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Cornwall FLOW Accelerator

# FLOW farm model at specific Celtic Sea sites (beta version)

## $E^C$ Simulator Impact Case Study

| Document Title | | FLOW farm model at specific Celtic Sea sites (beta version) | |
|---|---|---|---|
| **Document Reference** | | CFAR-UE-046-30052023 | |
| **Date of Issue** | | 30/05/2023 | |
| **Authors** | | Kinana Youssef, Dr. Barton Chen, Dr. Adam Roberts, Jiaxin Chen, Dr. Chenyu Zhao, Prof. Lars Johanning, Justin Olosunde | |
| **Revision History** | **Date** | **Amended by** | **Reviewed By** |
| First Draft | 25/05/2023 | | Prof. Lars Johanning |
| Second Draft | - | | |
| First Issue | 30/05/2023 | | Prof. Lars Johanning |
| Rev 1 | | | |
| Rev 2 | | | |



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## Contents

# Executive summary

This report introduces the $E^c$ simulator, which is capable of assessing the economics and sustainability of a floating offshore wind farm concept in a holistic fashion. Covering various development phases from design to decommissioning, the $E^c$ simulator streamlines the process of setting up the models and calculations necessary for a concept analysis. This report overviews the core functionality of the modules within the $E^c$ simulator, before demonstrating the outputs it can produce using a baseline case study. This focuses on showing how varying parameters such as site location influence the key performance indicators (i.e., costs, carbon emissions, and energy invested, electricity generation) of a wind farm concept.

# 1 Introduction

Cornwall FLOW Accelerator (CFA) is a collaborative project between research institutes and industry partners. The project aim is to accelerate the development of the floating offshore wind (FLOW) industry in Cornwall and the Celtic Sea by facilitating stakeholder cooperation and providing consultation. The Celtic Sea presents a large opportunity for FLOW projects, having been previously overlooked for fixed offshore deployment due to its water depths. Following the Crown Estate's latest leasing proposal, it now set to provide up to 4GW of new floating offshore wind capacity by 2035. This date is significantly closer than it may seem, as FLOW projects can take between eight and ten years to develop. There is therefore a need for urgent action from local authorities and industry to develop the required manufacturing, logistical, and network infrastructure.

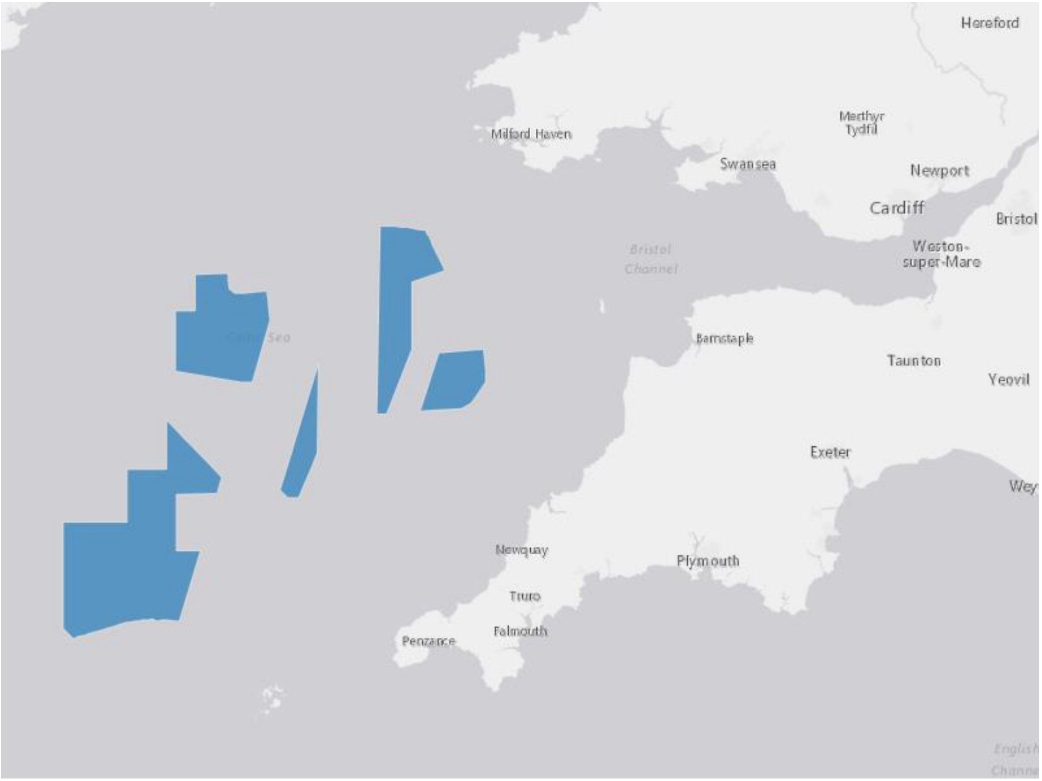


*Figure 1: Celtic Sea Floating Offshore Wind Programme*

As part of the CFA project, the University of Exeter is developing the $E^c$ simulator. This is a web-based tool that can provide a user with key performance indicators (levelised cost of energy, carbon emissions, and energy return on energy invested) for a FLOW farm concept. This is achieved by using numerical models to calculate the design requirements of the farm and simulate the assembly, operation, and decommissioning processes that occur over its lifecycle. The $E^c$ simulator has been designed to enable site developers and key stakeholders to easily obtain estimates of critical farm design parameters, reducing the risk towards economical and sustainable farm design. This will facilitate faster and more robust concept development, ultimately providing assistance with:

- Identifying resource availability and competition;
- Identifying the need for local infrastructure upgrades;
- Identifying the advantages of using local manufacturing, installation, and O&M bases;
- Quantifying the effect of turbine design variations, mooring system innovation, and other technological advances on economics and sustainability;

- Quantifying the impact of installation duration and strategy on sustainability and levelised cost of electricity.

The aim of this report is to introduce the functionality of the beta version of the $E^c$ simulator. This is done by overviewing the $E^c$ simulator and presenting the results of an example case study that was conducted using its modules. The case study explores different scenarios for 1 GW FLOW farm sites in the Celtic Sea, detailing the output of the $E^c$ simulator to provide predictions for investment, development, and operational costs, carbon intensity and carbon dioxide equivalent emission savings, and energy return on investment at various phases of development. The results of the case study scenarios are also compared against a baseline to show how adjusting parameters can influence the feasibility of floating offshore wind farms in the Celtic Sea.

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## 2 The $E^c$ simulator

The $E^c$ simulator is a web-based tool that provides a holistic lifecycle simulation and assessment for floating offshore wind farm (FLOW) projects. The purpose is to assist developers and policy makers investigating the economics and sustainability of FLOW projects in order to accelerate their development. The $E^c$ simulator brings together three numerical models (referred to as modules) and enables a user to interact with them via a graphical user interface, as shown in Figure 2. Data for the $E^c$ simulator (including user defined parameters, constants, and results) is stored within an SQL database, with a data manager handling the transfer of data from the database to the modules according to the requirements of the $E^c$ simulator.

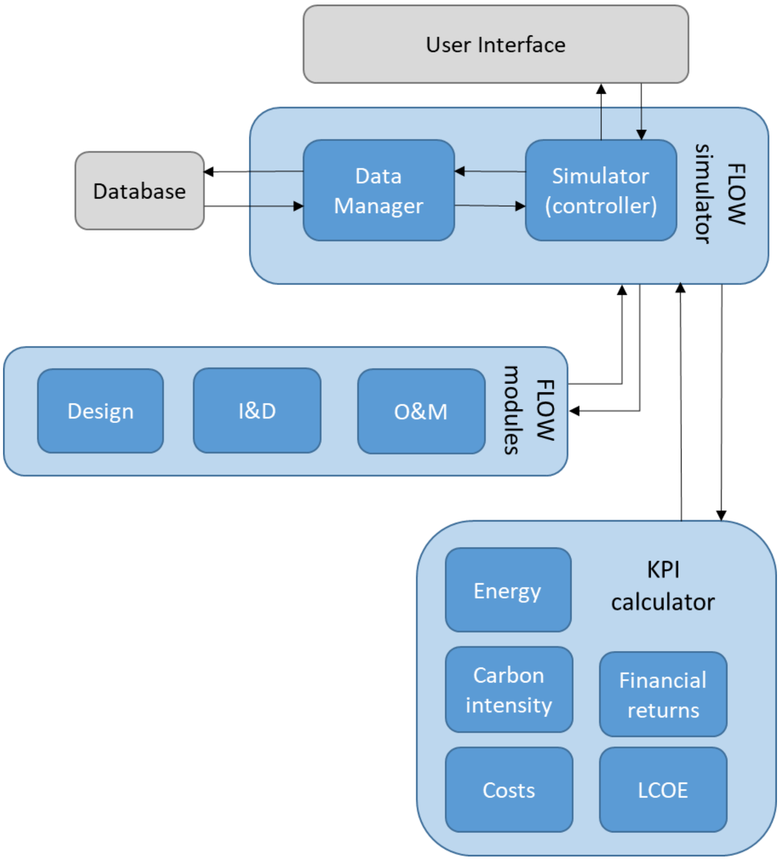


*Figure 2: Diagram overview of the $E^c$ simulator architecture. Note that I&D stands for installation and decommissioning, while O&M stands for operation and maintenance.*

The three modules that comprise the $E^c$ simulator cover:

1. Design (covering layout, mooring and anchor loads, and annual energy production considering local meteorological conditions and wake loss);
2. Installation (predicting the costs, timescales, and utilisation of vessels during the installing and decommissioning a wind farm);
3. Operation and maintenance (predicting the occurrence, costs, and downtime associated with turbine repair and maintenance over the operation lifespan);

In addition to these, the beta version of the $E^c$ simulator also includes a final calculation that uses the model predictions to create Key Performance Indicators (KPIs) summarising the economics and sustainability of the proposed farm. This KPI calculation also considers a user-specified strike price and cost of capital, to produce estimates for the levelised cost of electricity, net present values, and ultimately to quantify what (if any) return on investment would be provided to the developer. The KPI calculation also considers the energy and carbon embodied within the farm itself, as well as that used during installation, maintenance, and decommissioning operations. This enables it to provide estimates of sustainability in terms of carbon intensity and energy return on energy invested. All these components of the $E^c$ simulator are described in more detail in Sections 2.2 to 2.4.

To interact with the $E^c$ simulator, a user must first log in with a username and password. Upon doing so, they will be presented with the $E^c$ simulator home page. A screenshot of this is shown in Figure 3, which highlights the navigation bar at the top of the home screen. This bar is present in every page within the $E^c$ simulator web app and provides links to the relevant pages for creating custom parameters, setting up new simulations, accessing previous simulations for results analysis, accessing an explanatory help page providing an overview of the $E^c$ simulator, as well as logging out.

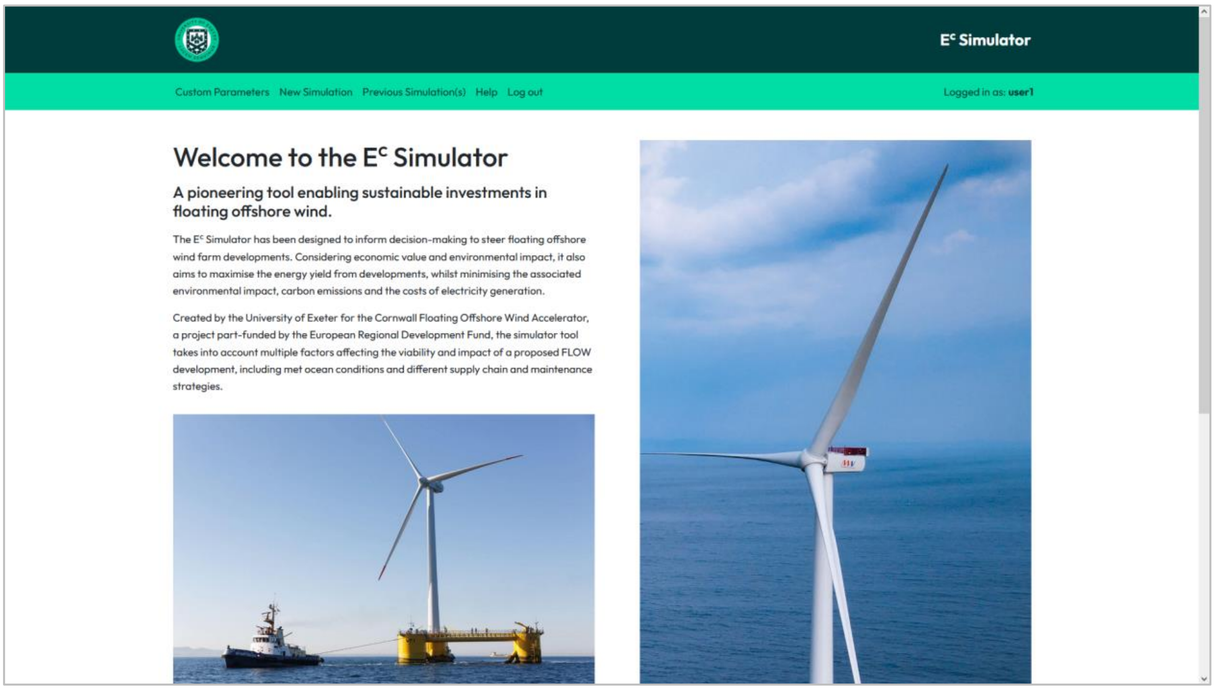


*Figure 3: Screenshot of the $E^c$ simulator homepage.*

A suggested workflow for using the $E^c$ simulator is provided in Figure 4. A user first has the option to define custom parameters for the simulation, such as a new wind farm concept (in terms of its location, power capacity, and turbine spacing) or a specific list of vessels within an installation fleet. A screenshot showing the data entry form for a new wind farm concept is shown in Figure 5.

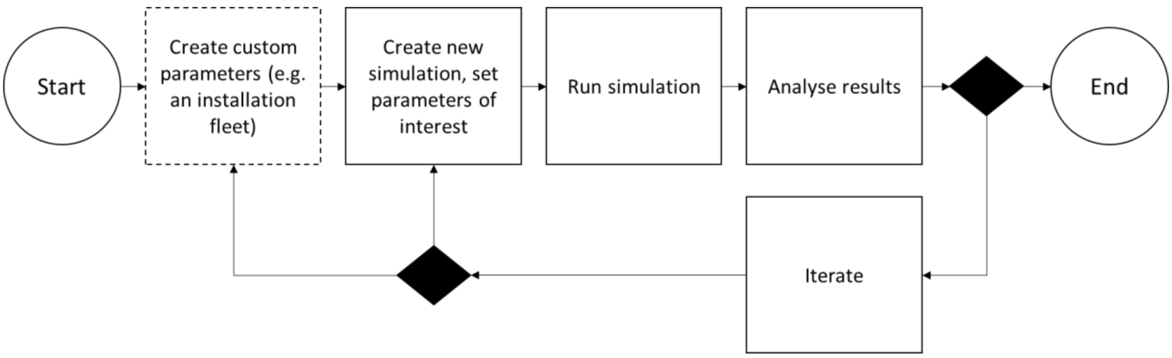


*Figure 4: Suggested workflow for using the $E^c$ simulator. A dashed box indicates an optional step. A black diamond indicates a decision point.*

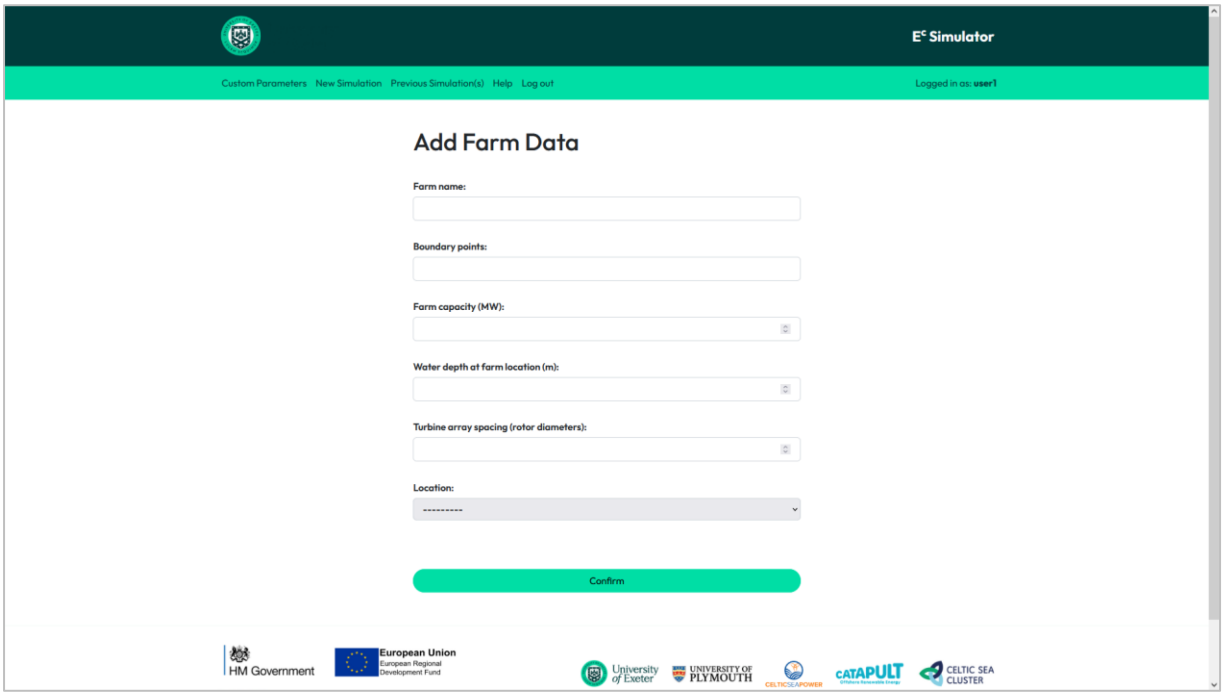


*Figure 5: Page for defining a new wind farm concept; required data includes a unique name, the boundary points of the farm, the power capacity of the farm (in MW), the average water depth at the form site, the turbine spacing (in rotor diameters), and the farm location.*

Regardless of whether custom parameters are defined, the user must then setup the parameters for a new simulation. In this step, the user specifies the required inputs for each of the flow modules. For the design module, this includes: the farm concept to be analysed, the type of wind turbine, floater, mooring, anchor system, and subsea cables to be used, and whether the design module should calculate the number of offshore substations required or whether to use a user specified number. For the installation module, input parameters include the ports and installation fleet to be used during the installation process, the manufacturing capacity (number of parallel production lines) available for producing components such as blades or towers, and the specific tasks (and associated decommissioning tasks) involved in the installation process. For operation and maintenance, parameters include the operation and maintenance port, the number of simulations runs, and whether to optimise the results.

