generates a daily activity schedule and checks the forecast for a weather window in which to carry out the necessary repairs. Vessels and crew are allocated and repairs are completed according to a prioritised list. Both costs and energy produced are calculated by the model; e.g., vessel fuel costs and the cost of spare parts are tracked as the model simulates activities, as well as WEC downtime and the associated lost production.

O&M Expert uses Monte Carlo simulation to model the uncertainty in the results. This involves running multiple simulations of a single maintenance strategy, where each simulation randomises the value of stochastic variables (i.e. elements with inherent variability). In this case, the stochastic variable is the time to failure for each component. Using the results of the Monte Carlo simulation, statistics such as the mean and standard deviation of the results can be produced. In this way, the user gets an insight into the uncertainty of the model predictions.

4.1 O&M EXPERT OVERVIEW

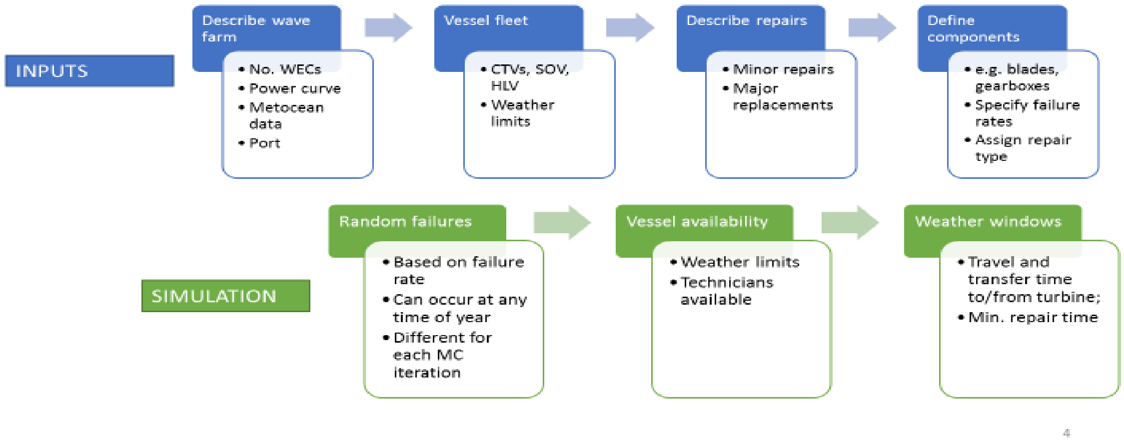


Figure 4-1:Required inputs to O&M Expert

In a similar manner to the installation model, the user provides the main inputs which describe wave farm such as the number of devices, power curves for the devices and metocean data. The user is also required to give details on overall O&M strategy: mainly what is the vessel fleet available (pre-owned or chartered) and all weather limits for said vessels. Details must be provided on the repairs that can potentially occur over the O&M project's lifespan. Define the individual components and their respective failure rate and assign repair types to each component.

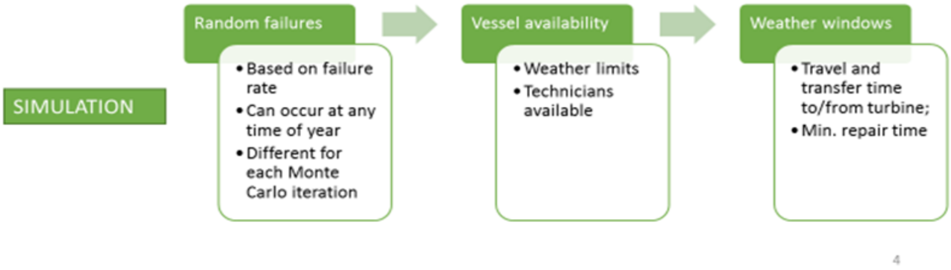


Figure 4-2: Simulation Process

Failure rates are currently based on random failure coefficients. i.e a coefficient of 0.1 means an expected failure rate once every 10 years.

The model looks at a list of tasks for that day: checks for available vessels, checks vessels' weather limits and technicians available for the task. It then looks for good weather windows of sufficient time, allowing for travel to site, transfer of technicians and completion of repairs. If there remains sufficient time in the weather window, then schedule to carry out the next repair or else return to base.

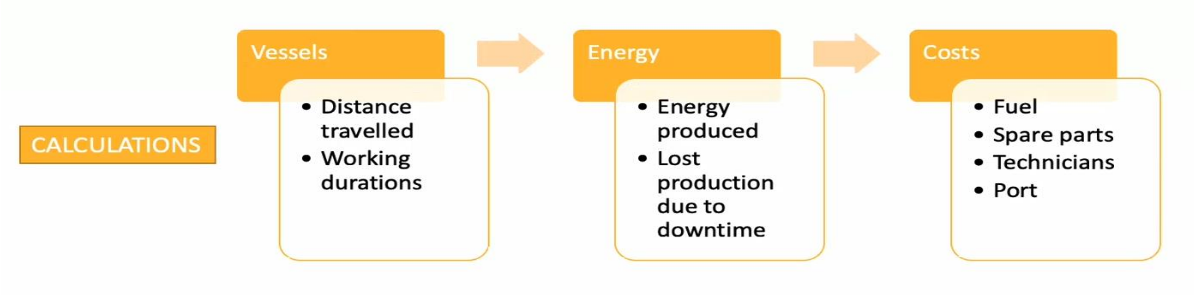


Figure 4-3: List of calculations performed by the model

The software tracks the distance travelled, working durations, energy produced and conversely lost production due to downtime. Additionally all expenditure, such as spare parts, technicians & port fees are accounted for.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

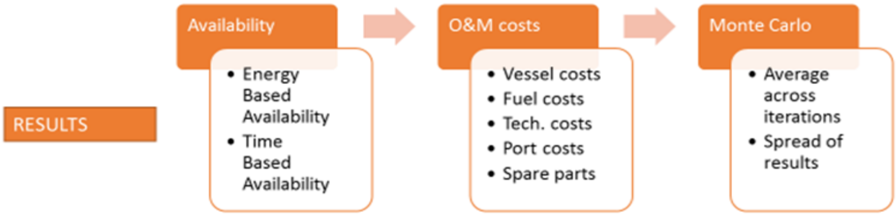
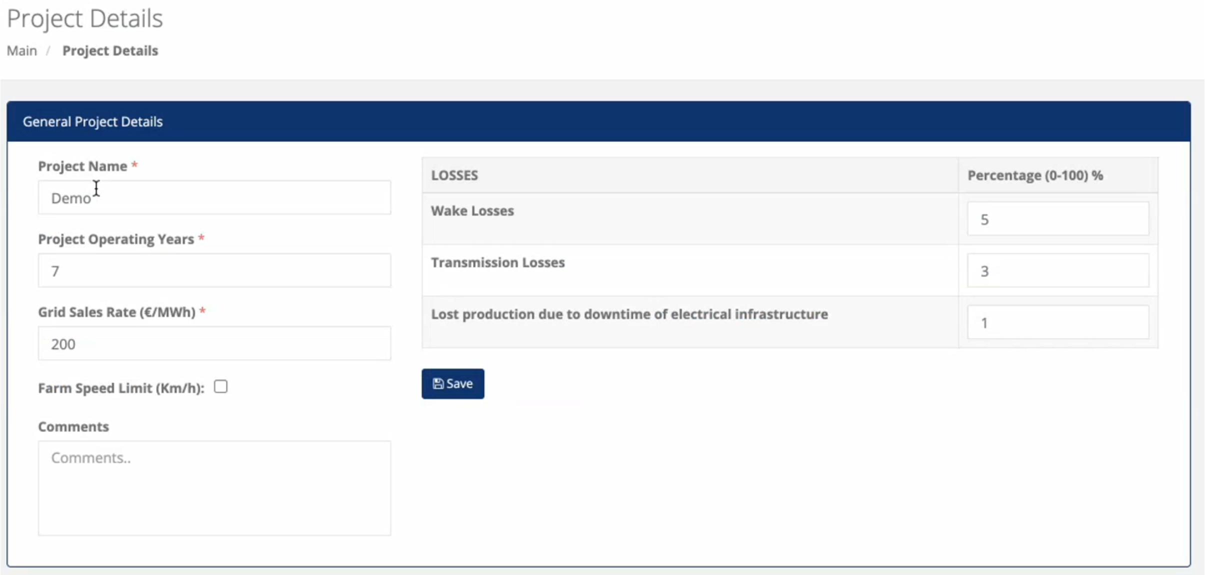


Figure 4-4: List of Results generated by the model

Results give farm availability, a breakdown of costs per year and per Monte Carlo iterations. Results are then averaged across all iterations.