Some general parameters must also be provided, including energy loss coefficients for the cables and substations, as well as the length of the export cable(s) between the farm and land. Once a user has set all the required parameters, they can submit the simulation for analysis. Submission is only permitted when all required parameters have been provided.

Progress can be monitored on the Previous Simulation(s) page of the $E^c$ simulator, which will highlight when a run has finished. Depending on the complexity of the analysis and the parameters used regarding optimisation and the number of operation and maintenance simulation runs, it may take anywhere from several minutes to several hours for an analysis to complete. Once it is complete, a user can see the results of the simulation by clicking the appropriate button on the Previous Simulation(s) page. This brings up the results screen, where the user can view charts summarising the results, tables summarising the output of each module, and key plots from the modules covering things like the available wind resource and farm and cable layout.

Following a review of the results, tabular data can be exported in Excel format for further analysis, and a user can decide whether to amend input parameters and run another simulation. Parameters can be changed relatively easily by amending a previous simulation; this creates a new dataset based on the parameters of the old one, avoiding the need to create a new simulation from scratch just to change one input parameter.

Once a user has run all the analyses they are interested in, they can export data in a Microsoft Excel format for the further study if desired and then log out. Custom parameters and submitted simulations (including their inputs and outputs) will be preserved in the database for the next session.

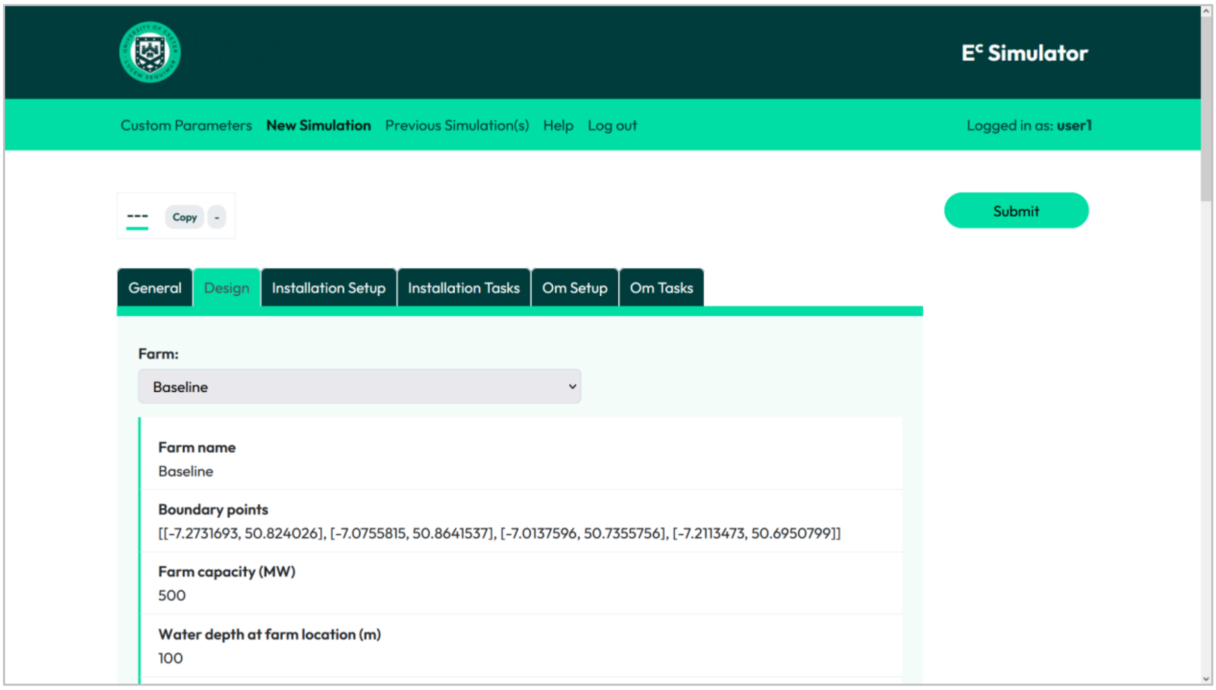


*Figure 6: Setting design parameters during the creation of a new simulation.*

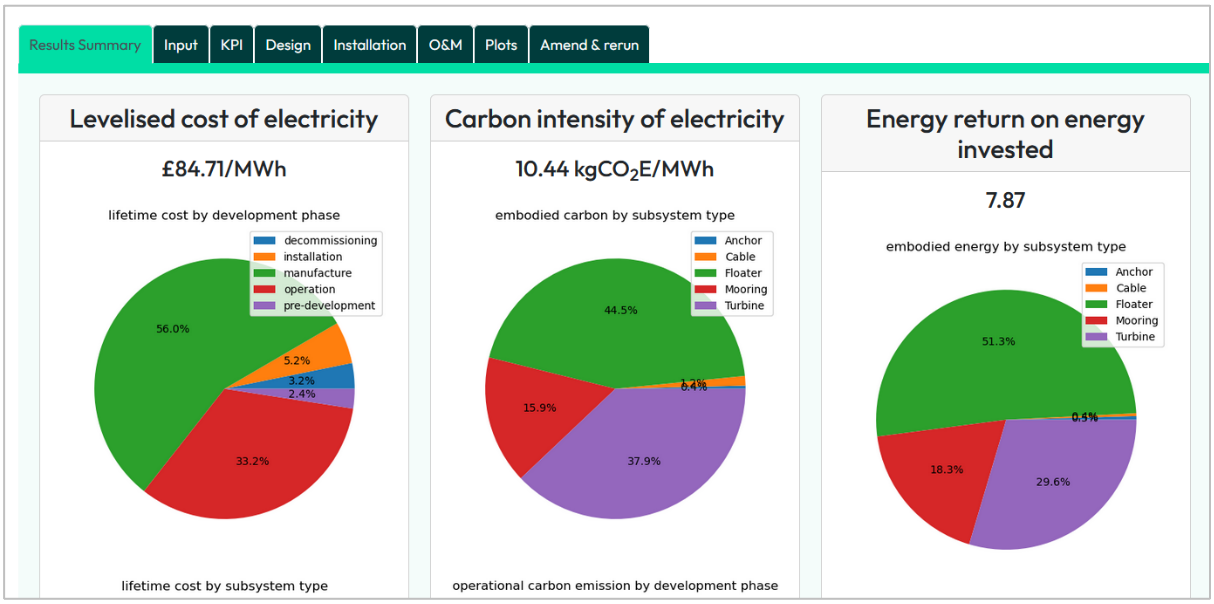


*Figure 7: Summary pie charts showing the levelised cost of electricity, carbon intensity of electricity, and energy return on energy invested for a baseline test case used during simulator verification.*

## 2.1 Design module

The design module configures major elements of a floating offshore wind farm (FOWF) development concept. The output from the design module serves multiple purposes, including providing detailed configurations of major elements in the FOWF concept, estimating capital expenses, predicting energy production, facilitating subsequent life cycle phases such as installation, and operations and maintenance (O&M) scheduling, and serving as a foundation for future design expansions.

The design module consists of two main components: the FOWF layout design and the individual floating offshore wind turbine (FOWT) design. The FOWF layout design encompasses determining the positions of the offshore substation (OSS), the FOWTs, and the routing of inter-array cables. The individual FOWT design, which is based on the designed FOWF layout, focuses on selecting the appropriate floater type and configuring the corresponding moorings and anchors.

The E$^c$ simulator offers users a high level of flexibility when interacting with the design module, allowing them to input specific design requirements while also providing default designs and optimization possibilities. A flowchart summarising the functionality of the design module is shown in Figure 8.

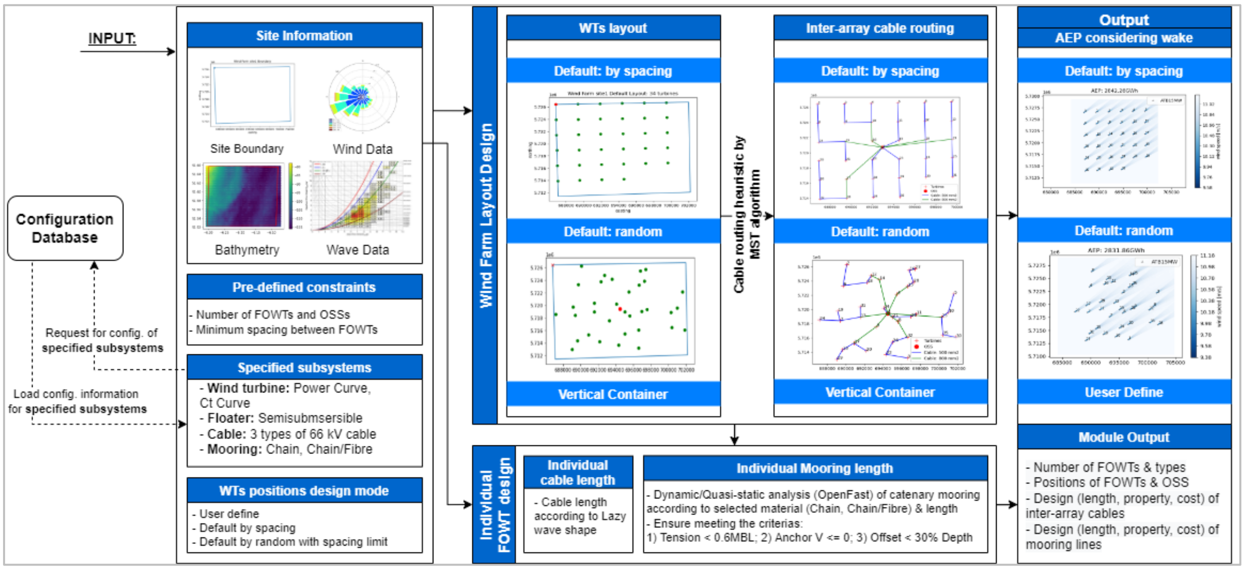


*Figure 8: Flowchart summarising design module functionality.*

As with all numerical models, the design module is based on several assumptions. Key assumptions include:

- The extreme environmental condition for mooring line analysis at each site is determined by generating the 50-year return contour from 11 years of historic ERA-5 data using the inverse FORM method (Winterstein, et al., 1993).
- Each electrical substation can support up to a maximum capacity of 500 MW and 10 feeder cables, with a number recommended based on this assumption that can be optionally overridden.
- Turbines are subdivided into groups based on the number of substations using the KMeans clustering Lloyd's algorithm (Lloyd, 1982), with each group connected to one substation that is positioned at the centre of the turbine group.

- Cable routing is determined using the minimum spanning tree algorithm (Esau & Williams, 1966).
- The mooring design and strength check follows the guidelines outlined in DNV-OS-E301 (DNV, 2008) and is based on steel catenary mooring theory using the quasi-static method in the MAP++ Python package, with turbine motion under obtained according to meteorological data via OpenFAST analysis package (NREL, 2023). Wind and wave conditions are applied in the same direction, which is assumed to represent the most unfavourable scenario for a single mooring line.
- The inclusion of the Exeter tether in the mooring system is assumed to reduce extreme loads by 15% without impacting the system stiffness.
- Farm sites are currently assumed to be rectangular in shape.

The design module requires specific inputs to define and calculate the necessary parameters for a FOWF concept. Module inputs include the subsystem parameters defined in Table 1, as well as:

- Target wind farm capacity (in MW)
- Site boundary: specified by four corner coordinates.
- Site-specific meteorological data, including wind speed (m/s at 10-m height, can be transfer to hub height speed in module), wind direction (°), significant wave height (m), peak wave period (s), mean wave direction (°), surface current speed (m/s), and surface current direction (°).
- Bathymetry: water depth within boundary (one value or high-resolution data if possible); seabed property if available.
- Number of offshore substations (user specified or auto generated according to farm capacity and turbine type).
- Minimum spacing between FOWTs (in rotor diameters, set to 8 as default)

*Table 1: Subsystems input parameters*

| *Subsystem* | *Input name* | *Parameter (unit)* |
|---|---|---|
| *Wind turbine:* | Power capacity | (MW) |
| | Power curve | Wind speed (m/s), Power (MW) |
| | Power coefficient curve | Wind speed (m/s) |
| | Rotor diameter | (m) |
| | Rotor hub height | (m) |
| *Floater:* | Type | Semisubmersible (UMaine VolturnUS-S) default |
| | Platform mass | (tonnes) |
| *Cable:* | Power capacity | (MW) |
| | Cross-section area | ($mm^2$) |
| | Unit cost | (£/m) |
| *Mooring:* | Property database | Chain, Exeter tether |
| | Anchor point | (m) |
| | Line length | (m) |
| | Number of moorings per turbine | No. |
| | Diameter | (m) |
| | Mass density in air | (kg/m) |
| | Axil stiffness EA | (N) |
| | Cable/seabed friction coefficient | ($C_b$) |

Following analysis, the design module returns:

- The number of FOWTs, as well as their positions within the farm;
- The positions of the offshore electrical substations within the farm;

- Key parameters (including the number, capacity, layout, and capital cost) of the inter-array electrical cables connecting the turbines to the substations.
- Key parameters (configurations, size, and capital cost) of the mooring and anchoring system, both with and without the Exeter tether.

## 2.2 Installation & decommissioning module

The installation & decommissioning module simulates the upstream and midstream logistics of a floating offshore wind farm using a discrete event method. Discrete event simulations are widely used in logistics and manufacturing for assessing processes and equipment utilisation. It involves decomposing real world systems into a series of separate time-dependant events, which for FLOW enables it to model the chain of process steps in manufacturing, storing, assembling, transporting, and installing the FLOW farm elements. The installation module specifically uses a Petri Net model. As shown in Figure 9, the Petri Net model for an installation task can consider whether all the conditions for a task to start are met, the time delay that arises from carrying out a specific process, and the influence of weather and resource availability on task completion.

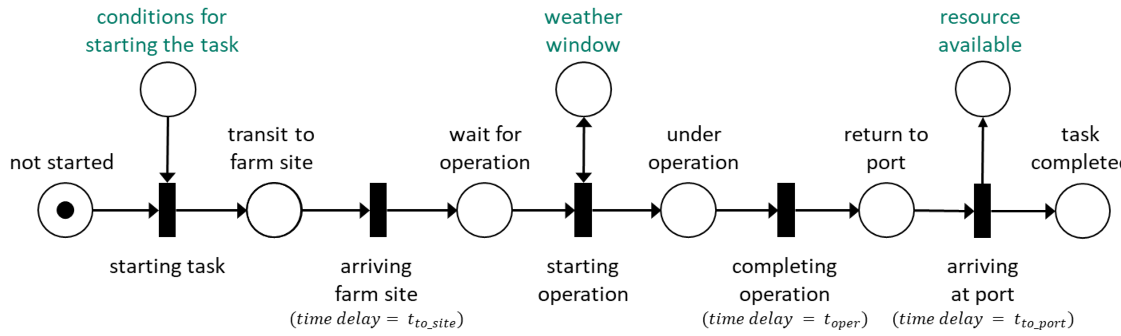


*Figure 9: A Petri-net model for installation task.*

The installation module is broken into three main steps: input data preparation, simulation processes, and output calculations. The input data has three types of data: technology-dependent, project-dependent, and location dependent as outlined in Figure 10.

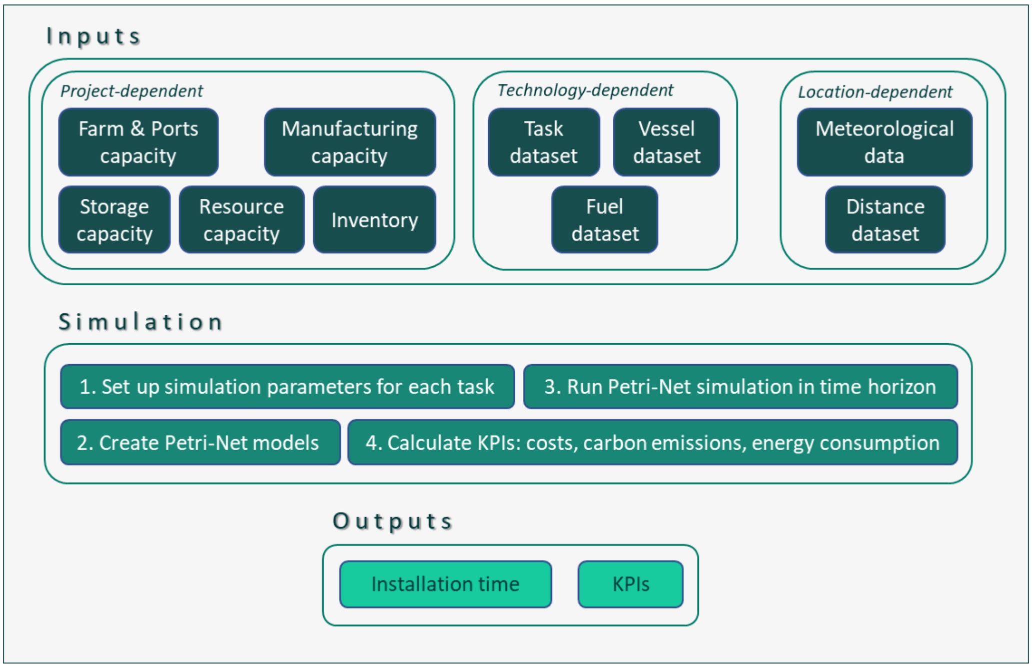

*Figure 10: Installation module categorised parameters, inputs, simulation, and outputs.*

Project-dependent inputs are parameters related to the development plan of the FLOW farm. These include:

- Farm power capacity;
- Ports used during upstream and midstream operations e.g., staging and logistics ports;
- Storage capacities (wet or dry storage);
- Resource capacities of the installation fleet and other heavy-duty equipment such as cranes and/or lorries;
- Manufacturing capacities for farm components such as towers, floating platforms, and blades;
- The make-up of the project inventory over time (i.e., the quantity of blades, cables, etc. available at any given moment).