4.2 O&M EXPERT INPUTS



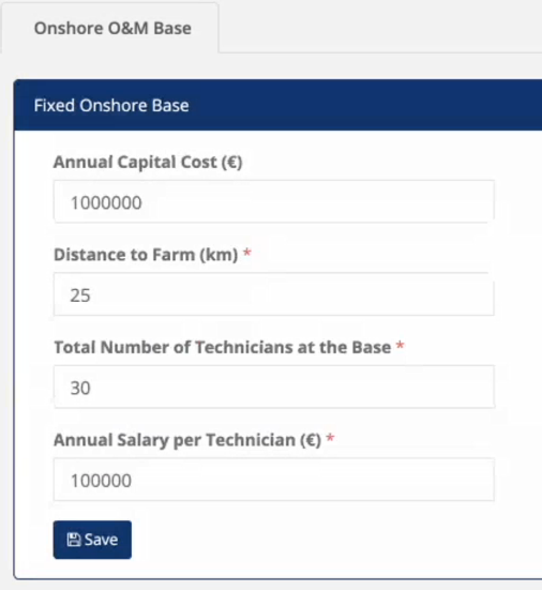
Project Name *	Demo
Project Operating Years *	7
Grid Sales Rate (€/MWh) *	200
Farm Speed Limit (Km/h):	☐
Comments	Comments..

LOSSES	Percentage (0-100) %
Wake Losses	5
Transmission Losses	3
Lost production due to downtime of electrical infrastructure	1

Figure 4-5: O&M Project details, operating years, electricity price, loses etc

The project details sheet is shown in Figure 4-5, where the user details the number of years the project is expected to be operating for, the cost of electricity, vessel transfer speed limit and hydrodynamic (array effects) as well as electrical losses.

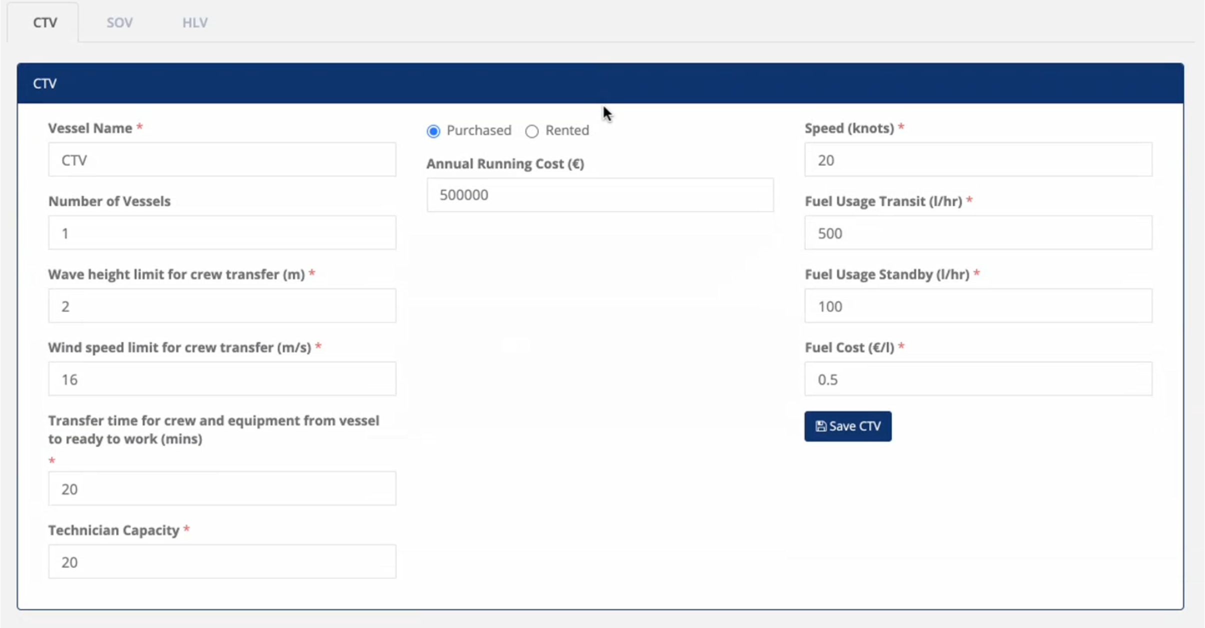
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.



Fixed Onshore Base

Annual Capital Cost (€): 1000000
Distance to Farm (km) *: 25
Total Number of Technicians at the Base *: 30
Annual Salary per Technician (€) *: 100000

Figure 4-6: O&M facilities and technician details



CTV

Vessel Name *: CTV
Number of Vessels: 1
Wave height limit for crew transfer (m) *: 2
Wind speed limit for crew transfer (m/s) *: 16
Transfer time for crew and equipment from vessel to ready to work (mins) *: 20
Technician Capacity *: 20
● Purchased ○ Rented
Annual Running Cost (€): 500000
Speed (knots) *: 20
Fuel Usage Transit (l/hr) *: 500
Fuel Usage Standby (l/hr) *: 100
Fuel Cost (€/l) *: 0.5

Figure 4-7: Vessel details, currently three main categories, CTV,SOV & HLV.

Currently the model caters for three different vessel types (although it is relative easy to implement more).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

CTV

- Specify number of vessels available. Specify a wave height and wind speed limit for safe transport to and from site. Transfer time for crew and equipment to be ready to work. The capacity of the vessel as well as the annual running cost. Vessel can be owned or chartered. Input, vessel speed, fuel usage during transit and standby as well as fuel cost (€/l).

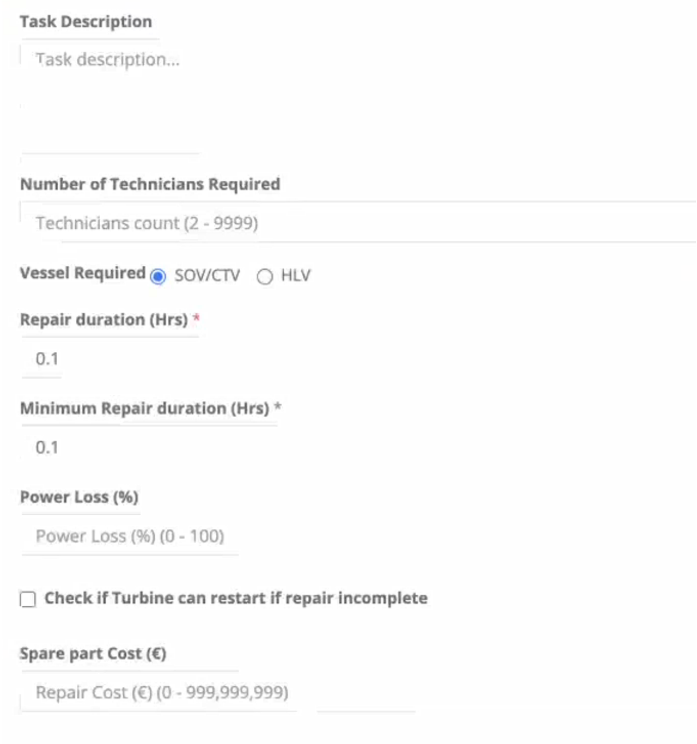
SOV and HLV

- Can stay offshore for longer periods of time. Specify operational tour duration (period during which work can be carried out). Once this time has elapsed the vessel returns to shore to resupply over a certain amount of time (additional input). Vessel may also have to return to shore if severe weather limits are exceeded. Vessel can have a number of so called "daughter" vessels (CTVs) to carry out additional work.