Technology-dependent inputs focus on the selected technology for the design and construction of the floating wind farm, including parameters such as:

- Installation task details and number;
- The duration of the installation process;
- The resources, vessels and fuel required to execute each task;

Location-dependent inputs relate to the location of the FLOW farm and installation ports. These feed into identification of the distances (and therefore travel times) between the locations used in the simulation and identifying the corresponding meteorological data at farm and port.

The simulation processes section comprises of four main procedures:

1. The parameters of each task defined are set up based on the input datasets. For example, transit time for a particular task is calculated based on the distances between locations and the speeds of the required vessels.
2. Three types of Petri Net model are created: task, resource, and inventory. To link the Petri-Net models with time-series data, synthetic places are created to represent the status of a weather window for tasks. The number of tokens in the place is synchronised with the value of a time-series data. The transitions in different models can be synchronised to simulate the corresponding action.
3. The Petri-Net simulation is run in a time stepping fashion (e.g., every hour). At each time step, the token number in synthetic places is updated first, and then all transitions are checked. Any enabled transition is fired based on the order of creation. The simulation advances in time once all transitions are checked, and will end successfully if all tasks are completed, or terminate if the simulation time is out of the range of time-series data.
4. The main parameters for the KPI module (i.e., costs, carbon emissions, and energy consumption) are derived from the results and summarised. Summarised cost includes vessel and equipment usage costs, fuel costs, and usage fees for ports. Carbon emissions and energy consumption are based on the energy use (e.g., fuels for vessels and cranes) of each task.

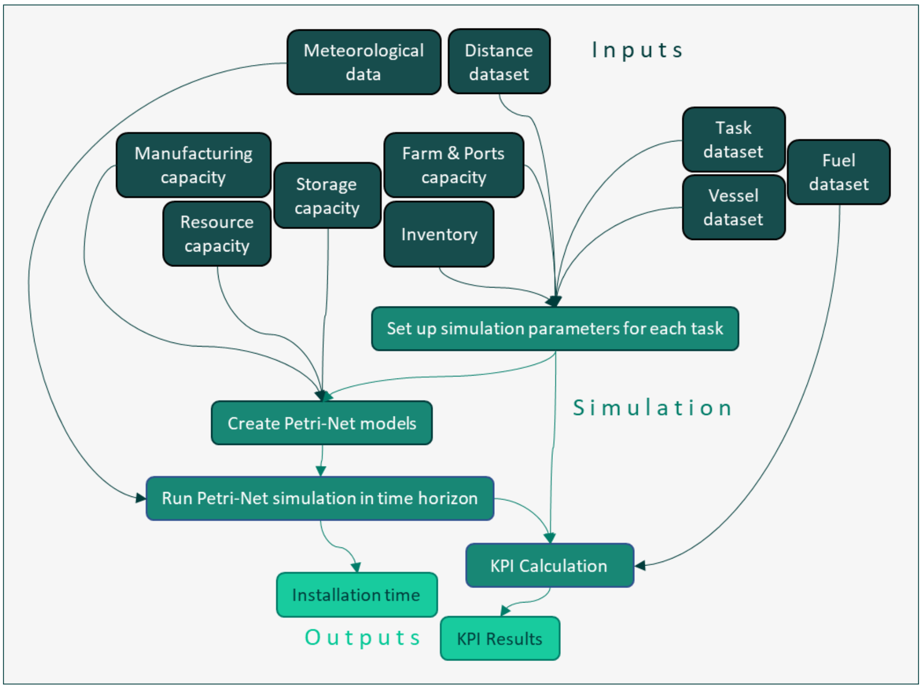


*Figure 11: Structure of the Installation module.*

### 2.2.1 Module inputs

The installation and decommissioning model inputs can be categorised into the following sub systems:

*Farms and ports*

Farm data is a global input to the $E^c$ simulator. It includes factors such as power capacity and turbine spacing, which in conjunction with the rated power and diameter of the selected turbine design ultimately dictates the number of turbines and substations to be installed in the farm, and the subsequent number of installation tasks and components.

Port data specifies the name and location of a port, along with its allocated purpose (e.g., whether it is the main staging port or used in upstream manufacturing logistics). The installation module has several activity ports set in the database that the user can specify.

*Manufacturing capacity*

This capacity input is specific to the installation module (manufacturing). It represents the number of available production lines available at any given time to produce specific components. This capacity is an integer (a whole number) and cannot be less than 1. A component manufacturing task will require a certain capacity for the duration of time required to produce it. For example, producing 20 wind turbine towers per year with a tower_capacity =1 would need a production time of 18.25 days. If tower manufacturing time is known to take longer than 18.25 days, then a greater number of production lines would be required to achieve the desired yearly output.

*Resource capacity*

The resource capacity comprises any marine vessels, cranes, or even land transport to be used by a given task. The capacity can be set by the user and must exceed the number of vessels used for one task, e.g., if "transport floater" uses 2 tugs, the tug resource capacity must be 2 or higher. The required resource must also match a corresponding entry in the database vessel table, to ensure that the required parameters (such as hiring costs and speed) are available. Users can add custom vessels to the vessels' database if they desire as shown in Table 4.

### *Storage capacity*

A storage capacity represents the available storage space for keeping components in inventory during the installation process. It is defined in terms of $m^2$ of available area for the farm installation activities and should have a corresponding storage cost defined in £/$m^2$.day.

### *Inventory inputs and outputs*

Inventory usage is a task feature that can be defined when generating a given task. Every task has a resource_stock cell (taking stock out of the inventory, i.e., inputting it into the task) and a resource_product cell (putting a finished product into the inventory, i.e., the output of the task). Examples are shown in Table 2.

*Table 2: Inventory inputs*

| *Input name* | *Description (example)* |
|---|---|
| *Resource product:* | Defined in each task that require control of produced components, e.g., a tower manufacturing task will produce 1 tower. |
| *Resource stock:* | This takes stock out of inventory, e.g., assembly of the WTG takes 1 tower, 1 floater, 1 nacelle, and 3 blades. |

### *Task dataset*

The task dataset summarises the general parameters of a given task. These parameters are summarised in Table 3.

*Table 3: Tasks inputs parameters*

| *$E^c$ simulator name* | *Translation* | *Input Description (unit)* |
|---|---|---|
| *task_name* | Task Name | Input by user |
| *no_unit_group* | Task multiplier | Number of units per group (integer) |
| *operation_time* | Operation time | Duration of task (day) |
| *operation_length* | Operation length | Export cable laying (km) |
| *op_time_factor* | Factor reduction of vessel operation time | 1 or less (not 0) |
| *port_time* | Loading/unloading time at port | Loading/unloading (day) |
| *precedence_task* | Precedence task to be finish ahead of task | Task name |
| *departure_location* | Departure location | Port activity name |
| *destination_location* | Destination location | Port activity name or farm site |
| *resource_vessel* | Resource vessel required for the task | Name & No. vessels |
| *resource_manufacturing* | Resource manufacturing | Name & no. of lines |
| *resource_stock* | Inventory – stock out | As per inventory |
| *resource_product* | Inventory – stock in | As per inventory |
| *operation_limit* | Wind & wave limits and other time limits | Wind (m/s), wave (m), time limit name |
| *storage_in* | From manufacturing or deliveries | Name & area of storage used per task |
| *storage_out* | Using components in assembly tasks | Name & area of storage released by task |

### *Vessel dataset*

The vessel dataset is a list of vessel parameters that is taken directly from the database, and contains parameters such as vessel cost, fuel usage, and speed. It is used by the installation module to calculate how long a vessel will take to complete a specified task. Table 4 shows an example of the parameters that populate this dataset.

*Table 4: Example of vessel parameters used by the installation module.*

| *name* | *transit speed* | *installation rate* | *mobilisation cost* | *demobilisation cost* | *day rate* | *fuel* | *fc rate transit* | *fc rate operation* |
|---|---|---|---|---|---|---|---|---|
| Units: | (knot) | (m/day) | (£) | (£) | (£/day) | - | (l/km) | (l/h) |
| *HLV* | 12.5 | - | 27,000 | - | 150,000 | MGO | 48.7 | 376 |
| *AHTS DP2* | 10 | - | 250,000 | 125,000 | 25,000 | MGO | 56.5 | 262 |
| *tug* | 3 | - | - | - | 18,125 | MGO | 50 | 69 |
| *crane vessel* | 9 | - | - | - | 36,250 | MGO | 100 | 3,309 |
| *export cable laying* | 7 | 2,000 | - | - | 90,625 | MGO | 38.6 | 167 |

### Fuel dataset

As with vessels, fuel parameters are taken directly from the database. Fuel parameters include the energy density and carbon intensity values for different fuels, enabling operations emissions and energy usage to be predicted. Table 5 summarises these parameters.

*Table 5: Fuel parameters*

| *name* | fuel type | CO2 emission factor | fuel density | energy density | fuel price |
|---|---|---|---|---|---|
| | - | (kg_(CO2_eq )/litre) | (kg/litre) | (MJ/litre) | (£/litre) |
| *diesel* | diesel | 2.546 | 0.85 | 36.0 | 1.00 |
| *MGO* | marine gas oil | 3.206 | - | 42.7 | 0.65 |
| *low carbon fuel* | low carbon fuel | 1.273 | - | 36.0 | 1.50 |

### Meteorological data

Meteorological data is a global input used across all modules of the $E^c$ simulator. The data used cover each farm site for 11 years, Jan. 2010 - Dec. 2020, with a 1-hour period recording wind speed (m/s) and wave height (m).

### Distance dataset

The distance dataset is used in the transit part of the installation task. The database contains a list of oceanic travel distances between all the named locations that can be selected. Upon running an installation task that involves travel from one point to another, the installation module refers to this list to get the travel distance (in km).

### Decommissioning

Decommissioning represents an extension of the installation module. These calculations are simplified by associating a decommissioning task with the corresponding installation task (e.g., the deactivation of a wind turbine at the end of its life would be associated with the activation of the wind turbine at the beginning of its life or commissioning task). Costs and energy consumption are approximated from the installation task by using cost factors, as shown in Table 6.

*Table 6: Decommissioning task parameters.*

| *decom task* | cost factor | energy consumption factor | fuel |
|---|---|---|---|
| *turn WTG off* | 0.2 | 0.2 | low carbon fuel |
| *remove inter-array cable* | 0.2 | 0.2 | low carbon fuel |
| *transport WTG from site* | 0.9 | 0.9 | low carbon fuel |
| *disassemble WTG* | 0.9 | 0.9 | low carbon fuel |
| *remove anchor* | 0.5 | 0.5 | low carbon fuel |

### 2.2.2 Module assumptions

- Current definitions of ports, manufacturing capacity, and available storage area assume ports will be upgraded to meet requirements;
- Installation tasks consider the weather conditions at offshore sites and at port, meaning meteorological data should be provided by the user if implementing new ports;
- Multiple vessels can be assigned to each task and the weather limits are also entered for each task, therefore if two vessels have different operation limits, the lowest should be applied to both vessels. Otherwise, the task should be split in two tasks, one for each vessel with its relevant operating limits.
- Weather limits are currently based on expert advice and some known limits for installation tasks but are likely to change depending on task specifics.
- Weather waiting time is defined based on whether a vessel is available but weather-related task inhibitors (such as wind speed being greater than wind limit) or other time series restrictions exist. An example of weather waiting time is show in the appendix in Figure 30 and Figure 31.
- The cost and energy consumption factors for decommissioning tasks have been estimated based on expert advice and are subject to change.
- Vessels used for decommissioning are assumed identical to the vessels used in installation, except for fuel type used. The change of fuel type – from marine gas oil to low carbon fuel, arises from the assumption that net zero targets will result in vessels using low carbon fuels by the end of a new offshore wind farm with a 25-year service life.

## 2.3 Operations and maintenance (O&M) module

The O&M module aims to identify the high-level production drivers and deliver important early insights, particularly into yield (and thus revenue), availability and reliability of the farm. As a widely used methodology for the simulation of O&M problems, Markov Chain Monte Carlo is applied in the O&M module. This method can effectively consider all the necessary aspects that define the dynamic factors of a FLOW farm, such as environmental conditions, logistics, spare parts, and maintenance vessels. This approach also supplies insight and flexibility essential to capture the nuances of operational activities and has been successfully deployed/validated by a wide range of academic and industrial projects.

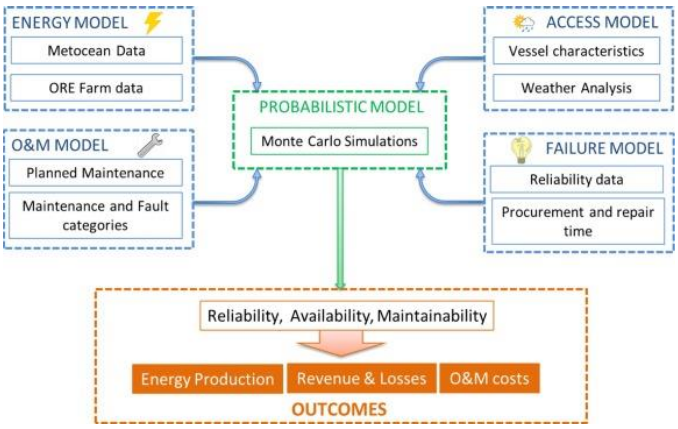


*Figure 12: The workflow of the O&M module*

The workflow of the O&M module is illustrated in Figure 12. Several inputs, such as O&M task information, vessel information, wind turbine components information, weather data, and industrial limitations, are required. These are defined in the E$^c$ simulator database and are passed to the O&M module when it is called. Examples of these parameters are summarised in Table 7, Table 8, and Table 9.

*Table 7: O&M vessels. *The numbers shown here are calculated under a 91km O&M port distance. The values are scaled linearly when the O&M port distances change.*

| *Name of the vessel* | *CTV* | *SOV* | *TOW +HLV* | *HLV* | *TOW+AHV* | *TOW+CLV* |
|---|---|---|---|---|---|---|
| *Identification number of the vessel* | 1 | 2 | 3 | 4 | 5 | 6 |
| *Vessel speed (km/h)* | 42 | 23 | 5.5 | 22.7 | 5.5 | 5.5 |
| *Fleet* | 100 | 100 | 100 | 100 | 100 | 100 |
| *Day rate (£)* | 3500 | 26000 | 200000 | 150000 | 120000 | 190000 |
| *Mobilisation cost (£)* | 17000 | 130000 | 750000 | 750000 | 105000 | 750000 |
| *Mobilisation time (hour)* | 6 | 24 | 24 | 24 | 24 | 24 |
| *Transit fuel cost (£)* | 510 | 2550 | 15000 | 10000 | 10200 | 15300 |
| *Transit fuel burn (litres)** | 500 | 2833 | 12000 | 11333 | 10200 | 15000 |
| *Operation fuel burn (litres/hour)* | 304 | 392 | 1300 | 1200 | 1941 | 1300 |
| *Wave limitations (m)* | 1.75 | 5 | 5 | 5 | 5 | 5 |
| *Wind limitations (m/s)* | 21 | 21 | 8 | 8 | 21 | 21 |

*Table 8: O&M tasks*

| *O&M tasks* | *Floating platform repair* | *Mooring minor repair* | *Mooring major repair* | *Power cable minor repair* | *Power cable major repair* | *Turbine minor 1* | *Turbine minor 2* | *Turbine major 1* | *Turbine major 2* |
|---|---|---|---|---|---|---|---|---|---|
| *Subsystem* | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 4 | 4 |
| *Repair time* | 12 | 12 | 24 | 12 | 24 | 12 | 24 | 24 | 48 |
| *Annual Failure rate* | 0.5 | 0.167 | 0.167 | 0.3 | 0.3 | 1.17 | 0.167 | 0.167 | 0.167 |
| *Vessel Selection* | CTV | SOV | TOW+AHV | SOV | TOW+CLV | CTV | SOV | TOW+HLV | TOW+HLV |
| *Cost Replacement (£)* | 128,253 | 9,638 | 568,000 | 597,396 | 5,723,161 | 5000 | 10000 | 50000 | 100000 |

*Table 9: General Meteorological data information*

| *Scenarios* | *Considered time length (Year)* | *Time step (hour)* | *Average significant wave height (m)* | *Average Peak period (s)* | *Average wind speed at 10m(m/s)* |
|---|---|---|---|---|---|
| *Site 1* | 11 | 6 | 1.88 | 8.82 | 8.17 |
| *Site 2* | 11 | 6 | 1.96 | 10.31 | 7.18 |
| *Site 3* | 11 | 6 | 2.48 | 10.40 | 8.20 |

Once the simulations are completed, a series of results describing the farm performance (i.e., data for KPIs) are obtained. These include energy production accounting for maintenance downtime, availability, revenue, and overall O&M costs. More detailed information lists the number of failures per component or the hours of operation of each vessel. The results contain the full statistical distribution of each parameter, including mean value, standard deviations, and confidence bounds. These results permit the identification of underlying problems in the operation of the FLOW farm and, if needed, the proposal of corrective measures. This model supports the decision-making process required for successfully managing a project. Lastly, statistical indicators, such as exceedance probabilities and progressive average values over the simulations, can be analysed to evaluate the confidence level in the results obtained.

The main assumptions of the O&M module are:

- Each O&M task covers a single wind turbine: this assumption simplifies the module by maintaining a one-to-one relationship between tasks and turbines. It eliminates the complexity of concurrent tasks on multiple turbines.
- Each turbine can only have a single failure: this implies that there cannot be multiple concurrent failures in the same turbine. Further, a failure cannot occur in a turbine already in downtime.
- Failure rates and cost are derived from those of a 15MW turbines, which are detailed in Table 8. For a 12MW turbine case, the failure rates are assumed to be higher, while the repair costs are lower. Specifically, the failure rate is 1.2 times higher, and the repair cost is 0.8 times lower. This is based on internal discussions and with subject matter experts.
- For cases that do not require towing to port, the TOW+HLV vessel will be replaced by the HLV. The cost of related O&M tasks (Turbine major repair 1 & 2) will be 1.5 times higher than that of the towing to port cases.

## 2.4 Key performance indicator module

The key performance indicator ($KPI$) module of the lifecycle assessment simulator calculates three main indicators: the levelised cost of energy or ($LCOE$), carbon intensity, and energy returned on energy invested ($ERoEI$). These indicators provide valuable insights into the economic and environmental aspects of the floating offshore wind farm project.

### 2.4.1 Levelised Cost of Energy ($LCOE$)

The $LCOE$ is a comprehensive metric that considers the lifetime costs of a floating offshore wind farm, these include the pre-development, manufacturing, installation, operation, and decommissioning phases. The pre-development phase accounts for the costs associated with the consenting application process and site surveys. Manufacturing costs encompasses various elements such as turbine cost, cables, and mooring systems. Installation costs include the expenses related to each installation task, fuel costs, daily vessels rates, and storage costs at the port. Operation phase covers the cost of the O&M fleet minor and major repairs, and insurance expenses. Finally, the decommissioning cost is calculated from the decommissioning tasks as a percentage factor of the installation task cost.

The LCOE equation considers the total capital and operational expenditures over the project's lifetime, over the discounted sum of energy generated during each phase.

$$LCOE = \frac{\sum_n \frac{total\ capex\ and\ opex_n}{(1 + discount\ rate)^n}}{\sum_n \frac{energy\ generation_n}{(1 + discount\ rate)^n}}$$

$Where: n = time\ period$

Calculations for levelised cost of energy require robust assumptions for factors such as the cost of capital or discount rate, particularly for renewable energy projects as capital costs can vary dramatically depending on location and technology (Steffen, 2020). The cost of capital is commonly taken to mean "the expected rate of return that market participants require in order to attract funds to a particular investment". It is important to stress that the cost of capital is the return on investment expected by those providing the capital, i.e., banks and private investors, and is therefore not the rate of return that will be obtained by the project developers. This means it is a forward-looking measure comprising the time-value of money and a risk premium and is equivalent to the discount rate as used in investment appraisals. The project rate of return is instead dependent on the project cash flows and the money (if any) remaining after paying off all costs (including the costs of capital).

Several different equations can be used to calculate the cost of capital, depending on the investment structure used to fund the project (Steffen, 2020). For investments using more than one type of capital (such as combination of equity and debt), the overall cost of capital is a combination of the returns of the different components. The simplest formulation of this is the weighted average cost of capital (WACC), which is often known as "vanilla WACC":

$$WACC_{vanilla} = \delta C_d + (1 - \delta) C_e$$

Where $\delta$ is the debt share (as a percentage), $C_d$ is the cost of debt (as a percentage), and $C_e$ is the cost of equity (as a percentage).

In most nations, interest payments are tax-deductible expenses, meaning debt comes with tax benefits. This can be accounted for by using after-tax WACC:

$$WACC_{after-tax} = \delta(1-\tau)C_d + (1-\delta)C_e$$

Where $\tau$ is the corporation tax rate. It may also be preferable to calculate pre-tax WACC in some scenarios:

$$WACC_{pre-tax} = \delta C_d + \frac{(1-\delta)}{(1-\tau)}C_e$$

Where $1 / ((1-\tau))$ is commonly referred to as the tax wedge on the cost of equity. Since the debt share of a project varies over time and given the advantage of tax-deductible interest payments in project finances, after-tax WACC is generally recommended for calculating the cost of capital If the tax rate is known and constant in time, it is possible to convert after-tax WACC into pre-tax WACC.

Lastly, although WACC is commonly expressed in nominal terms, it is also possible to account for the effects of an expected inflation rate ($w$):

$$1 + WACC_{nominal} = (1 + WACC_{real})(1 + w)$$

Under the general settings page of the $E^c$ simulator, a user can set the discount rate used in KPI analysis by choosing between vanilla, pre-tax, or after-tax weighted average cost of capital equations and entering the appropriate equation parameters. A strike price for electricity can also be entered to facilitate return on investment and cashflow calculations.

### 2.4.2 Carbon intensity

The carbon intensity indicator evaluates the environmental impact of the floating offshore wind farm in terms of carbon emissions. Similarly to the $LCOE$, the calculation considers the carbon emissions during each development phase.

$$carbon\ intensity = \frac{\sum C_{pd} + C_c + C_{op} + C_d}{\sum E_g}$$

Where $C_{pd}$ is the carbon emissions during the predevelopment phase, $C_c$ is the carbon emissions during construction, $C_{op}$ is the carbon emissions during the operation phase, $C_d$ is the carbon emissions during the decommissioning phase, and $E_g$ is the energy production. The typical unit of carbon intensity for electricity generation is $kg_{CO2eq.}/MWh-ele$.

Carbon emissions are categorised into direct and indirect activities. Direct emissions arise from fuel consumption during various development phases, such as crane usage during assembly tasks and vessel fuel consumption during operations and/or transit. Indirect emissions, known as embodied carbon, are typically provided by the suppliers or manufacturers for each component such as blades, rotor hub, floater, and mooring system.

### 2.4.3 Energy Return on Energy Investment ($ERoEI$)

The $ERoEI$ indicator measures the energy return on the energy invested throughout the entire lifecycle of the floating offshore wind farm. It calculates the ratio of total energy produced to the total energy consumed during all development phases.

$$ERoEI = \frac{\sum E_g}{\sum E_{pd} + E_c + E_{op} + E_d}$$

Where $E_g$ is the energy produced, $E_{pd}$ is the energy consumption during the predevelopment phase, $E_c$ is the energy consumption during construction, $E_{op}$ is the energy consumption during the operation phase and $E_d$ is the energy consumption during the decommissioning phase.

By assessing the energy inputs and outputs, the $ERoEI$ provides insight into the project's energy efficiency and sustainability. A higher $ERoEI$ indicates a more favourable energy return relative to the energy invested, highlighting the overall viability of the project.

These key performance indicators, through the $KPI$ module's output, offer a comprehensive assessment of the floating offshore wind farm project's economic feasibility, environmental impact, and energy efficiency. The results obtained through the lifecycle assessment simulator will aid in decision making processes and inform future development and optimisation strategies.

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# 3 Case study

This case study uses the modules to explore different scenarios for 1 GW FLOW farm sites in the Celtic Sea. The aim is to showcase the predictions that can be provided for investment, development, and operational costs, carbon intensity and carbon dioxide equivalent emission savings, and energy return on investment at various phases of development. The modules were run separately to the $E^c$ simulator to provide adequate data for testing and verification. Results for CFA-B-001 (a baseline 1 GW farm at CFA Site 1 with 15 MW turbines) are compared against the output provided by the $E^c$ simulator for the same case in Section 3.2.5.

## 3.1 Case study settings

### 3.1.1 Farm locations

Three wind farm sites were chosen at the start of the project in 2021 based on considerations and development zones agreed with CFA project partners. Longitude and latitude coordinates for these sites are provided in Table 10, while the general location of the sites within the Celtic Sea is shown in Figure 13.

*Table 10: Longitude and latitude coordinates for the corner points of the 3 CFA sites.*

| *Parameter* | *Unit* | *Site 1* | *Site 2* | *Site 3* |
|---|---|---|---|---|
| *Power Capacity* | MW | 1000 | 1000 | 2000 |
| *Corner 1* | Longitude | 51.6577176° N | 50.6116960° N | 49.8240260° N |
| | Latitude | 6.2989939° W | 5.8725554° W | 7.2731693° W |
| *Corner 2* | Longitude | 51.6557592° N | 50.6579970° N | 49.8641537° N |
| | Latitude | 6.0799149° W | 5.6762446° W | 7.0755815° W |
| *Corner 3* | Longitude | 51.5235705° N | 50.5327542° N | 49.7355756° N |
| | Latitude | 6.0855971° W | 5.6012716° W | 7.0137596° W |
| *Corner 4* | Longitude | 51.5227848° N | 50.4875852° N | 49.6950799° N |
| | Latitude | 6.3027820° W | 5.7956095° W | 7.2113473° W |

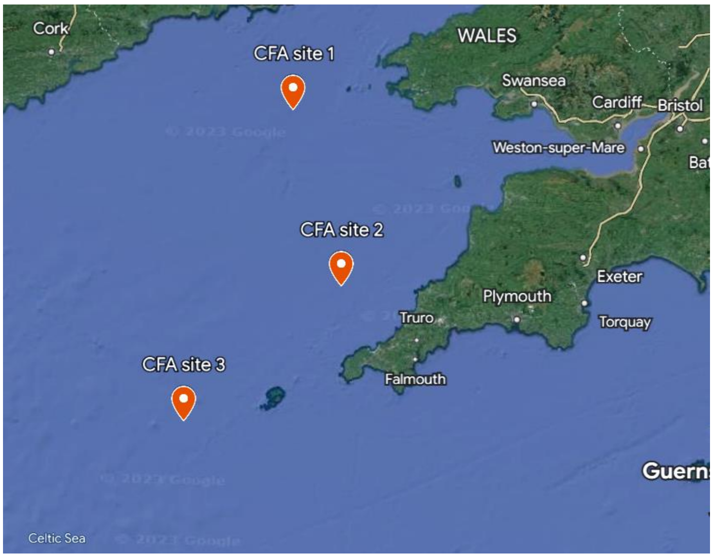


*Figure 13: General location of the 3 CFA sites within the Celtic Sea.*

It should be noted that following the site selection during this project, the Crown Estate refined the areas of development within the Celtic Sea and released the Bilateral Engagement Sub Areas (The Crown Estate, 2023). As a result, the three selected sites are now located outside of the current development areas but have been kept here for the purposes of demonstrating the $E^c$ simulator.

### 3.1.2 Wind turbines

Two different wind turbines have been defined within the $E^c$ simulator for the case study: the IEA 15MW and NREL 12MW turbine. Turbine size has been limited to 15MW at present to ensure sufficient data and the use of validated models and assumptions within the design, installation, and O&M modules. Designs for 17MW and 20MW turbines are available but will increase the number of required modelling assumptions and thus increase uncertainty within the results. The parameters of these wind turbines used are summarised in with the power curves used taken from the specified references. Cost and carbon references for these turbines, as well as the floating platforms, mooring lines, and anchors, were provided by OREC.

*Table 11: Summary of wind turbine parameters. Data sourced from NREL (2020a) for the IEA 15 MW RWT and from NREL (2020b) for the NREL 2020 ATB Reference 12.*

| Parameter | Unit | IEA 15 MW RWT | NREL 2020 ATB Reference 12 |
|---|---|---|---|
| Rated power | MW | 15.0 | 12.0 |
| Rated wind speed | m/s | 10.6 | 11.0 |
| Cut-in wind speed | m/s | 3.0 | 4.0 |
| Cut-out wind speed | m/s | 25 | 25 |
| Rotor diameter | m | 240 | 214 |
| Hub height | m | 150 | 136 |

### 3.1.3 Floating platform

The semi-submersible UMaine VolturnUS-S platform developed for the IEA 15MW wind turbine (Allen, et al., 2020) was used in the case study. The parameters of this platform are summarised in Table 12 and a rendered image is provided in Figure 14.

*Table 12: Summary of parameters for the semi-submersible UMaine VolturnUS-S floating platform. Note that system excursion describes the volume encompassed by the complete structure, and that total system mass and tower mass account for the mass of an IEA 15 MW RWT turbine.*

| *Parameter* | *Unit* | *IEA 15 MW RWT* |
|---|---|---|
| *Turbine rating* | MW | 15.0 |
| *Hub height* | m | 150 |
| *Excursion (L x W x H)* | m | 90.1 x 102.1 x 290.0 |
| *Platform type* | - | Semi-submersible |
| *Freeboard* | m | 15 |
| *Draft* | m | 20 |
| *Total system mass* | t | 20,093 |
| *Platform mass* | t | 17,839 |
| *Tower mass* | t | 1,263 |
| *RNA mass* | t | 991 |
| *Water depth* | m | 200 |
| *Mooring system* | - | Three-line catenary |

*Figure 14: A render of the UMaine VolturnUS-S platform supporting the IEA-15-240-RWT turbine (Allen, et al., 2020).*

### 3.1.4 Anchors and mooring

The E[c] simulator database contains parameters for several different anchor systems and mooring chains. For this case study, two different drag anchor types were used: the Vryhof Stevpris MK6 for Sites 1 and 2, and the Vryhof Stevpris REX for Site 3. Different anchors were used due to the different seabed sediments at these locations, with the seabed at Site 1 and 2 featuring clay while the seabed at Site 3 is primarily silica sand. Both anchors feature removable ballast and come in different sizes, enabling the anchor mass, and holding capacity to be adjusted according to requirements (Vryhof, 2018). The design module calculates the required anchor mass based on the predicted mooring loads, with the values used for the 3 sites during the case study shown in Table 13. As can be seen, Site 2 also used thicker mooring chain. This is because the shallower water depth limits the overall length of a catenary mooring line while also providing greater wave excitation of a floating turbine.

*Table 13: Anchor and mooring parameters at the three sites for the IEA 15 MW RWT as generated by the design module.*

| | *Site 1* | *Site 2* | *Site 3* |
|---|---|---|---|
| *Average water depth (m)* | 107 | 72.2 | 117 |
| *Soil type* | Medium clay | Sand and hard clay | Sillica sand |
| *Chain type* | R5 studless | R5 studless | R5 studless |
| *Chain bar diameter* | 0.19 | 0.26 | 0.19 |
| *Anchor type* | Stevpris MK6 | Stevpris MK6 | Stevpris REX |
| *Anchor mass (t/anchor)* | 17.97 | 24.09 | 17.54 |
| *Horizontal anchor load (kN)* | 10,296 | 14,690 | 10,967 |

### 3.1.5 Inter-array cables and substations

When setting up a simulation, a user can specify a list of inter-array cable types that they want the design module to utilise when designing the wind turbine array. The parameters for these cables, including the rated power capacity, the number of wind turbines they can support (accounting for 3 phase power) and their costs and energy loss coefficients, are shown in Table 14. All three types of cabler were made available to the design module during the case study. The appropriate number of substations was also auto generated by the design module according to farm capacity and the number of wind turbines.

*Table 14: Summary of cable parameters within the $E^c$ simulator.*

| *Parameter* | *Cable 1* | *Cable 2* | *Cable 3* |
|---|---|---|---|
| *Nominal voltage (kV)* | 66 | 66 | 66 |
| *Nominal current (A)* | 394 | 533 | 711 |
| *Nominal power (MW)* | 26.0 | 35.2 | 46.9 |
| *Cross-sectional area (mm2)* | 300 | 500 | 800 |
| *15 MW turbine capacity* | 3 | 4 | 5 |
| *12 MW turbine capacity* | 3 | 5 | 6 |
| *Cost (£/m)* | 289 | 383 | 531 |
| *Nominal power losses (W/m)* | 0.057 | 0.0342 | 0.021375 |

### 3.1.6 Port locations

The case study used the Welsh ports scenario, which is summarised in Table 15.

*Table 15: Port location - Welsh scenario*

| *Subsystem; component* | *Manufacture* | *Assembly and installation* | *O&M* |
|---|---|---|---|
| *Tower* | Belfast | Port Talbot | Milford Haven |
| *Turbine rotor; blade* | Teesport | Port Talbot | Milford Haven |
| *Nacelle; hub* | Teesport | Port Talbot | Milford Haven |
| *Anchor* | Liverpool | Milford Haven | Milford Haven |
| *Mooring line* | Liverpool | Milford Haven | Milford Haven |
| *Export cable* | Wrexham (Prysmian Cables) | Port of Mostyn | Milford Haven |
| *Inter-array cable* | Wrexham (Prysmian Cables) | Port of Mostyn | Milford Haven |
| *Floating platform* | Ferrol, Spain | Port Talbot | Milford Haven |
| *Offshore substation* | Aalborg, Denmark | Port Talbot | Milford Haven |

## 3.2 CFA-B-001: baseline

The baseline wind farm case study (CFA-B-001) simulated a 1 GW wind farm at Site 1. The farm had an operation life of 25 years and consisted of 67 IEA 15 MW 240 wind turbines. The baseline scenario focusses on the midstream logistics of installation, i.e., assembly and installation, with all upstream logistics (such as manufacturing supply chains) assumed to be resolved. It is also assumed that the offshore and onshore substations have been installed ahead of all the other the midstream activities. A summary of the farm parameters for CFA-B-001 is provided in Table 16.

*Table 16: Summary of inputs for CFA-B-001.*

| | | |
|---|---|---|
| *Farm* | Farm capacity | 1,005 MW |
| | Farm location | CFA site 1 coordinates |
| | Development period | 2 years |
| | Construction period | 3 years |
| | O&M period | 25 years |
| | Decommissioning period | 2 years |
| | Discount rate | 10% |
| | Cost reference | OREC, farm (database) |
| | Commissioning mode | Yearly |
| | Operation delay | 1 year |
| *Turbine* | Model | IEA15MW |
| | Template | OREC, 15MW (database) |
| | Power capacity | 15 MW |
| | Power curve | IEA 15MW OSW reference |
| | Energy loss | 3% |
| | Cost reference | OREC, turbine 15MW (database) |
| | Material reference | OREC, May 2023, 15MW turbine, steel tower (database) |
| | Number | 67 turbines |
| | Link | Farm |
| *Floater* | Name | pw, WindFloat, 15MW |
| | Name subs | IEA steel semi-sub floating platform |
| | Mass | 4,000 tonnes |
| | Material composition | Steel |
| | Cost factor | 3.0 |
| | Cost reference | Material cost (database) |
| | Link | Turbine |
| *Mooring* | Name subs | Steel chain |
| | Material composition | Low carbon steel |
| | Link | Floater |
| *Anchor* | Name subs | Drag anchor |
| | Material composition | Low carbon steel |
| *Cable inter-array* | Name subs | inter-array cable, 66 kV |
| | Energy loss | 5.8% |
| *Offshore substation* | Name subs | Offshore substation, HVAC |
| | Energy loss | 0.5% |
| | Power capacity | 1,005 MW |
| | Number | 1 |
| *Cable export* | Name subs | Offshore export cable, HVAC |
| | Energy loss | 1.1119% |
| | Length | 94,000 meters |
| | Number | 2 |

Installation and decommissioning tasks are shown in Table 17 and Table 6.