Wave height limits for technician transfer (SOV to CTF) and additional option for access system to platform directly from SOV (generally with higher wave height limit).
Define technician shift hours (8,12 etc. and start and end times).

Figure 4-8 displays how the user specifies repair operations, by assigning the resources required, in terms of vessels and technicians required as well as the total time to complete the task and minimal time (minimum duration is only applicable if repair work can be carried out piecewise and the vessel does not have time to complete 100% of task). Specify power loss associated with repair type. 100% power loss means WEC is fully down while repairs are being carried out. Define a spare parts cost of failed component.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.



Task Description

Task description...

Number of Technicians Required

Technicians count (2 - 9999)

Vessel Required ● SOV/CTV ○ HLV

Repair duration (Hrs) *

0.1

Minimum Repair duration (Hrs) *

0.1

Power Loss (%)

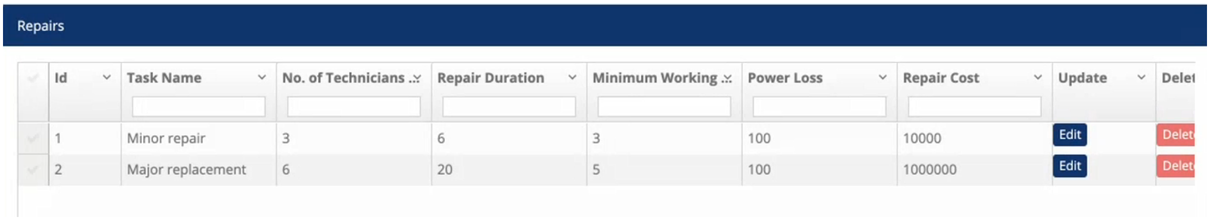
Power Loss (%) (0 - 100)

☐ **Check if Turbine can restart if repair incomplete**

Spare part Cost (€)

Repair Cost (€) (0 - 999,999,999)

Figure 4-8: Tasks (repairs) are created with description of resources required.



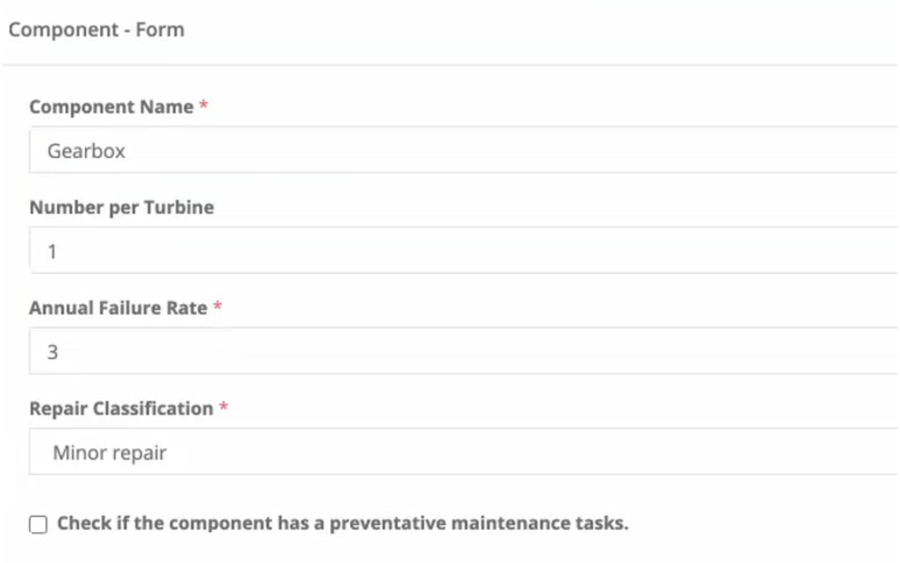
Repairs

Id	Task Name	No. of Technicians ..	Repair Duration	Minimum Working ..	Power Loss	Repair Cost	Update	Delet
1	Minor repair	3	6	3	100	10000	Edit	Delet
2	Major replacement	6	20	5	100	1000000	Edit	Delet

Figure 4-9: Categories of repair (minor or major), number of technicians required, duration and associated power loss.

Each task created in this way, is then summarised and stored as shown in Figure 4-9.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.


Component - Form

Component Name *
Gearbox

Number per Turbine
1

Annual Failure Rate *
3

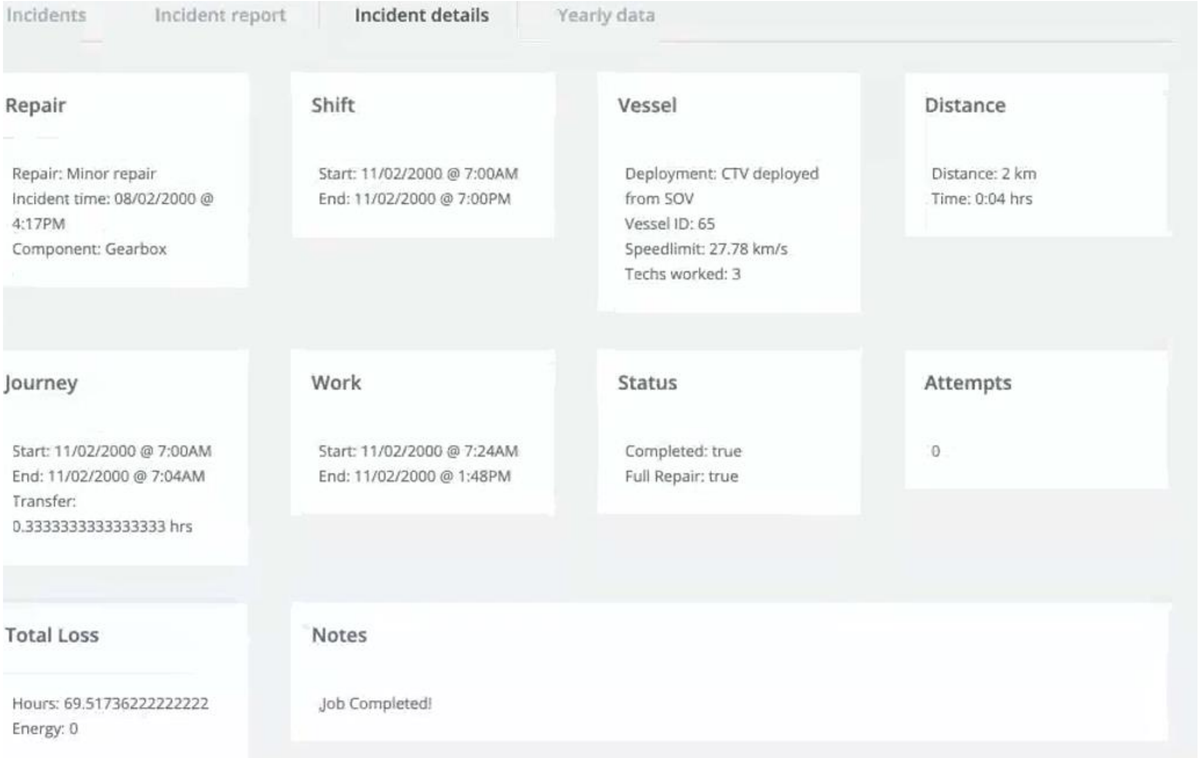
Repair Classification *
Minor repair

☐ **Check if the component has a preventative maintenance tasks.**

Figure 4-10: Assign components to the devices.

Figure 4-10 shows how components are created for the device. There is an option for preventative maintenance of components (e.g. an annual service of a specific part). Corrective repairs always take priority over preventative repairs.

The model keeps track of all repairs job details as shown in Figure 4-11. Details logged include the time of initial failure, time repair was carried out, including delay due to suitable weather window obtained.