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*Table 17: BCFA_001 installation tasks*

| | *Store mooring* | *Install anchor* | *Store blades* | *Tower, nacelle, floater delivery* | *Store cables* | *Assembly WTG* | *Transit to site & connect anchor* | *Install cables* | *commission* |
|---|---|---|---|---|---|---|---|---|---|
| *No_unit_group* | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| *Operation_time* | - | 1.5 | - | - | - | 6 | 5 | 3 | 1 |
| *Oper_time_factor* | - | - | - | - | - | 0.1 | - | - | - |
| *Port_time* | - | 0.2 | - | - | - | - | - | - | - |
| *Departure* | - | Talbot | - | - | - | - | Talbot | Talbot | Talbot |
| *Destination* | - | CFA site 1 | - | - | - | - | CFA site 1 | CFA site 1 | CFA site 1 |
| *Resource vessels* | - | Two AHTS DP 2 | - | - | - | Ŧ | One AHTS DP 2 + tug | ¥ | One CTV |
| *Operation limit* | - | 12.5 m/s 1.8 m | - | - | - | 10 m/s 50 m | 14.5 m/s 1.9 m | 14.5 m/s 1.9 m | - |
| *Resource stock* | - | N.1.1 | - | - | - | N.3 & N.4 | N.6 & N.1.1 | N.7 & N.5 | N.8 |
| *Resource product* | N.1 | N.2 | N.3 | N.4 | N.5 | N.6 | N. 7 | N.8 | N.9 |
| *Storage in* | M.1 | - | B.1 | - | C.1 | - | - | - | - |
| *Storage out* | - | M.2 | - | - | - | B.2 | - | C.1 | - |

Ŧ one crane vessel and one onshore crane 1000t
¥ one inter-array cable laying vessel
€ tower: 1, nacelle: 1, floater: 1
N.1: three anchors, three moorings
N.1.1: one anchor, one mooring (as the no. unit group is 3 meaning it will repeat three times)
N.2: one anchor installed, one mooring installed (repeated three times)
N.3: three blades, N.4: one tower, one nacelle, one floater, N.5: one inter-array cable
N.6: one assembled WTG, N.7: anchored WTG, N.8: WTG ready for commissioning, N.9 WTG commissioned
M.1: mooring system storage: 1500 m$^2$, M.2: mooring system out: 500 m$^2$, B.1: blade storage: 600 m$^2$, B.2: blade out: 200 m$^2$, C.1: cable storage in and out: 10 m$^2$.

It is important to note that the results of any analysis are highly dependent on the inputs and assumptions provided. The results presented here are intended to demonstrate the capability of the E$^c$ simulator, rather than provide an accurate assessment of a real-life FLOW farm concept for the Celtic Sea.

### 3.2.1 Design module outputs

The design module first calculates the 50-year extreme weather conditions based on the input meteorological data for the site. This condition and other parameters (e.g., specification of subsystems, environment data) are used to estimate the key design parameters for mooring lines and anchors (e.g., mass and dimensions) and their manufacturing costs. These outputs are summarised in Table 18.

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*Table 18: Summary of design module outputs for CFA-B-001.*

| *Module function* | *Parameter* | *Value* |
|---|---|---|
| *meteorological data* | 50-year extreme weather condition | Hs:8.57 [m], Tz:10.19 [s], Tp: 14.26 [s], V_wind: 25.86 [m/s] |
| *wind generation and wake effect* | annual electricity generation (GWh) | 5,864 |
| | wake loss | 1.2% |
| *mooring parameter* | mooring bar diameter (m) | 0.19 |
| | mooring length (m) | 720 |
| | anchor point (m) | -750 |
| | mooring mass (kg) | 517,241 |
| *anchor parameter* | H force on anchor (N) | 10,296,211 |
| | anchor mass (kg) | 17,967 |
| | anchor cost (£) | 62,884 |
| *inter-array cable routing* | inter-array cable mass (kg/cable) | 36,042 |
| | no. of offshore substation | 2 |

### 3.2.2 Installation and decommissioning module outputs

The key results of the installation module are summarised in Table 19, Table 20 and. Table 19 shows the costs and fuel consumption of installation tasks that are considered in the baseline case. Table 20 shows the storage requirements for these tasks. The cost and fuel usage during associated decommissioning tasks at the end of the farm life are shown in Table 21. These values are estimated from a corresponding installation task by using cost and energy factors. Low-carbon fuels have been specified for the decommissioning tasks it is assumed that these fuels will be commonplace by 2050 due to the UK's net zero targets.

*Table 19: Summary of installation module task output for CFA-B-001.*

| *Subsystem type* | *Installation task* | *Vessel name* | *Vessel no* | *Fuel type* | *Fuel consumption (litre)* | *Task cost (£)* |
|---|---|---|---|---|---|---|
| *Anchor* | install anchor | AHTS DP2 | 2 | MGO | 29,119 | 918,902 |
| *Turbine* | assemble WTG in staging port | crane vessel | 1 | MGO | 79,416 | 414,051 |
| | | onshore crane, 1000t | 1 | diesel | 16,941 | 126,941 |
| | transit WTG to site and connect with anchors | tug, assistant | 1 | MGO | 16,780 | 126,892 |
| | | AHTS DP2 | 1 | MGO | 41,045 | 601,643 |
| *Cable* | install dynamic inter-array cable | cable laying vessel, inter-array cable | 1 | MGO | 24,569 | 450,948 |

*Table 20: Storage use during installation for CFA-B-001*

| *Storage* | *Hiring duration (days)* | *Storage area (m2)* | *Storage costs (£)* |
|---|---|---|---|
| *anchor and mooring storage* | 521 | 16,000 | 2,500,800 |
| *inter-array cable storage* | 552 | 1,000 | 110,400 |
| *WTG staging storage* | 531 | 20,000 | 3,186,000 |

*Table 21: Summary of installation module decommissioning task output for*

| Decommissioning task | Cost factor | Energy factor | Fuel type for decom. | Decom. cost | Decom. fuel consumption (litre) |
|---|---|---|---|---|---|
| Remove anchor | 0.5 | 0.5 | Low-carbon fuel | 459,451 | 14,559 |
| Disassembly WTG in harbour | 0.9 | 0.9 | Low-carbon fuel | 97,379 | 17,344 |
| Transport turbine from site to port | 0.9 | 0.9 | Low-carbon fuel | 655,682 | 52,043 |
| Remove inter-array cable | 0.2 | 0.2 | Low-carbon fuel | 90,190 | 4,914 |

The installation considers the weather limits and duration for each installation task. Figure 15 shows the monthly availability of weather windows i.e., the fraction of time that has weather window for certain operation.

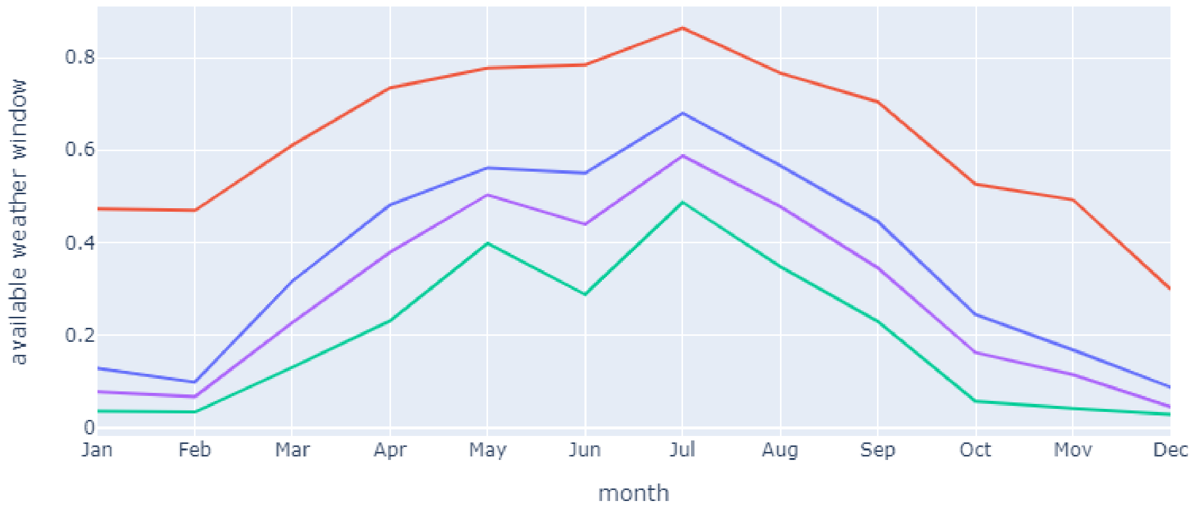


*Figure 15: Average weather window by months (CFA site 1, 11 years, 2010 - 2020)*

### 3.2.3 Operation and maintenance module outputs

The key outputs of the O&M Module are the average downtime of the wind farm, and the costs and energy consumption associate with operation and maintenance tasks. Table 22 summarises the annual average results following multiple simulation runs using the Monte Carlo method.

*Table 22: Summary of the operation and maintenance module outputs for CFA-B-001.*

| Results for the wind farm (67 turbines) | Floating platform | Mooring minor repair | Mooring major repair | Power cable minor repair | Power cable major repair | Turbine minor 1 | Turbine minor 2 | Turbine major 1 | Turbine major 2 |
|---|---|---|---|---|---|---|---|---|---|
| vessel | CTV | SOV | AHV | SOV | CLV | CTV | SOV | HLV | LHV |
| tow-to-port (0: disabled, 1: enabled) | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| simulated failure per year (times/year) | 34.4 | 40.8 | 41.3 | 19.9 | 2.9 | 71.1 | 9.9 | 10.3 | 10.4 |
| simulated downtime per year (hour/year) | 5324 | 8135 | 15030 | 3169 | 4860 | 10901 | 1702 | 2057 | 2653 |
| annual repair/replacement cost (m£/year) | 4.41 | 0.39 | 23.43 | 11.87 | 16.39 | 0.36 | 0.10 | 0.51 | 1.04 |
| annual vessel charter cost (m£/year) | 0.11 | 0.98 | 17.29 | 0.48 | 3.04 | 0.23 | 0.38 | 6.96 | 11.16 |

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| Results for the wind farm (67 turbines) | Floating platform | Mooring minor repair | Mooring major repair | Power cable minor repair | Power cable major repair | Turbine minor 1 | Turbine minor 2 | Turbine major 1 | Turbine major 2 |
|---|---|---|---|---|---|---|---|---|---|
| annual vessel mobilisation cost (m£/year) | 0.59 | 5.30 | 4.33 | 2.58 | 2.15 | 1.21 | 1.29 | 7.72 | 7.77 |
| annual transit fuel burn (litre/year) | 34,418 | 231,121 | 841,593 | 112,547 | 85,909 | 71,145 | 56,145 | 246,982 | 248,727 |
| annual repair fuel burn (litre/year) | 125,558 | 191,880 | 3,843,603 | 93,439 | 357,382 | 259,539 | 93,225 | 642,153 | 1,293,382 |

### 3.2.4 KPI calculator outputs

The costs, carbon emissions, and energy invested/generation of the wind farm are obtained based on the given input data (e.g., cost estimation parameters, mass, and materials of components) and the results from each module. The key KPIs (LCOE, carbon intensity, and ERoEI) are summarised in Table 23, while energy production and energy losses are summarised in Table 24.

*Table 23: Summary of the KPI calculator outputs for CFA-B-001.*

| KPI | Unit | Value | Key assumption |
|---|---|---|---|
| Levelised cost of electricity (LCOE) | £/MWh | 112.6 | Discount rate 10% |
| Carbon intensity | kgCO2-eq/MWh-ele | 14.6 | |
| Energy return on energy invested (ERoEI) | - | 7.2 | |
| Lifetime cost (undiscounted) | £ | 6,800,223,844 | Operation duration 25 years |
| Lifetime energy invested | MJ | 56,634,642,421 | |
| Lifetime electricity exported | MWh-ele | 111,944,045 | |
| Lifetime carbon emissions | kgCO2-eq | 1,638,201,096 | |

*Table 24: Summary of the energy production and losses for CFA-B-001.*

| KPI | Unit | Value |
|---|---|---|
| Annual wind power generation | MWh/year | 5,413,000 |
| Annual export electricity | MWh/year | 4,477,000 |
| Energy loss from generation to export | | |
| Downtime (from O&M module) | % | 9.7 |
| Energy loss in export cable | % | 1.0 |
| Energy loss in offshore substation | % | 0.5 |
| Energy loss in inter-array cables | % | 5.8 |
| Energy loss due to wake effect | % | 1.2 |

In CFA-B-001, the majority of the LCOE arises from the manufacturing of subsystems, which account for about 60% of the LCOE. The operational costs are second largest and for 30% of the LCOE, with pre-development, installation, and decommissioning comprising the remainder as shown in the left-hand side of Figure 16. In terms of the LCOE breakdown by type of subsystems, the wind turbines themselves are the major elements, accounting for over a third of the total cost. The floating platforms, mooring lines, and cables comprise the next largest contributions, as shown by the right-hand side of Figure 16. Since most of these costs arise in manufacture, this expenditure occurs in the early years of the wind farm lifecycle, as shown by Figure 17.

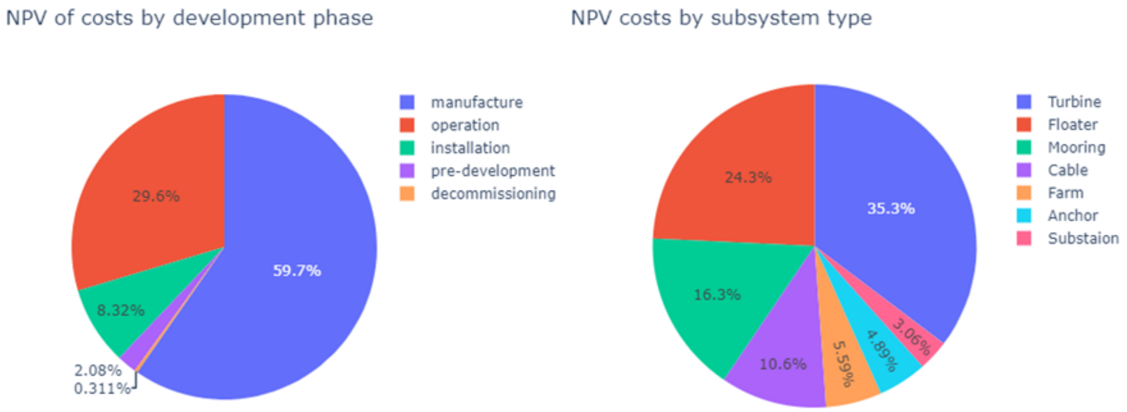


*Figure 16: Contributions of development stages (left hand side) and subsystems (right hand side) to the net present cost values for CFA-B-001.*

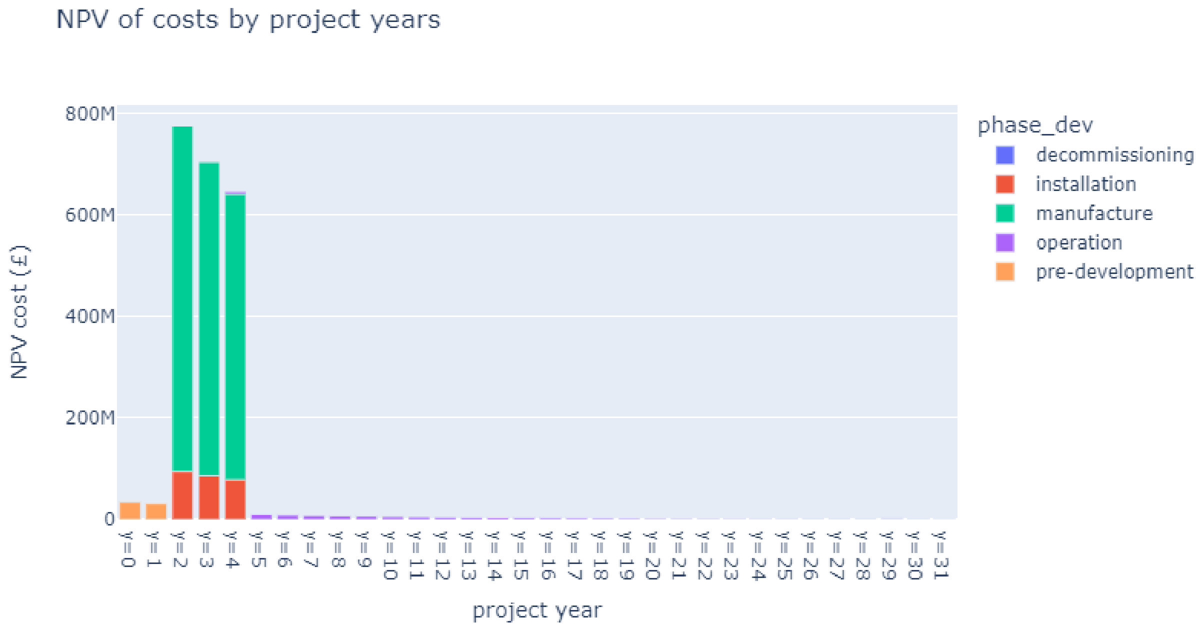


*Figure 17: Timeline of net present cost values for CFA-B-001.*

While a 10 % discount rate has been used for illustrative purposes during this analysis, the effect of variable discount rate on the levelised cost of electricity for CFA-B-001 is shown in Figure 18. This highlights the significant impact that investment costs and assumptions can have on the output of any analysis, with a discount rate of 5 % reducing the levelised cost of electricity by almost £20/MWh compared to a discount rate of 10 %. The use of accurate data for calculating discount rate and weighted average cost of capital will therefore be essential if accurate predictions of project economics are to be obtained.