Repair
Repair: Minor repair
Incident time: 08/02/2000 @ 4:17PM
Component: Gearbox

Shift
Start: 11/02/2000 @ 7:00AM
End: 11/02/2000 @ 7:00PM

Vessel
Deployment: CTV deployed from SOV
Vessel ID: 65
Speedlimit: 27.78 km/s
Techs worked: 3

Distance
Distance: 2 km
Time: 0:04 hrs

Journey
Start: 11/02/2000 @ 7:00AM
End: 11/02/2000 @ 7:04AM
Transfer: 0.3333333333333333 hrs

Work
Start: 11/02/2000 @ 7:24AM
End: 11/02/2000 @ 1:48PM

Status
Completed: true
Full Repair: true

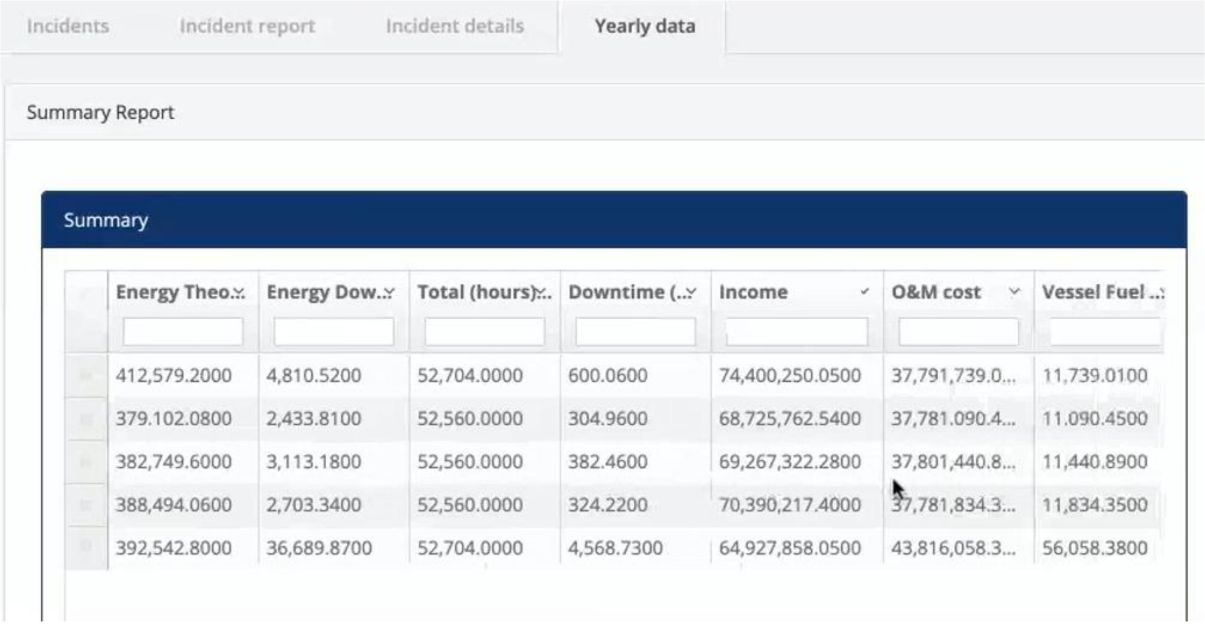
Attempts
0

Total Loss
Hours: 69.51736222222222
Energy: 0

Notes
Job Completed!

Figure 4-11: Log of all repair tasks carried out

Time duration of repair operation and associated downtime, as well as O&M costs data are stored for each separate incident. Yearly data is collated for each iteration, and each iteration is then averaged. Results saved to iteration summary file.

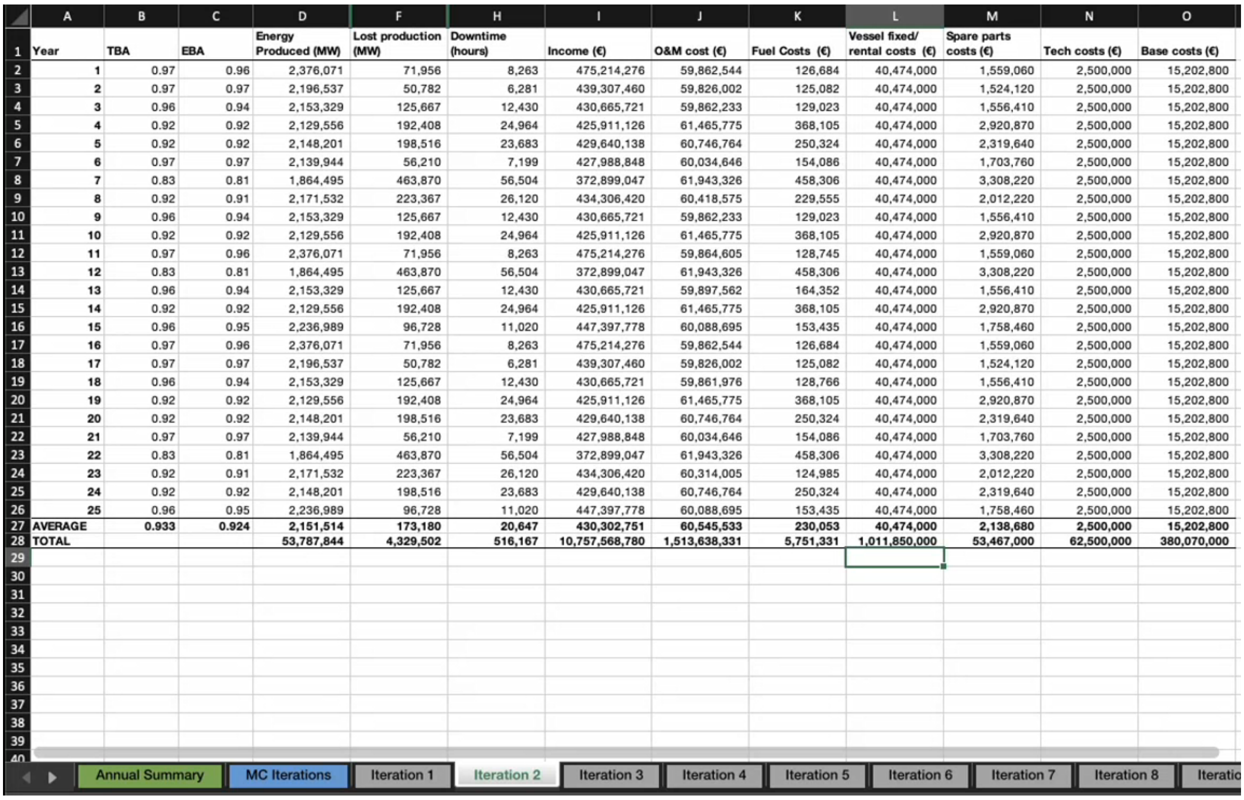


Energy Theo...	Energy Dow...	Total (hours)...	Downtime (...	Income	O&M cost	Vessel Fuel ...
412,579.2000	4,810.5200	52,704.0000	600.0600	74,400,250.0500	37,791,739.0...	11,739.0100
379.102.0800	2,433.8100	52,560.0000	304.9600	68,725,762.5400	37,781.090.4...	11.090.4500
382,749.6000	3,113.1800	52,560.0000	382.4600	69,267,322.2800	37,801,440.8...	11,440.8900
388,494.0600	2,703.3400	52,560.0000	324.2200	70,390,217.4000	37,781,834.3...	11,834.3500
392,542.8000	36,689.8700	52,704.0000	4,568.7300	64,927,858.0500	43,816,058.3...	56,058.3800

Figure 4-12: O&M Expert Summary Report

The results from the O&M Expert model are converted into Excel files (Figure 4-13), so that they can passed on to WP8 who are undertaking an LCOE model for the LiftWEC device. Average and standard deviation costs of important metrics across all iterations can then be used.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.