*Figure 18: Effect of discount rate on the levelised cost of electricity for CFA-B-001.*

The lifetime carbon emissions for CFA-B-001 are shown in Figure 19, which indicates that the embodied cardbon due to manufacturing processes provides the greatest contribution to the carbon footprint of the wind farm. Components that rely on a significant quantity of steel, such as the turbines, mooring lines, and floating platforms, account for over 90% of the total carbon emissions.16

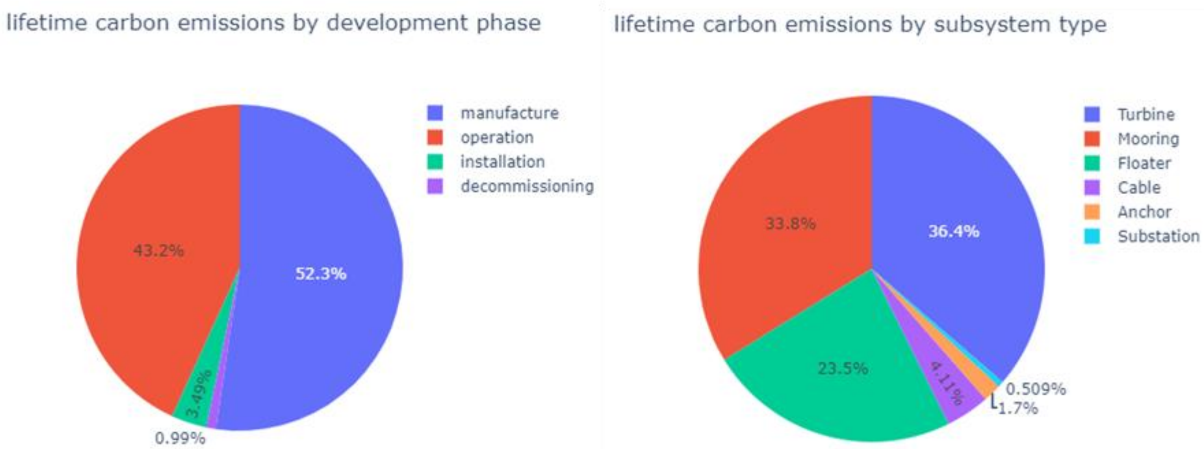


*Figure 19: Lifetime carbon emissions of CFA-B-001 by development phase (left hand side) and subsystem type (right hand side).*

As shown in Figure 20, the energy invested during manufacturing the components (also called embodied energy) represents the greatest contribution (over 80%) of the energy investment for building the wind farm. Wind farm operation (due to fuel consumptions for O&M activities) results in a much smaller contribution. In a similar fashion to the carbon emissions, floating platforms, turbines, and mooring lines account for over 90% of energy investment for the whole wind farm, again due to the high quantity of steel associated with these systems.

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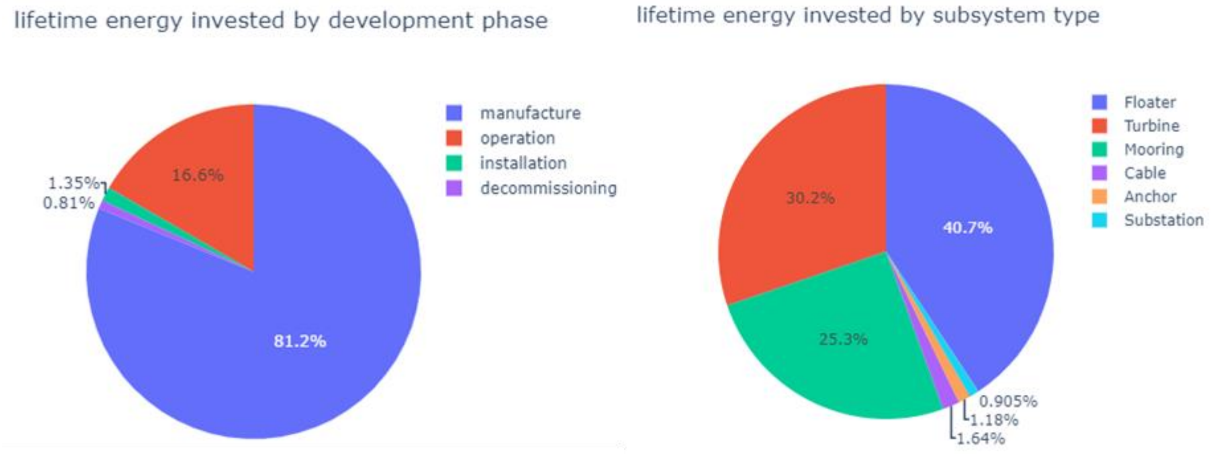


*Figure 20: lifetime energy investment by development phase (left hand side) and subsystem type (right hand side) for CFA-B-001.*

### 3.2.5 E$^c$ simulator verification

The summarised KPI output for CFA-B-001 from the E$^c$ simulator is shown in Figure 21. The LCOE of £109.99/MWh predicted by the E$^c$ simulator compares to £112.6/MWh for the module run case, the carbon intensity of 10.65 kgCO2-eq/MWh-ele compares to 14.6 kgCO2-eq/MWh-ele, and the EROI of 7.71 compares to 7.2 from the module run.

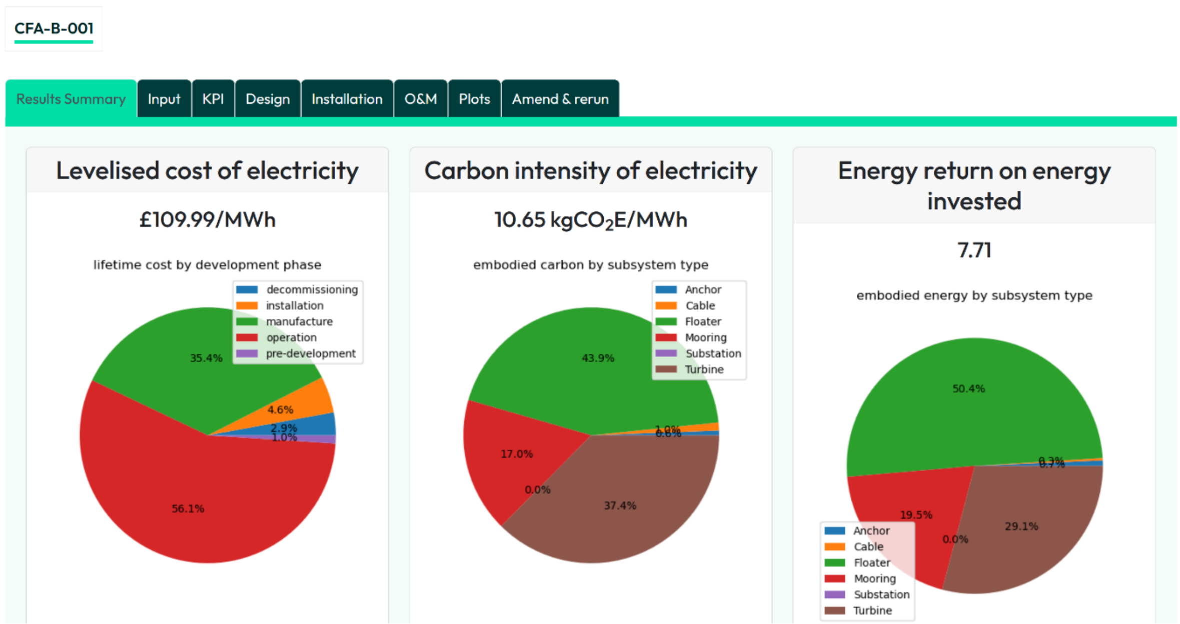


*Figure 21: Screen capture of the E$^c$ simulator output for CFA-B-001.*

These results indicate reasonable agreement between the E$^c$ simulator and the modules, demonstrating that the E$^c$ simulator is functioning as intended. There are some differences in the results, which are currently ascribed to the following factors:

1. The E$^c$ simulator using a single turbine power curve, whereas the modules use individual power curves. The variation in the curve used by the design module has reduced the annual energy production predicted by the E$^c$ simulator (5.51 GWh/year) in comparison to the modules (5.86 GWh/year).

2. The stochastic nature of the O&M module, which results in some randomness regarding the number of vessel trips and subsequent costs, carbon, and energy emissions.

Further testing of the $E^c$ simulator will continue for the remainder of the CFA project to confirm these explanations and provide further verification.

## 3.3 Site comparison

This section presents a comparative analysis of three wind farms at Site 1 (CFA-B-001), Site 2 (CFA-B-002), and Site 3 (CFA-B-003). The aim is to evaluate the impact of wind farm location, which will influence meteorological conditions, seabed types, and distance to installation and O&M ports, on the design, installation, operation, and decommissioning of the wind farm, and therefore affects the KPIs of the whole wind farm.

### 3.3.1 Input

To assess the impact of farm site only, most of the input parameters, such as number of turbines, the selection of key technologies (e.g., 15 MW turbine, steel semi-submersible floating platform, drag embedment anchors), and locations of ports to support the installation and O&M activities, are kept the same between each case.

*Table 25: Summary of varied input parameters for the site comparison case study.*

| *Case* | *CFA-B-001* | *CFA-B-002* | *CFA-B-003* |
|---|---|---|---|
| *Site* | CFA site 1 | CFA site 2 | CFA site 3 |
| *Meteorological data location* | 51.5, -6.0 | 50.5, -5.5 | 50.0, -7.0 |
| *Water depth (m)* | 107 | 72 | 117 |
| *Soil type* | Medium Clay | Sand and Hard Clay | Silica Sand |
| *Anchor type* | Stevpris MK6 | Stevpris MK6 | Stevpris REX |
| *Distance to ports (km)* | Port Talbot: 170<br>Milford Haven: 91<br>Mostyn: 325 | Port Talbot: 177<br>Milford Haven: 146<br>Mostyn: 425 | Port Talbot: 310<br>Milford Haven: 270<br>Mostyn: 540 |

### 3.3.2 Design module output

From the calculated 50-year extreme weather conditions, Site 3 is predicted to have highest significant wave height and high wind speed, as shown in Table 26. Even so, the results of the mooring and anchor calculation show that the mooring lines and anchors at Site 2 are notably larger than those at the other two sites. It is mainly attributed to shallower water depth at site 2. In shallow water, mooring lines for Floating Offshore Wind Turbines (FOWTs) require more weight to provide the necessary restoring force to the turbine. Additionally, the response of the FOWT in shallow water is larger, contributing to increased costs.

It is important to note that the design of moorings for each site is not necessarily fixed. It is possible for the specified moorings to be inadequate for the site conditions, meaning an element trial and error with different properties may be required to reach a mooring design that is capable of meeting loading requirements in a cost-effective fashion. Nevertheless, the results of the current case study indicate that the maximum load for each case under the selected extreme conditions is close to the minimum breaking load. This suggests that the selected properties are reasonable and not overly conservative, which would avoid unnecessary costs in this instance.

*Table 26: Summary of design module output for CFA-B-001, CFA-B-002, and CFA-B-003.*

| *Module function* | *Parameter* | *CFA-B-001* | *CFA-B-002* | *CFA-B-003* |
|---|---|---|---|---|
| *meteorological data* | 50-year extreme weather condition | Hs: 8.57 [m], Tz: 10.19 [s], Tp: 14.26 [s], V_wind: 25.86 [m/s] | Hs :8.59 [m], Tz: 11.2 [s], Tp: 15.68 [s], V_wind: 24.03 [m/s] | Hs: 10.2 [m], Tz: 11.52 [s], Tp: 16.13 [s], V_wind: 25.54 [m/s] |
| *wind generation and wake effect* | annual electricity generation (GWh) | 5,864 | 5,094 | 5,879 |
| | wake loss | 1.2% | 1.6% | 1.4% |
| *mooring parameter* | mooring bar diameter (m) | 0.19 | 0.26 | 0.19 |
| | mooring length (m) | 720 | 860 | 820 |
| | anchor point (m) | -750 | -900 | -850 |
| | mooring mass (kg) | 517,241 | 1,156,906 | 589,080 |
| *anchor parameter* | H force on anchor (N) | 10,296,211 | 14,690,305 | 10,967,149 |
| | anchor mass (kg) | 17,967 | 24,089 | 17,538 |
| | anchor cost (£) | 62,884 | 84,310 | 61,384 |
| *inter-array cable routing* | inter-array cable average length (m/cable) | 2,243 | 2,170 | 2,220 |

### 3.3.3 Installation module output

Table 27 summarises the time required to install the wind farm alongside its associated KPIs for each run. It suggests that the installation duration at Site 3 is twice longer than other two sites, which is mainly due to two reasons:

1. The weather conditions (especially significant wave height) at Site 3 being more severe than at the other two sites.
2. The distance between installation port and wind farm (310 km) being nearly twice those of the other sites (170 and 177 km).

*Table 27: Key outputs from the installation module for CFA-B-001, CFA-B-002, and CFA-B-003.*

| | *CFA-B-001* | *CFA-B-002* | *CFA-B-003* |
|---|---|---|---|
| *installation duration (days)* | 559 | 569 | 1,199 |
| *installation rate (day/turbine)* | 8.2 | 8.4 | 17.6 |
| *installation cost (£)* | 344,968,542 | 347,328,015 | 369,796,742 |
| *installation carbon emissions (kgCO2-eq)* | 57,253,115 | 62,363,296 | 75,589,400 |
| *installation energy consumption (MJ)* | 764,949,155 | 833,010,526 | 1,009,166,061 |

The installation costs for Site 3 are not significantly different to those of the other two sites, which is due to the weather waiting time costs not being included in this case study. Further analysis and data regarding vessel hire (e.g., short-term, or long-term hiring methods) is needed to quantify the impact of weather waiting time and installation costs.

The monthly available weather window diagram of site 1, 2 and 3 is shown in Figure 22, which shows that site 3 has demonstrably less available weather windows than the other two sites.

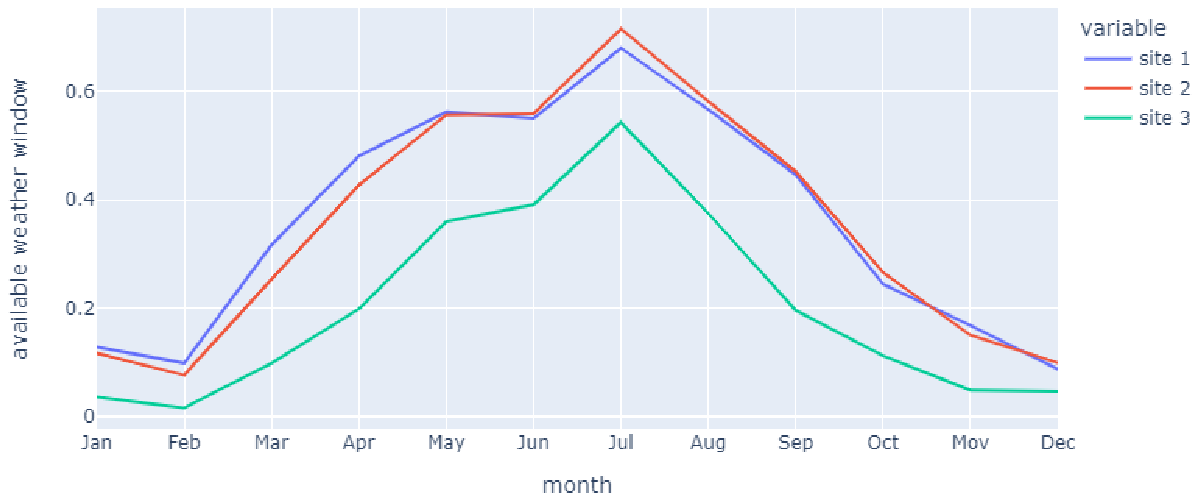


*Figure 22: Average weather window by months (limit: oper 36; [farm] wind 12.5; [farn] wave 1.8, 11 years, 2010 -2020)*

### 3.3.4 O&M module output

The principal findings from the O&M Module analysis, which include factors like electricity generation loss from downtime and O&M-related KPIs, are summarised in The distance from Site 3 to the O&M port is 270 km, considerably further than the distances from Site 1 (93 km) and Site 2 (146 km). An interesting observation from the O&M output is that the annual failure occurrences at Site 3 are slightly lower than those of the other two sites. This is because most failures typically happening during turbine operation. Hence, the higher downtime at Site 3 leads to fewer total failures. This factor in turn reduces O&M costs for Site 3 compared to the other sites. It should be noted that longer transit distance to the O&M port in Site 3 escalates both higher carbon emissions and energy consumption, undermining the benefits of its lower O&M costs and failures.

Table 28. It can be observed that Site 3 suffers a smaller loss in electricity generation than the other two sites, although its annual subsystem downtime is higher. The main contributing factor to this outcome is that Site 3 experiences more challenging weather conditions than the other two locations, as depicted in Table 9, where the average wave height surges to 2.48 m. Such conditions inherently cause prolonged delays in maintenance activities because the weather exceeds the operational limitations of the vessels (see Table 7).

The distance from Site 3 to the O&M port is 270 km, considerably further than the distances from Site 1 (93 km) and Site 2 (146 km). An interesting observation from the O&M output is that the annual failure occurrences at Site 3 are slightly lower than those of the other two sites. This is because most failures typically happening during turbine operation. Hence, the higher downtime at Site 3 leads to fewer total failures. This factor in turn reduces O&M costs for Site 3 compared to the other sites. It should be noted that longer transit distance to the O&M port in Site 3 escalates both higher carbon emissions and energy consumption, undermining the benefits of its lower O&M costs and failures.

*Table 28: Key outputs from the O&M module for CFA-B-001, CFA-B-002, and CFA-B-003.*

| | *CFA-B-001* | *CFA-B-002* | *CFA-B-003* |
|---|---|---|---|
| *production loss due to downtime, max (%)* | 91.9 | 91.5 | 89.9 |
| *production loss due to downtime, min (%)* | 87.8 | 85.0 | 82.8 |
| *production loss due to downtime, mean (%)* | 90.3 | 89.6 | 86.4 |

| | | | |
|---|---|---|---|
| *annual failure number (failure/year)* | 294.4 | 292.9 | 284.8 |
| *annual subsystem downtime (hour/year)* | 65,795 | 68,834 | 90,371 |
| *O&M cost (£/year)* | 149,368,723 | 148,692,460 | 144,817,754 |
| *O&M carbon emissions (kgCO2-eq/year)* | 28,304,966 | 31,902,486 | 39,184,625 |
| *O&M energy consumption (MJ/year)* | 376,987,532 | 424,902,103 | 521,891,295 |

### 3.3.5 Output: KPI calculations

The results shown in Table 29 and Figure 23 show that the LCOE the wind farms have significant variation among three sites. CFA site 1 is close to the installation and O&M ports, and not too far from the grid connection point on the shore. As a result, CFA site 1 has comparatively low lifetime costs and high electricity export, resulting in the lowest LCOE among three sites. The LCOE of CFA site 3 is more than £10/MWh-ele higher than that of Site 1. This arises due to low lifetime electricity export (arising from greater periods of downtime) and relatively high costs for the longer offshore export cables.

CFA site 2 has highest predicted LCOE of the three sites due to its higher manufacturing costs (with the major difference arising due to larger diameter mooring lines) and lower electricity generation (due to a lower overall wind resource, at least based on the historical meteorological data of 2010-2020 used for this case study). From Figure 24, it can also be seen that CFA Site 1 and 2 have broadly similar levels of energy loss, while Site 3 exhibits a greater quantity of energy lost due to higher downtime and higher power loss in the longer export cables.

*Table 29: Summary of KPIs for CFA-B-001, CFA-B-002, and CFA-B-003. Note that the lifetime figures have been rounded to the nearest thousand.*

| *KPI* | *Unit* | *CFA-B-001* | *CFA-B-002* | *CFA-B-003* |
|---|---|---|---|---|
| *levelised cost of energy* | £/MWh-ele | 108.69 | 130.48 | 121.12 |
| *carbon intensity* | kgCO2-eq/MWh-ele | 14.63 | 19.07 | 18.88 |
| *ERoEI* | | 7.12 | 5.24 | 6.03 |
| *lifetime cost total* | £ | *6,800,224,000* | 7,111,762,000 | 6,864,438,000 |
| *lifetime carbon emission total* | kgCO2-eq | *1,638,201,000* | 1,914,559,000 | 1,955,738,000 |
| *lifetime energy consumption total* | MJ | *56,634,642,000* | 69,019,272,000 | 61,893,232,000 |
| *lifetime energy export* | MWh-ele | *111,944,000* | 100,390,000 | 103,586,000 |

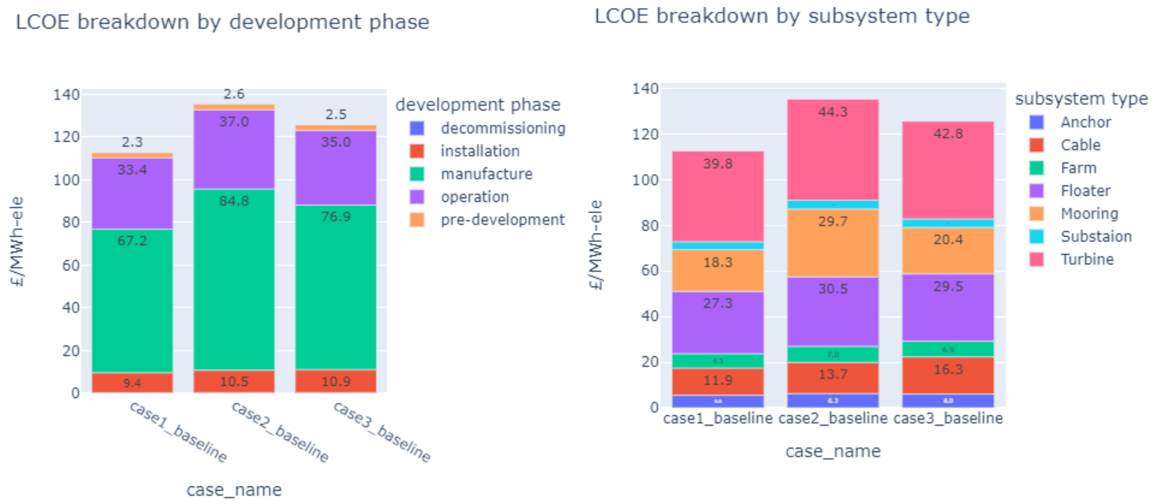


*Figure 23: Comparison of the breakdown of levelised cost of electricity by development phase (left) and subsystem (right) for CFA-B-001, CFA-B-002, and CFA-B-003.*

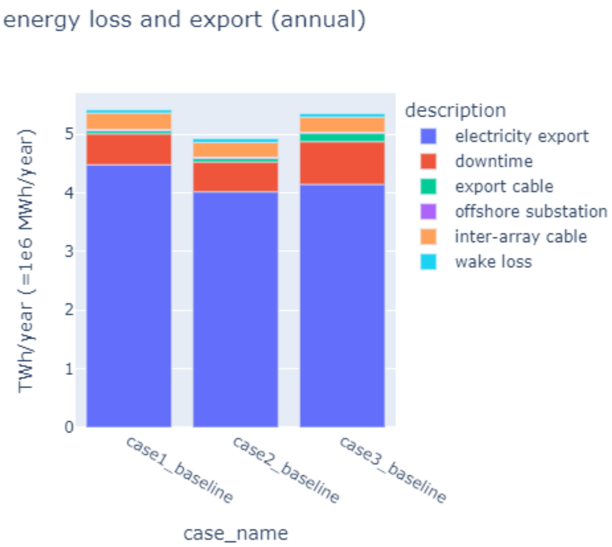


*Figure 24: Comparison of predicted energy exports for CFA-B-001, CFA-B-002, and CFA-B-003.*

Key performance indicators for carbon intensity for the 3 cases are compared in Figure 25. In a similar fashion to the LCOE, CFA-B-001 showed the lowest carbon intensity due to the shorter distance to the shoreline and the service ports for CFA Site 1. Site 2 and Site 3 are predicted to have similar carbon intensity levels; however, the sources of these emissions vary. Site 2 has higher embodied carbon from the larger quantities of steel in the mooring lines, while Site 3 has higher operational carbon emissions for the associated O&M activities. These factors highlight the improvements that could be made by technology innovation in mooring design and manufacture as well as vessel propulsion.

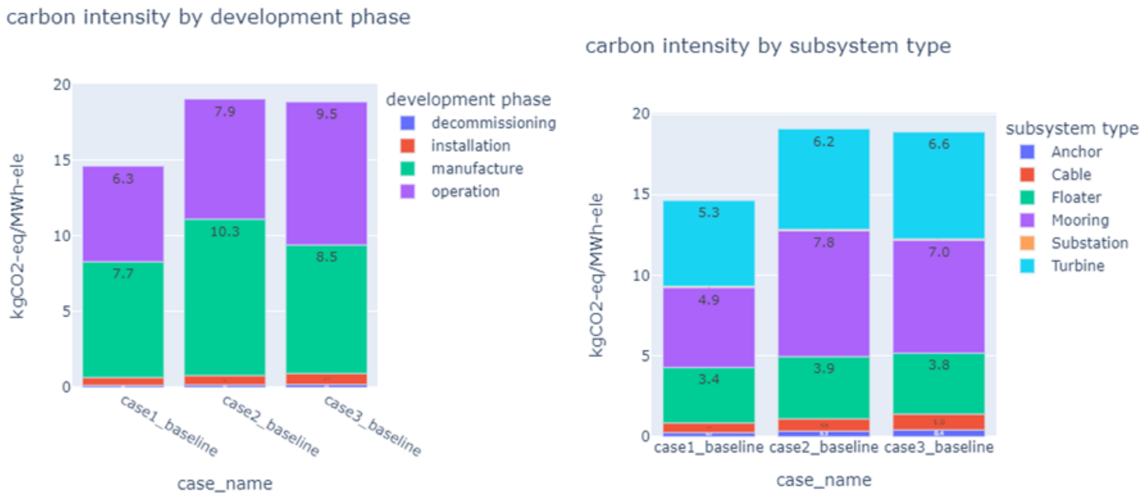


*Figure 25: Comparison of the breakdown of carbon intensity by development phase (left) and subsystem (right) for CFA-B-001, CFA-B-002, and CFA-B-003.*

Results for lifetime energy invested are shown in Figure 26. These show that the lifetime energy requirements of wind farms mainly come from the embodied energy involved in manufacture. Since CFA Site 2 has a high mass of steel mooring lines due to the shallow water depth, its energy investment is higher than the other sites where less substantial moorings are necessary. Although the operational energy consumptions for Site 3 is much higher than other sites, it requires less energy than Site 2 overall due to the lower mass of the mooring lines more than making up for the increased operational energy expenditure.

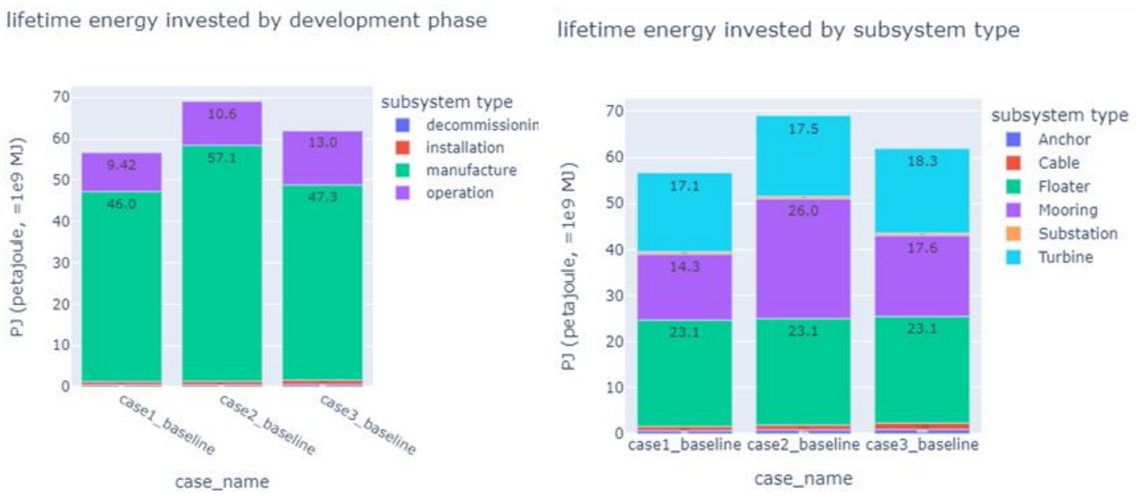


*Figure 26: Comparison of the breakdown of energy investment by development phase (left) and subsystem (right) for CFA-B-001, CFA-B-002, and CFA-B-003.*

## 3.4 Wind turbine size

This section presents results exploring how wind turbine size can influence the KPIs for a wind farm concept. The results provide an illustration of how increasing turbine size and power capacity from 12 MW to 15 MW can benefit the economics and sustainability of a 1 GW wind farm. This analysis was conducted at CFA Site 1, with the results of case study CFA-B-001 used for the 15 MW case, and CFA-B-004 used for the 12 MW turbine case.

*Results are summarised in **Table 30** to **Table 33**. **Table 30** shows how changing turbine size affects the number of turbines, wake loss, mooring lines, anchors, and cables for a given wind farm concept. Using large turbines naturally allows fewer turbines to be used, resulting in reduced wake losses and a lower number of larger mooring lines and anchors*

Table 31 shows how reducing the number of turbines by moving to larger sizes can reduce the time, energy, carbon, and cost required to install a farm. Table 32 shows that using a smaller number of large turbines reduces operation costs, energy, and carbon, while potentially resulting in slightly worse production losses due to downtime at a single turbine having a greater relative effect on farm output.

*Table 30: Summary of design module outputs for the 15 MW (CFA-B-001) and 12 MW (CFA-B-004) cases.*

| Parameter | Unit | CFA-B-001 | CFA-B-004 |
|---|---|---|---|
| wind farm power capacity | MW | 1005 | 1008 |
| turbine power capacity | MW | 15 | 12 |
| no of turbines | - | 67 | 84 |
| type of turbines | - | IEA15MW | NREL12MW |
| power curve | - | IEA 15MW OSW reference | NREL reference 12MW |
| hub height | m | 150 | 136 |
| blade diameter | m | 240 | 214 |
| Wake loss | % | 1.22% | 1.44% |
| mass of platform | kg | 4,000,000 | 3,500,000 |
| no of mooring/anchor | | 201 | 252 |
| mooring bar diameter | m | 0.19 | 0.183 |
| mooring mass | kg | 517,240.80 | 479,830.39 |
| anchor mass | kg/anchor | 17,966.72 | 14,360.59 |
| inter-array cable mass (kg/cable) | kg/cable | 36,041.98 | 32,907.47 |

*Table 31: Summary of installation module output for the 15 MW (CFA-B-001) and 12 MW (CFA-B-004) cases.*

| Parameter | Unit | CFA-B-001 | CFA-B-004 |
|---|---|---|---|
| installation duration | Days | 559 | 619 |
| installation rate | Day/turbine | 8.22 | 7.37 |
| installation cost | £ | 344,968,542 | 417,114,046 |
| installation carbon emissions | kgCO2-eq | 57,253,114 | 70,724,435 |
| installation energy consumption | MJ | 764,949,154 | 944,937,191 |

*Table 32: Summary of O&M module output for the 15 MW (CFA-B-001) and 12 MW (CFA-B-004) cases.*

| Parameter | Unit | CFA-B-001 | CFA-B-004 |
|---|---|---|---|
| production loss due to downtime, max | % | 91.90 | 90.52 |
| production loss due to downtime, min | % | 87.77 | 86.49 |
| production loss due to downtime, mean | % | 90.28 | 89.05 |
| annual failure number | Per year | 294 | 435 |
| annual subsystem downtime | Hours/year | 65,795 | 97,119 |
| O&M cost | £/year | 3,734,218,077 | 4,856,573,170 |
| O&M carbon emissions | kgCO2-eq/year | 707,624,138 | 1,043,156,858 |
| O&M energy consumption | MJ/year | 9,424,688,296 | 13,893,573,872 |
| production loss due to downtime, max | % | 91.90 | 90.52 |

KPIs for the 15 MW and 12 MW turbine cases are summarised in Table 33. This again highlights the advantages that can be gained by moving to larger turbines, with 15 MW devices showing improved energy return on investment, lower levelised cost of electricity, and reduced lifetime carbon emissions. The majority of these gains are seen during the operation and maintenance phase as well as manufacture, as summarised by Figure 27 to Figure 29.

*Table 33: Summary of KPIs for the for the 15 MW (CFA-B-001) and 12 MW (CFA-B-004) cases.*

| Parameter | Unit | CFA-B-001 | CFA-B-004 |
|---|---|---|---|
| ERoEI | - | 7.12 | 5.81 |
| carbon intensity | kgCO2-eq/MWh-ele | 14.6 | 19.3 |
| levelised cost of exported electricity | £/MWh-ele | 109 | 130 |
| lifetime carbon emission total | kgCO2-eq | 1,638,201,096.75 | 2,062,562,112.49 |
| lifetime cost total | £ | 6,800,223,844.58 | 8,169,776,588.27 |
| lifetime energy consumption total | MJ | 56,634,642,421.34 | 66,123,559,927.13 |
| lifetime energy export | MWh-ele | 111,944,045.26 | 106,633,612.85 |

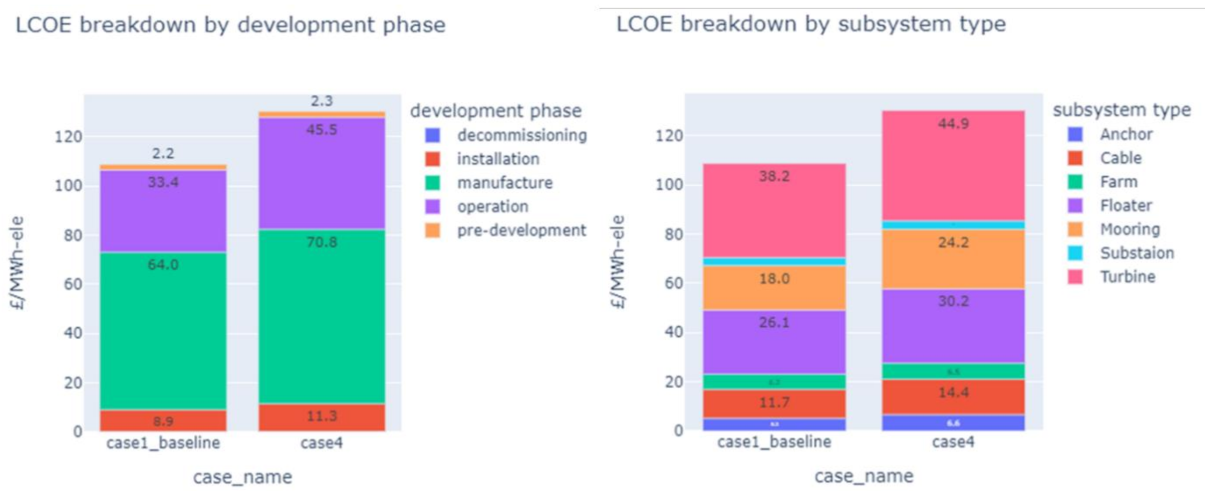


*Figure 27: Comparison of the breakdown of levelised cost of electricity by development phase (left) and subsystem (right) for CFA-B-001 and CFA-B-004.*