	A	B	C	D	F	H	I	J	K	L	M	N	O
1	**Year**	**TBA**	**EBA**	**Energy Produced (MW)**	**Lost production (MW)**	**Downtime (hours)**	**Income (€)**	**O&M cost (€)**	**Fuel Costs (€)**	**Vessel fixed/ rental costs (€)**	**Spare parts costs (€)**	**Tech costs (€)**	**Base costs (€)**
2	1	0.97	0.96	2,376,071	71,956	8,263	475,214,276	59,862,544	126,684	40,474,000	1,559,060	2,500,000	15,202,800
3	2	0.97	0.97	2,196,537	50,782	6,281	439,307,460	59,826,002	125,082	40,474,000	1,524,120	2,500,000	15,202,800
4	3	0.96	0.94	2,153,329	125,667	12,430	430,665,721	59,862,233	129,023	40,474,000	1,556,410	2,500,000	15,202,800
5	4	0.92	0.92	2,129,556	192,408	24,964	425,911,126	61,465,775	368,105	40,474,000	2,920,870	2,500,000	15,202,800
6	5	0.92	0.92	2,148,201	198,516	23,683	429,640,138	60,746,764	250,324	40,474,000	2,319,640	2,500,000	15,202,800
7	6	0.97	0.97	2,139,944	56,210	7,199	427,988,848	60,034,646	154,086	40,474,000	1,703,760	2,500,000	15,202,800
8	7	0.83	0.81	1,864,495	463,870	56,504	372,899,047	61,943,326	458,306	40,474,000	3,308,220	2,500,000	15,202,800
9	8	0.92	0.91	2,171,532	223,367	26,120	434,306,420	60,418,575	229,555	40,474,000	2,012,220	2,500,000	15,202,800
10	9	0.96	0.94	2,153,329	125,667	12,430	430,665,721	59,862,233	129,023	40,474,000	1,556,410	2,500,000	15,202,800
11	10	0.92	0.92	2,129,556	192,408	24,964	425,911,126	61,465,775	368,105	40,474,000	2,920,870	2,500,000	15,202,800
12	11	0.97	0.96	2,376,071	71,956	8,263	475,214,276	59,864,605	128,745	40,474,000	1,559,060	2,500,000	15,202,800
13	12	0.83	0.81	1,864,495	463,870	56,504	372,899,047	61,943,326	458,306	40,474,000	3,308,220	2,500,000	15,202,800
14	13	0.96	0.94	2,153,329	125,667	12,430	430,665,721	59,897,562	164,352	40,474,000	1,556,410	2,500,000	15,202,800
15	14	0.92	0.92	2,129,556	192,408	24,964	425,911,126	61,465,775	368,105	40,474,000	2,920,870	2,500,000	15,202,800
16	15	0.96	0.95	2,236,989	96,728	11,020	447,397,778	60,088,695	153,435	40,474,000	1,758,460	2,500,000	15,202,800
17	16	0.97	0.96	2,376,071	71,956	8,263	475,214,276	59,862,544	126,684	40,474,000	1,559,060	2,500,000	15,202,800
18	17	0.97	0.97	2,196,537	50,782	6,281	439,307,460	59,826,002	125,082	40,474,000	1,524,120	2,500,000	15,202,800
19	18	0.96	0.94	2,153,329	125,667	12,430	430,665,721	59,861,976	128,766	40,474,000	1,556,410	2,500,000	15,202,800
20	19	0.92	0.92	2,129,556	192,408	24,964	425,911,126	61,465,775	368,105	40,474,000	2,920,870	2,500,000	15,202,800
21	20	0.92	0.92	2,148,201	198,516	23,683	429,640,138	60,746,764	250,324	40,474,000	2,319,640	2,500,000	15,202,800
22	21	0.97	0.97	2,139,944	56,210	7,199	427,988,848	60,034,646	154,086	40,474,000	1,703,760	2,500,000	15,202,800
23	22	0.83	0.81	1,864,495	463,870	56,504	372,899,047	61,943,326	458,306	40,474,000	3,308,220	2,500,000	15,202,800
24	23	0.92	0.91	2,171,532	223,367	26,120	434,306,420	60,314,005	124,985	40,474,000	2,012,220	2,500,000	15,202,800
25	24	0.92	0.92	2,148,201	198,516	23,683	429,640,138	60,746,764	250,324	40,474,000	2,319,640	2,500,000	15,202,800
26	25	0.96	0.95	2,236,989	96,728	11,020	447,397,778	60,088,695	153,435	40,474,000	1,758,460	2,500,000	15,202,800
27	**AVERAGE**	**0.933**	**0.924**	**2,151,514**	**173,180**	**20,647**	**430,302,751**	**60,545,533**	**230,053**	**40,474,000**	**2,138,680**	**2,500,000**	**15,202,800**
28	**TOTAL**			**53,787,844**	**4,329,502**	**516,167**	**10,757,568,780**	**1,513,638,331**	**5,751,331**	**1,011,850,000**	**53,467,000**	**62,500,000**	**380,070,000**

Figure 4-13: Breakdown of yearly results (exported to Excel) generated by the model

Yearly data (for one iteration) is summarised, including, energy production, total downtime and lost production due to downtime. Income and expenditures, including, O&M costs fuel costs, vessel charter costs, technician and port/base costs are also summarised.

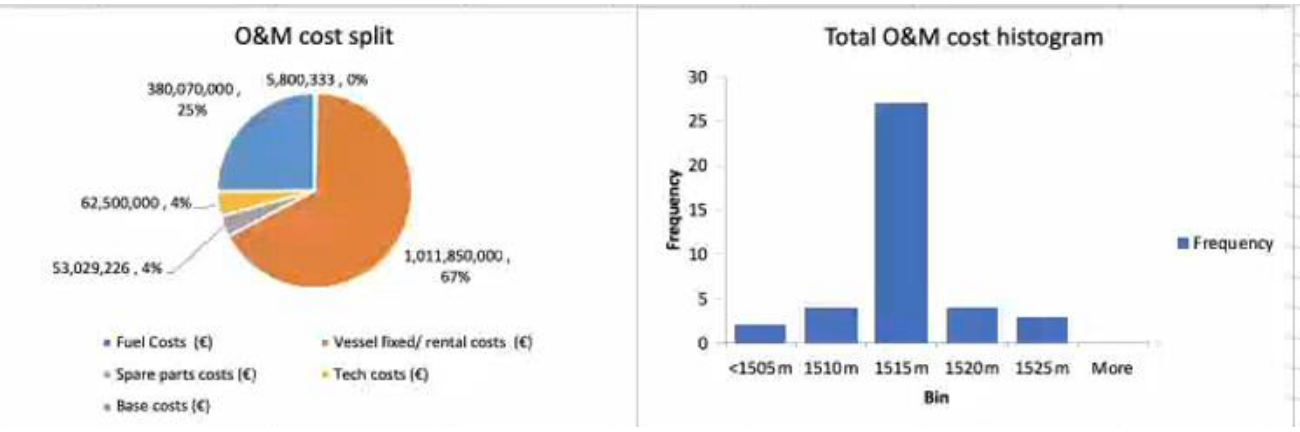
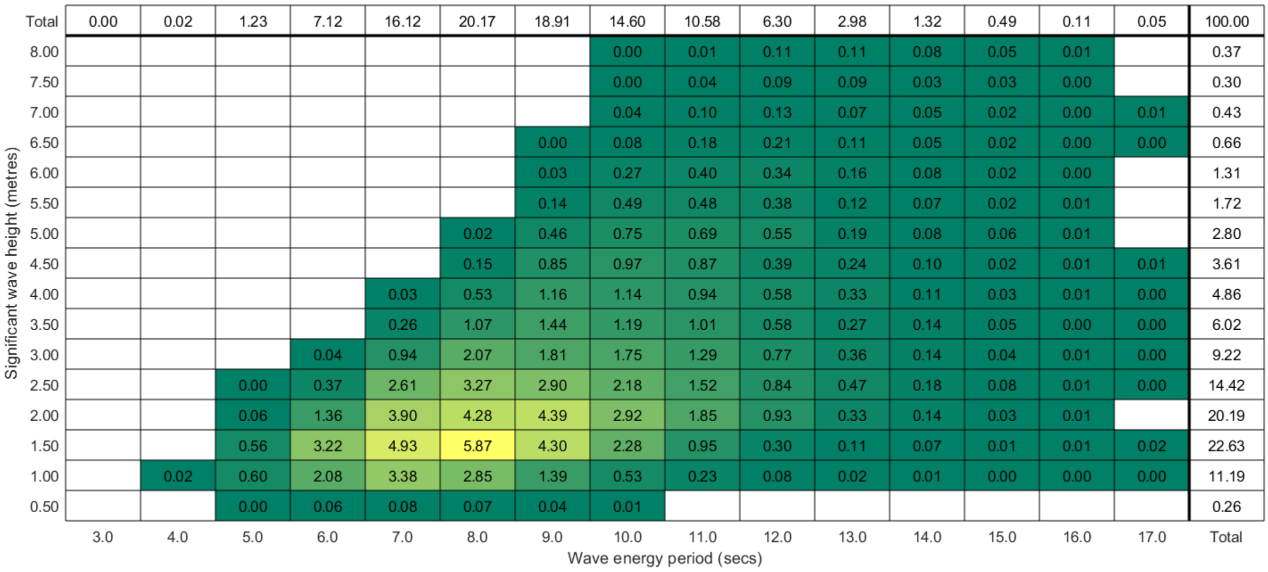


Figure 4-14: Sample O&M results for an offshore windfarm

Figure 4-14 displays example results (for an offshore wind farm), with both an average breakdown of O&M costs as well as a histogram showing the bins with the most likely overall O&M cost of the farm over its lifetime.



Total	0.00	0.02	1.23	7.12	16.12	20.17	18.91	14.60	10.58	6.30	2.98	1.32	0.49	0.11	0.05	100.00
8.00								0.00	0.01	0.11	0.11	0.08	0.05	0.01		0.37
7.50								0.00	0.04	0.09	0.09	0.03	0.03	0.00		0.30
7.00								0.04	0.10	0.13	0.07	0.05	0.02	0.00	0.01	0.43
6.50							0.00	0.08	0.18	0.21	0.11	0.05	0.02	0.00	0.00	0.66
6.00							0.03	0.27	0.40	0.34	0.16	0.08	0.02	0.00		1.31
5.50							0.14	0.49	0.48	0.38	0.12	0.07	0.02	0.01		1.72
5.00						0.02	0.46	0.75	0.69	0.55	0.19	0.08	0.06	0.01		2.80
4.50						0.15	0.85	0.97	0.87	0.39	0.24	0.10	0.02	0.01	0.01	3.61
4.00					0.03	0.53	1.16	1.14	0.94	0.58	0.33	0.11	0.03	0.01	0.00	4.86
3.50					0.26	1.07	1.44	1.19	1.01	0.58	0.27	0.14	0.05	0.00	0.00	6.02
3.00				0.04	0.94	2.07	1.81	1.75	1.29	0.77	0.36	0.14	0.04	0.01	0.00	9.22
2.50			0.00	0.37	2.61	3.27	2.90	2.18	1.52	0.84	0.47	0.18	0.08	0.01	0.00	14.42
2.00			0.06	1.36	3.90	4.28	4.39	2.92	1.85	0.93	0.33	0.14	0.03	0.01		20.19
1.50			0.56	3.22	4.93	5.87	4.30	2.28	0.95	0.30	0.11	0.07	0.01	0.01	0.02	22.63
1.00		0.02	0.60	2.08	3.38	2.85	1.39	0.53	0.23	0.08	0.02	0.01	0.00	0.00	0.00	11.19
0.50			0.00	0.06	0.08	0.07	0.04	0.01								0.26
	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	Total

Figure 4-15; Scatter diagram for the HOMERE Ifremer site (Boudière et al., 2013)

Currently the model is setup to estimate power capture, by reading the chosen sites hourly parameters of significant wave height and energy period. These hourly statistics would be taken from a resource of previous site data, which for the LiftWEC project is the INFREMER site (Boudière et al., 2013). The incident sea conditions are then randomised over the 25 year modelling duration of the project. Each monte carlo simulation would have it's own randomised 25 year data set. These hourly parameters are then feed into a corresponding lookup table (supplied initially by a numerical model and eventually physical model results) to estimate the average power capture for that hour. While a similar method has been used to evaluate power capture for offshore wind (extrapolating wind speed up to the hub height and estimating power capture): this hourly summary statistic method could potentially be more punitive towards wave devices (whose dynamics are significantly more complicated than wind as will be discussed in the following section). In other words by attempting to describe a sea state by only two parameters: what one gains from computation speed, one loses in fidelity to the actual scenario.

Take for example the possibility of a twin peaked spectrum (as in with identical Hs and Te/Tp parameters to the idealised or modelled spectrum e.g. Bretscheider for exposed Atlantic sites or JoNSWAP for North Sea sites. In the figure overleaf both the actual spectrum and the idealised Bretschneider spectrum have the same summary statistics values of Hm0 and T02. However one could imagine two very different power capture results, particularly for a device whose resonance peak occurs in the valley of the twin peaked spectra.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

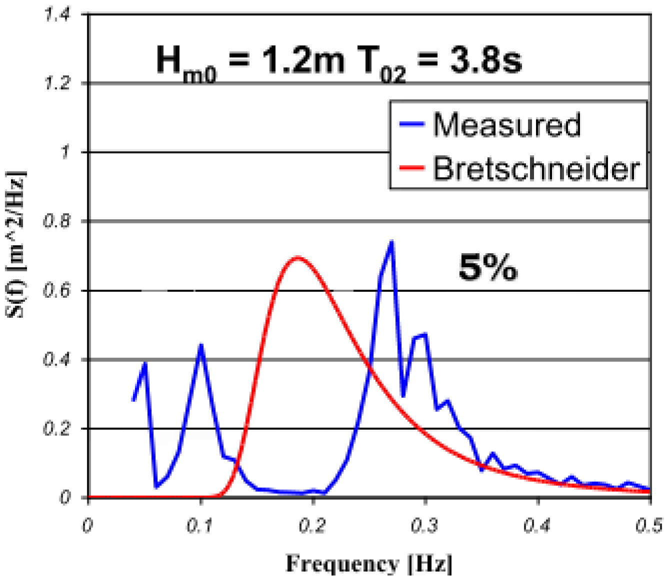


Figure 4-16: Comparison of Theoretical and Measured Spectral Shape (Barret, 2010).

As most floating wave energy convertors have a narrow response bandwidth, a high occurrence of twin peaked spectra may not produce the expected power production from the device, especially if resonance falls within the valley between the wind and swell spectral components. The occurrence of twin peaked spectra is site specific and these are only ever an issue for low sea state conditions. Additionally, since the LiftWEC device will be heavily controlled, the severity of the aforementioned twin peak spectra problem remains to be seen.

While it might be possible to carry out work on the incidents of twin peaked spectra and feed this information into the power capture results (weighted towards lower sea states. The proposed solution (particularly for more in depth analysis of later LiftWEC configurations) is to use actual sea spectra data from the site in question. Although not currently the method used, such a method should be easily implantable at the cost of longer simulation times.

A further proposed improvement to the model is the adaptation to failure rates so that they can be weighted towards becoming more likely during extreme sea states. Currently the failure rates are simply randomised over a number of years.

5 DECOMMISSIONING

The decommissioning model aims to estimate the cost of decommissioning a wave farm project and provide an estimate of the salvage revenue. The model takes into account the decommissioning strategy, vessels, ports and recycling centres used. User inputs are materials, weights and post-decommissioning strategy options e.g. recycling, disposal, reconditioning and re-sale. The model has a very similar design architecture to that of the installation model.