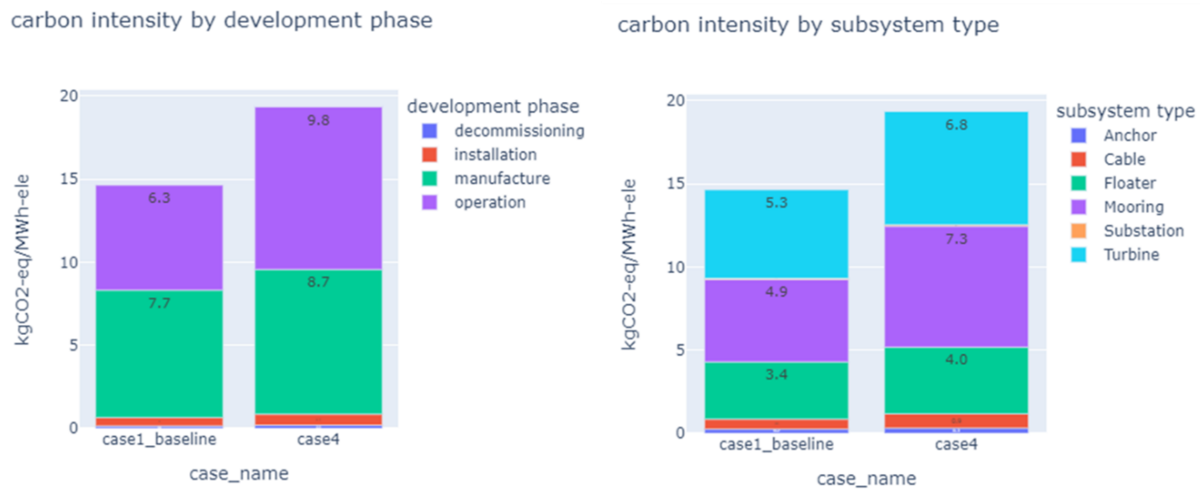


*Figure 28: Comparison of carbon intensity by development phase (left) and subsystem (right) for CFA-B-001 and CFA-B-004.*

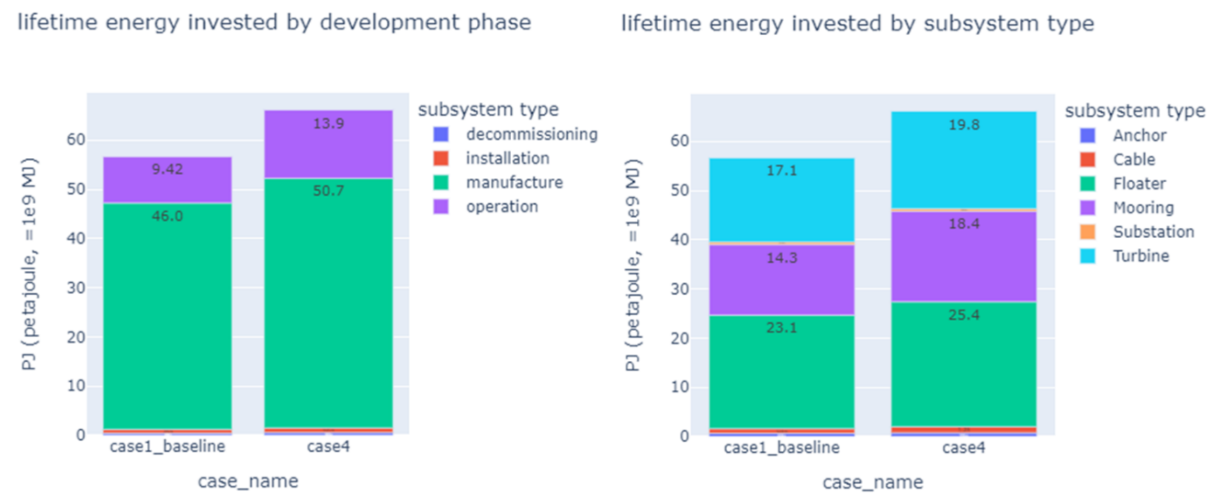


*Figure 29: Comparison of energy return on investment by development phase (left) and subsystem (right) for CFA-B-001 and CFA-B-004.*

# 4 Summary

This report has introduced the $E^c$ simulator, which is capable of assessing the economics and sustainability of a floating offshore wind farm across various development phases from design to decommissioning. The outputs of the $E^c$ simulator have been demonstrated using a baseline case study to show how varying inputs such as site location influence the key performance indicators (i.e., costs, carbon emissions, and energy invested, electricity generation) of a wind farm concept.

The $E^c$ simulator using a wide range of data covering environmental factors, economic considerations, logistical constraints, and technical specifications. By integrating this information into a sophisticated tool, it has helped streamline the process of analysing a FLOW farm concept and investigating the relationships between costs, carbon emissions, and energy invested of the floating offshore wind farms under different scenarios and system configurations.

## 4.1 Case study findings

The capabilities of the $E^c$ simulator have been demonstrated with a case study of FLOW farms at three different sites in the Celtic Sea. The key findings are as follows:

- Each site has variations in environmental conditions that influence the KPIs of the whole farm. For example, a shallower water depth at Site 2 leads to higher requirements for the mooring lines and a higher capital cost. Challenging weather conditions at Site 3 cause longer waiting time for installation and O&M tasks.
- The distances between the wind farm and other service infrastructures (e.g., installation and O&M ports, grid connection point at the shoreline) have a significant impact on the KPIs. Longer distance not only increase the costs and carbon emissions for export cables and O&M activities, but also reduce the electricity exported to the grid because of higher downtime and energy losses in export cables.
- Operation of wind farms is relatively carbon intensive. O&M activities only account for less than 20% of energy invested but 50% of carbon emissions. Decarbonising the vessel fleets used to install and maintain the wind farms is key to reducing carbon intensity of the floating offshore wind systems in future.

## 4.2 Future work

The results of the $E^c$ simulator are highly depending on the inputs and assumptions behind the data and models. The data used in the case study was selected primarily for demonstration purposes, meaning further validation and investigation about the inputs are required.

Moreover, in order to integrate multiple simulation and assessment methods without significantly increasing the computational costs, the current version of the $E^c$ simulator incorporates a certain level of simplification. To increase the fidelity of the simulation for certain components, further work with subject matter experts is needed to improve fidelity.

## 4.3 Conclusions

The lifetime assessment and simulation of floating offshore wind farms, as demonstrated through the case study of three CFA sites, offer valuable insights into the performance and viability of these projects. The modelling capabilities offered by the $E^c$ simulator provide a robust foundation for decision-making and should contribute to the acceleration of floating offshore wind in the Celtic Sea.

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# Appendix

## A. Summary of CFA reports

**Wind turbine blade**

- Manufacturing Variants and Future Steps (April 2023)
  https://celticseacluster.com/resources/new-report-manufacturing-variants-and-future-steps/
  Low Carbon Manufacturing Reports – wind turbine blades review (May 2022)
  https://celticseacluster.com/resources/cornwall-flow-accelerator-project-low-carbon-manufacturing-reports/

**Electrical transmission**

- **[Transmission network]** Innovation in Low Carbon Design and Manufacturability The South-West Transmission Network and Floating Offshore Wind Optimization in the Celtic Sea (March 2023) https://celticseacluster.com/resources/new-report-innovation-in-low-carbon-design-and-manufacturability-the-south-west-transmission-network-and-floating-offshore-wind-optimization-in-the-celtic-sea/
- [**offshore substation**] Innovation in Low Carbon Design and Manufacturability The Future Potential Role of Offshore Multipurpose Connectors (March 2023)
  https://celticseacluster.com/resources/new-report-innovation-in-low-carbon-design-and-manufacturability-the-future-potential-role-of-offshore-multipurpose-connectors/
- [**Cable connection**] Optimised Cable Connection Options For FLOW Report (October 2022)
  https://celticseacluster.com/resources/cornwall-flow-accelerator-project-innovation-in-low-carbon-design-and-manufacturability-optimised-cable-connection-options-for-floating-offshore-wind/

**Floating structure**

- Reducing Carbon Emissions from Floating Substructures Designs (February 2023)
  https://celticseacluster.com/resources/new-reports-released-reducing-carbon-emissions-from-floating-substructures-tower-designs/
- Low Carbon Manufacturing Reports – floating foundation review (May 2022)
  https://celticseacluster.com/resources/cornwall-flow-accelerator-project-low-carbon-manufacturing-reports/

**Tower**

- Reducing Carbon Emissions from Tower Designs (February 2023)
  https://celticseacluster.com/resources/new-reports-released-reducing-carbon-emissions-from-floating-substructures-tower-designs/
- Low Carbon Manufacturing Reports – tower review (May 2022)
  https://celticseacluster.com/resources/cornwall-flow-accelerator-project-low-carbon-manufacturing-reports/

**Mooring & anchor**

- Innovation in Low Carbon Design and Manufacturability – Mooring and Anchoring Systems (January 2023) https://celticseacluster.com/resources/new-report-released-innovation-in-low-carbon-design-and-manufacturability-task-4-mooring-and-anchoring-systems/

**Supply chain**

- [**Infrastructure**] Floating wind in Wales substructure and port review (September 2021) https://celticseacluster.com/resources/floating-wind-in-wales-substructure-and-port-review/
- [**Supply chain**] Benefits of Floating Offshore Wind to Wales and the South West (January 2020) https://celticseacluster.com/resources/benefits-of-floating-offshore-wind-to-wales-and-the-south-west/

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*Figure 30: installation tasks example*

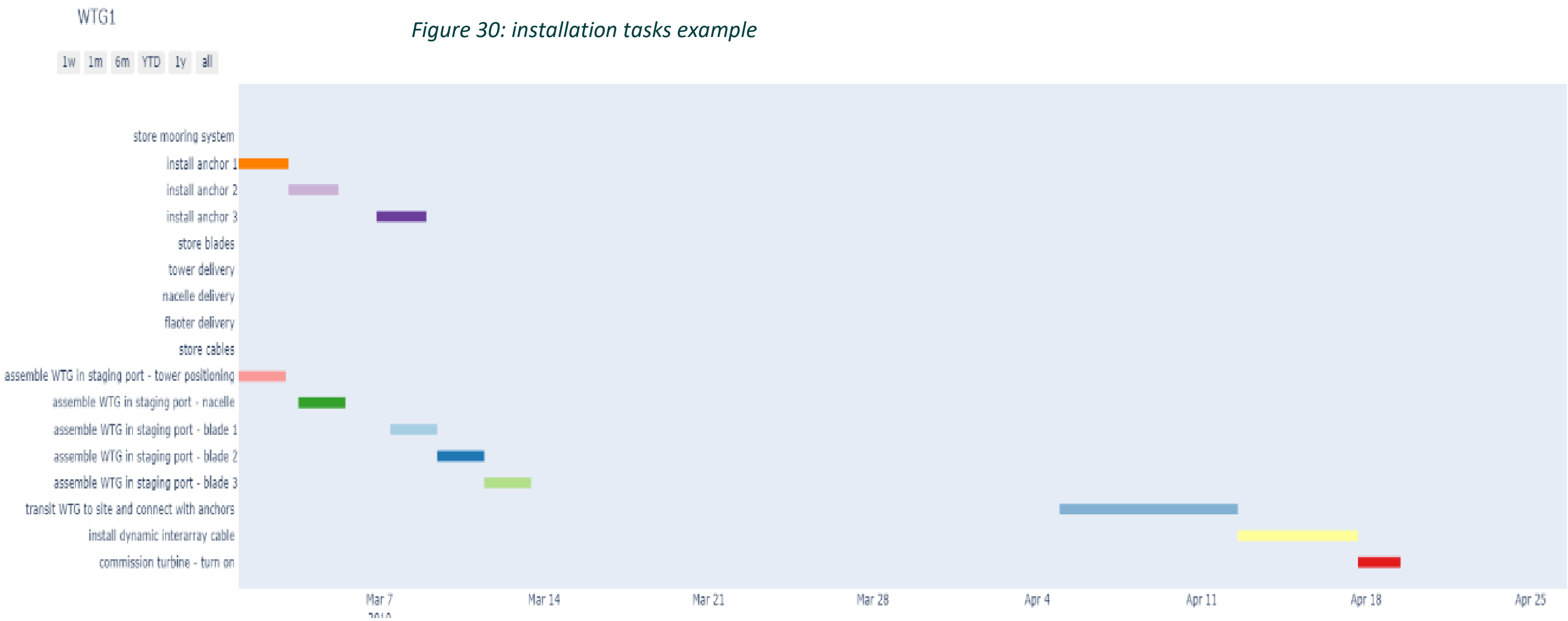


*Figure 31: weather waiting time (standby) in darker blue.*

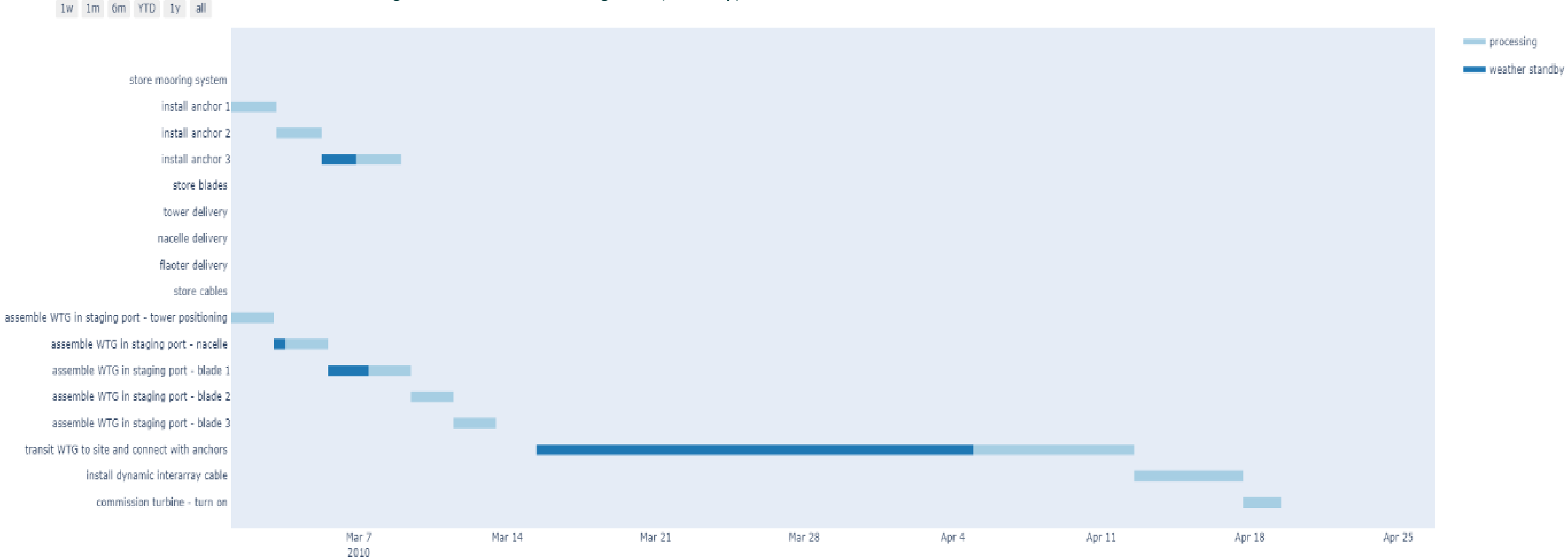

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*Table 34: Summary of subsystems in a floating offshore wind system*

| Primary category | Secondary category | Tertiary category | Capital cost | Embodied carbon & energy | Subsystem design | Manufacture & transport - upstream | Assembly & installation - midstream | Operations and maintenance | | Decom. | Recycle and reuse |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind farm | | | Pre-development assessment and survey | n/a | Farm location and layout | n/a | n/a | n/a | | Site clearing | n/a |
| Wind turbine | Tower | Tower structure, cathodic protection | by power rating and premium | Note 1 | select from database or user input | Note 2 | Assembly at the port; tow to offshore site; connecting to mooring | Major maintenance WTG | Minor maintenance WTG | Note 3 | Note 4 |
| | Rotor and blades | Rotor, blade, extender | | Note 1 | | Note 2 | | | | Note 3 | Note 4 |
| | Nacelle and hub | Shaft, main bearing, gearbox, generator, frame… | | Note 1 | | Note 2 | | | | Note 3 | Note 4 |
| Floating platform | Floating platform | Structure, protection… | by materials & manufacture cost | Note 1 | User input | Note 2 | | | | Note 3 | Note 4 |
| Mooring system | Mooring line | ?? | by materials & manufacture cost | Note 1 | Mooring design estimation | Note 2 | Assembly and anchoring | | | Note 3 | Note 4 |
| | Anchor | ?? | by materials & manufacture cost | Note 1 | Anchor mass estimation | Note 2 | | | | Note 3 | Note 4 |
| Electrical transmission | Inter-array cable | Cable, connector, buoyant, other accessories | by diameter and unit cost per length | Note 1 | Cable routing optimisation | Note 2 | Inter-array cable laying | Major maintenance shared | Minor maintenance shared | Note 3 | Note 4 |
| | Offshore substation | Pile, jacket, platform | by power rating | Note 1 | Substation location | Note 2 | Offshore substation installation | | | Note 3 | Note 4 |
| | Offshore export cable | Cable, protection… | by diameter and unit cost per length | Note 1 | Export cable length | Note 2 | Offshore export cable laying | | | Note 3 | Note 4 |
| | Others | Onshore export cable, onshore substation… | by power rating or estimation factor | Note 1 | n/a | n/a | n/a | O&M estimation | O&M estimation | Note 3 | Note 4 |
| Power-to-X | Hydrogen production platform | Electrolyser, desalination, compressor, hydrogen storage | by power rating, flow rate for pipeline | Note 1 | Power capacity of component, pipeline diameter | n/a | n/a | O&M estimation | O&M estimation | Note 3 | Note 4 |
| | Others | Battery… | by power rating | Note 1 | Power capacity of component | n/a | n/a | O&M estimation | O&M estimation | Note 3 | Note 4 |

Note 1: calculated based on the mass of each material in the subsystem; input required from users or default database.
Note 2: manufacturing duration and the transport form manufacturing sites to installation ports are considered in the installation module.
Note 3: the costs, carbon emissions, energy consumption of decommissioning tasks are estimated based on installation tasks.
Note 4: the reuse/recycling of materials can be estimated based on the mass and materials of each subsystem.