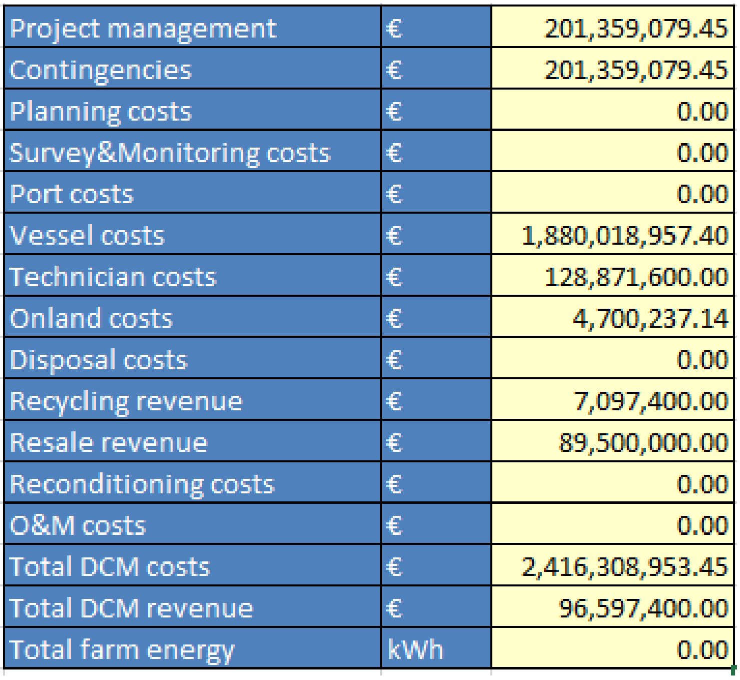
The stochastic variables considered in the module are the weather time series, costs and revenues. Cost and revenue figures can vary significantly (i.e. the price of steel, survey and monitoring, port costs

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

etc.). 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', $x_0 = (a*(a - (a*b)))$, and $x_1 = (a*(a + (a*b)))$.

Using 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 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 specified. This considers the average annual conditions calculated from the full time series provided. 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 (Frances Judge et al., 2019).

The salvage and decommissioning results sheet consists of a table relating to the various decommissioning costs and the potential revenue from salvage. The Figure below depicts the results table from the decommissioning output sheet.



Project management	€	201,359,079.45
Contingencies	€	201,359,079.45
Planning costs	€	0.00
Survey&Monitoring costs	€	0.00
Port costs	€	0.00
Vessel costs	€	1,880,018,957.40
Technician costs	€	128,871,600.00
Onland costs	€	4,700,237.14
Disposal costs	€	0.00
Recycling revenue	€	7,097,400.00
Resale revenue	€	89,500,000.00
Reconditioning costs	€	0.00
O&M costs	€	0.00
Total DCM costs	€	2,416,308,953.45
Total DCM revenue	€	96,597,400.00
Total farm energy	kWh	0.00

Figure 5-1: Decommissioning model output sheet

6 MODEL VALIDATION

Multiple paradigms and techniques for validation of computer models exist. For instance, operational validation can be defined as "determining that the model's output behaviour has a satisfactory range of accuracy for the model's intended purpose over the domain of the model's intended

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

applicability"(Hofmann et al 2014). This implies 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. Validation in this sense is challenging for offshore wind/wave farms due to the availability of such input and output data. Some reasons for this are that 1) real data often are commercially sensitive, and thus not readily available to the research community; and 2) real data are scarce due to limited operational experience with offshore wind/wave technologies. The latter restriction is generally more relevant for later phases of the lifecycle of an offshore wind/wave farm.

For the decommissioning phase historic data to support model validation is almost non-existent (Topham & McMillan, 2017) (Vindeby 2007), whereas for the installation phase, historic data is available from a large number of offshore wind farms currently operational (Lacal-Arántegui et al 2018).

6.1 INSTALLATION MODEL VALIDATION

The validation of the Installation module was performed in the LEANWIND project using published data from three different wind farms developed by EDF: C-Power Phase 1 (30 MW), C-Power Phase 2 & 3 (288 MW), and Teesside (62 MW). These case studies were chosen to represent as many different scenarios as possible to demonstrate that a range of different technologies and installation methods for various farm sizes could be modelled with an acceptable level of accuracy. For all three validation case studies considered, 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 underpredicting 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). 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 6-1 summarises the results of the sensitivity analysis for the CAPEX. As expected, increases in dry CAPEX (e.g. cost of the turbine, substructure etc.) 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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

common and maximum conditions at a given site. In conclusion, the variation of all variables considered in the sensitivity analysis caused the financial model to behave as expected.

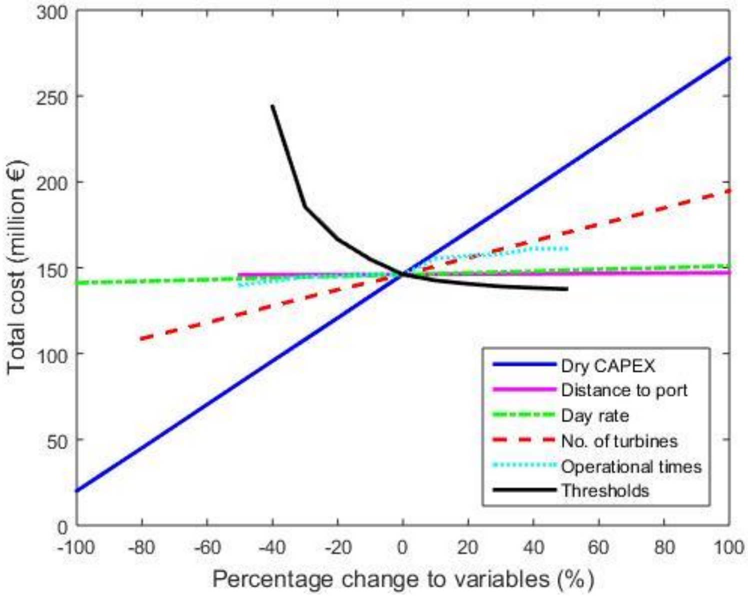


Figure 6-1 Installation module sensitivity analysis: Change in total costs versus changes to individual variables

Further details on validation of the installation model can be found in (Frances Judge et al., 2019).

6.2 O&M MODEL VALIDATION

The O&M expert tool, has only very recently been compled, with some features/bugs yet to be removed. Consequently the validation for this module is code to code based with NOWIcob model (Norwegian offshore wind power life cycle cost and benefit- SINTEF," 2020). The NOWIcob model is a long standing O&M model, being under devolpment for nearly a decade and has undergone several code to code based validation tests itself as well as case studies such as those in the LEANWIND project.

Summary comparioson results between the models are given for an offshore wind test case, as shown in Figure 6-2 overleaf.

		O&M Expert	NOWIcob
O&M Total Cost	€	1,513,249,559	1,540,431,122
O&M Cost	€/MW/yr	123,028	125,238
Energy produced	MWh	53,389,977	53,402,165
Capacity Factor	%	49.55%	49.56%

Figure 6-2: Summary results of both the O&M Expert and NOWIcob models for an offshore wind farm.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

The results are very promising with O&M Experts total expected cost being within 2% of the NOWIcob predicted costs. NOWIcob has been in development for nearly a decade and has undergone code to code validation studies (with models such as the ECUME model of EDF and models from University of Strathclyde and University of Stavanger), as well as the previously mentioned LEANWIND case studies. Further details on the validation efforts of the NOWIcob model can be found at (Dinwoodie et al 2015).

6.3 DECOMMISSIONING MODEL VALIDATION

Due to the relatively immature stage of development of the offshore wind industry, (even more so for wave energy) there is a limited knowledge of how decommissioning will be undertaken; i.e. 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 (Vattenfall, 2017) and Vindeby offshore wind farms(Open Ocean 2017)) 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 100 8MW turbines with monopile foundations cost €214,896 per MW. This is within the €200,000-€600,000 per MW range estimated by a 2015 DNV GL study cited by (Chamberlain, 2016). This indicates that the outputs from the present model are reasonable, although at the lower end of the DNV GL estimates. An estimate produced by BVG Associates for a similar 100 8MW turbine farm is €333,252 per MW (BVG Associates, 2012). However, it is important to remember that the BVG Associates estimates are for projects with Financial Investment Decision (FID) values 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 validated further and calibrated based on these data.

Given the difficulties validating costs, a sensitivity analysis was also conducted to confirm that the impact of variations were 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 6-3 illustrates the expected rise and fall in cost and decommissioning time when the number of resources (i.e. vessels and technicians) increases and decreases.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

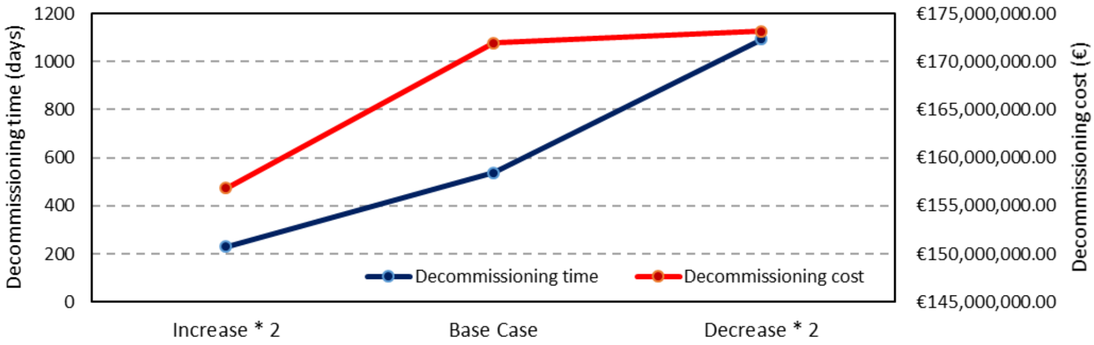


Figure 6-3 Decommissioning module sensitivity analysis: Impact of resources (numbers of vessels and technicians) (Frances Judge et al., 2019)

Sensitivity analysis also identified some interesting trends for further investigation:

- It was found that decommissioning took less time with more resources, and this outweighed the added cost.
- However, while decommissioning took more time with fewer resources, the reduced number of vessels and technicians mitigated a substantial increase in the overall cost. Therefore, more in-depth analysis could examine the optimal number of vessels and technicians considering the trade-off between time and cost-effectiveness.

7 DISCUSSION AND CONCLUSION

The installation and decommissioning models, originally created for modelling offshore wind (as part of the LEANWIND project) have been successfully adapted for wave energy devices.

The model that was lacking from UCC's arsenal was one which could handle operations and maintenance (the LEANWIND project relied on the SINTEF created NOWIcob model for this area). UCC's O&M Expert model was very recently created for the successor to LEANWIND, the Eirwind project (EirWind 2020). While the model is not 100% complete, with some minor adaptations yet to made, this model will be ready in time to run the O&M simulations on the preliminary LiftWEC configurations agreed upon during the consortium meetings in May. One encouraging result is that O&M Expert has been validated (for an offshore wind farm case study) with the NOWIcob model. This is an extremely promising result, as the NOWIcob model is one of the better O&M models available, being under development for nearly a decade at SINTEF. The results for each year of the O&M phase include the annual energy production and the total annual O&M costs, including personnel costs, vessel costs (fixed costs, on-demand charter costs and fuel costs), and spare part costs. Improvements to the model include the addition of hourly sea state spectral data for power calculations. Additionally it is proposed to model failure rates more realistically, such that (some) failures are more likely to occur during extreme sea states. Along similar lines of reasoning if some structural failures were deemed more likely due to prolonged/accumulated exposure to extreme weather conditions: perhaps in the form of a "wear and tear" coefficient which increases with yearly exposure to the waves and decreases with preventative maintenance.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

The next stage of the work, prior to running simulations of the preliminary configurations is to gather input data for the operations and failures etc. typical of a wave energy device. As part of previous work carried out: an extensive library of vessel types & charter rates, safe weather limits for actions, as well as offshore operations common to both wind and wave:, such as substations, import and export cables have been amassed. More details are required for weather limits for operating on wave devices, (which experience more significant motions than wind turbine platforms). Additional consultation with WP2 (concept development) and WP6 (structural design) for likely components/features involved with the different configurations, as well discussing with WP5 (Control) about extrapolating control requirements (in terms of equipment and sensors required) from TRL4 to TRL9.

Once this input data has been acquired, work can begin on modelling the lifecycle stages of the preliminary LiftWEC configurations.

8 REFERENCES

Barret, S. (2010). *Floating wave energy converters: wave measurement & analysis techniques* (University College Cork). https://doi.org/https://cora.ucc.ie/bitstream/handle/10468/3372/Floating%20Wave%20Energy%20Converters%20Wave%20Measurement%20%26%20Analysis%20Techniques-Sean%20Barrett.pdf?sequence=1&isAllowed=y

Boudière, E., Maisondieu, C., Ardhuin, F., Accensi, M., Pineau-Guillou, L., & Lepesqueur, J. (2013). A suitable metocean hindcast database for the design of Marine energy converters. *International Journal of Marine Energy*, *3–4*(December). https://doi.org/10.1016/j.ijome.2013.11.010

BVG Associates. (2012). *Offshore wind cost reduction pathways - Technology work stream*. (May), 1–215.

Chamberlain, K. (2016). Offshore Operators Act on Early Decommissioning – Wind Energy Update.

Dinwoodie, I., Endrerud, O.-E. V., Hofmann, M., Martin, R., & Sperstad, I. B. (2015). Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms. *Wind Engineering*, *39*(1), 1–14. https://doi.org/10.1260/0309-524X.39.1.1

EirWind - MaREI. (n.d.). Retrieved September 1, 2020, from https://www.marei.ie/project/eirwind/

Hofmann, M., Sperstad, I. B., & Kolstad, M. (2014). *Technical documentation of the NOWIcob tool (NOWIcob version 3.2)*. 53.

Home | LEANWIND. (n.d.). Retrieved September 1, 2020, from http://www.leanwind.eu/

Judge, F, Devoy McAuliffe, F., Flannery, B., Lynch, K., Bakken Sperstad, I., Espeland Halvorsen-Weare, E., … Jones, D. (2017). *LEANWIND: D7.2 Case study validation of combined financial and logistics tools*.

Judge, Frances, McAuliffe, F. D., Sperstad, I. B., Chester, R., Flannery, B., Lynch, K., & Murphy, J. (2019). A lifecycle financial analysis model for offshore wind farms. *Renewable and Sustainable Energy Reviews*, *103*, 370–383. https://doi.org/10.1016/j.rser.2018.12.045

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

Lacal-Arántegui, R., Yusta, J. M., & Domínguez-Navarro, J. A. (2018). Offshore wind installation: Analysing the evidence behind improvements in installation time. *Renewable and Sustainable Energy Reviews*, *92*, 133–145. https://doi.org/10.1016/J.RSER.2018.04.044

Lynch, K., O'Donoghue, C., & Devoy McAuliffe, F. (2016). *LEANWIND D8.2*.

NOWIcob (Norwegian offshore wind power life cycle cost and benefit) - SINTEF. (n.d.). Retrieved August 31, 2020, from https://www.sintef.no/en/projects/nowicob-norwegian-offshore-wind-power-life-cycle-c/

Open Ocean - Notre actualité - Vindeby (1991-2017): decommission of the world's first offshore wind farm. (n.d.). Retrieved October 27, 2017, from http://www.openocean.fr/fr/news/2017/03/21/vindeby-1991-2017-decommission-of-the-worlds-first-offshore-wind-farm/

Topham, E., & McMillan, D. (2017). Sustainable decommissioning of an offshore wind farm. *Renewable Energy*, *102*, 470–480. https://doi.org/10.1016/J.RENENE.2016.10.066

Vattenfall. (2017.). Vattenfall News: Without a trace. Retrieved January 1, 2017, from
http://news.vattenfall.com/en/article/without-trace

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.