corewind

# D6.1 General frame of the analysis and description of the new FOW assessment app

IREC

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# Table of contents

## Executive summary

This report shows the framework methodology to develop the Floating Offshore Wind Assessment app (FowApp) based on the previous FOWAT tool from LIFES 50+ project. In this sense, the initial steps that are required to perform the evaluation of floating offshore wind farms from the economic and environmental points of view are addressed in this document to meet the main objective of the WP6.

The parameters that define floating wind farms are described, as well as the available options for each parameter. Some of them have already been taken from other submitted deliverables, such as the selected substructures and sites, and some of them are defined for the first time, such as the wind farm layout or the grid connection aligned with the information received from the developments from WP1 to WP4.

Firstly, 15 reference scenarios are defined, each one with a combination of different options, such as a capacity ranging from 60 to 1200 MW. The reference scenarios show a variety of basic cases or baselines that will be enhanced later in the project, with the aim of lowering their LCOE and/or their LCA. The LCOE and the LCA of the reference scenarios, as well as future variations of the studied wind farms, will be assessed using the FowApp.

Then, an overview of the FOWAT and its features is provided, together with the reasons that have driven not its adaptation (as initially expected), but the development of a new application. Then, the new app is described, and the main differences between it and the FOWAT are condensed in a table. Two differences can be highlighted; on the one hand, the user friendliness of the FowApp has been considered during the full development, leading to an app with standard appearance. On the other hand, the new app allows the creation, full edition and deletion of wind farms, therefore it is not limited to the Corewind project and may be upgraded in the future without the need of starting from scratch. That last feature is the main drawback of the FOWAT, as it was designed as a project-specific tool, where the user cannot edit most of the information without modifying its source code.

The LCA model of the FowApp have been completely developed in the Corewind project to meet the objective of the subtask 6.1.3, as the source code of the LCA module of the FOWAT could not be used due to the restrictions of its developer. The report describes the LCA model, which follows the steps stablished by the ISOs 14040/44:2006 to define the goal and the life cycle inventory (LCI) aligned with the scope of the study focused on the life cycle stages: the component production, installation, use (maintenance) and decommissioning. The transport is the main aspect to consider in the last three mentioned stages, thereby its model is developed. An important development in the LCA model is the creation of different end-of-life scenarios after the decommissioning activities related to the destination of different materials or components; namely, landfill, incineration, recycling, reuse/sale and leave-on-site. The proportion of the materials going to the three first end-of-life scenarios is subjected to a best practice scenario and the end-of-life allocation 50-50 approach in the LCA, both of them defined by using scientific literature. The reuse scenario considers the residual environmental benefit of the component defined by the user to be used in a second life. The environmental metrics that involve the concerns associated with the climate change, primary energy demand, depletion of mineral resources, damage to the ecosystems and harm to human health, are defined. These metrics are used in the life cycle impact assessment stage as a measurement of the LCI flows to know the impacts. The results of the LCAs will be generated from the FowApp as graphics and tables to be interpreted by of the FOWF developers to generate conclusions, recommendations and decision makings.

## List of abbreviations

| Abbreviation | Description |
|---|---|
| AC | Alternating Current |
| CAPEX | Capital Expenditure |
| DC | Direct Current |
| DECEX | Decommissioning Expenditure |
| FOWAT | Floating Offshore Wind Assessment Tool |
| FOWF | Floating Offshore Wind Farm |
| FowApp | Floating Offshore Wind Assessment app |
| FU | Functional Unit |
| HVDC | High Voltage Direct Current |
| HVAC | High Voltage Alternating Current |
| HVDC-VSC | HVDC with a Voltage Source Converter |
| HAWC2 | Horizontal Axis Wind turbine simulation Code 2nd generation |
| LCA | Life Cycle Assessment |
| LCOE | Levelized Cost of Energy |
| LCC | Life Cycle Cost |
| OPEX | Operational Expenditure |
| OPF | Optimal Power Flow |
| O&M | Operation and Maintenance |
| PF | Power Flow |
| WT | Wind Turbine |

## List of figures

## List of tables

## Introduction

Corewind is a European research project that aims to strength the European Leadership on wind power technology (and specially floating). To contribute on this, a LCOE analysis and Life Cycle Assessment (LCA) is conducted in the WP6 of the project.

LCOE is a calculation method used to obtain the cost of one produced energy unit since it entails the relationship of the life cycle cost (LCC) to the total energy provided, for that reason, the LCOE is typically used to compare the cost competitiveness of different power generation technologies. In the Corewind context, the LCC involves the design cycle phases: wind farm development, manufacturing, acquisition and installation of components, operation, maintenance, and decommissioning. In other words, the LCOE considers the capital expenditure (CAPEX), operational expenditure (OPEX), and decommissioning expenditure (DECEX) of the floating offshore wind power turbines. On the other hand, the LCA is the tool allowing to evaluate the potential environmental impacts considering the entire life cycle of the floating wind farm, including extraction of raw material, transport, manufacture, operation and decommissioning. In other words, this describes the creation, use and end of life and the environmental impacts from cradle to grave.

This deliverable follows specific objectives to provide the methodological framework to describe both LCOE and LCA module architectures for the FowApp. The first objective is to define the reference scenarios (subtask 6.1.1), the second one is to conduct an adaptation of the LCOE module to provide a full economic assessment and third one is the development of the LCA module (subtask 6.1.3) of the FOWF technologies.

In general terms, this document provides information regarding the concepts and information regarding the use of the FowApp. Inputs from the turbine and substructure designs performed in WP1 were taken into account as well as technical information from developers involved in W2 to WP4 and WP7 for a consistent analysis. The outputs of this report will be useful to the task 6.2 in charge of estimation of total LCOE for each FOWT concept reference scenario and the initial LCA conduction, considering quantitative data from the industrial partners, and also for the task 6.3 dedicated to review the CAPEX, OPEX and LCOE after optimization for cost-reduction scenarios.

# 1 Definition of reference scenarios for the LCOE and LCA assessment

The LCOE and the LCA will be assessed in the FowApp to evaluate the Corewind solutions. To do this, reference scenarios are firstly defined as a framework for the assessment, and will be optimised later.

## 1.1 Considered wind farm characteristics

The main characteristics of a floating offshore wind farm are described, as well as the considered options according the turbine and the substructures involved in the project.

### 1.1.1 Wind turbine

As reported in D1.1 [1], a 15 MW reference wind turbine will be used in the tool. The turbine is the IEA 15 MW defined by NREL with HAWC2[1] implementation by DTU. Its official definition was already published on March 2020 to serve as an open benchmark that is defined with publicly available design parameters to be used as a baseline for studies [2]. The overall parameters of this turbine are shown in Table 1.

**Table 1. Overall parameters for the IEA 15MW turbine (adapted from [2]~~D1.1~~).**

| Parameter | Specification or quantity and units |
|---|---|
| Specific rating | 332 W/m2 |
| Rotor orientation | Upwind |
| Control | Variable speed, collective pitch |
| Cut-in wind speed | 3 m/s |
| Rated wind speed | 10.6 m/s |
| Cut-out wind speed | 25 m/s |
| | |
| Rotor diameter | 240 m |
| Hub height | 150 m |
| Hub diameter | 7.9 m |
| | |
| Drive train | Low speed, direct drive |
| Design tip speed ratio | 9.0 |
| Minimum rotor speed | 5.0 rpm |
| Maximum rotor speed | 7.6 rpm |
| Maximum tip speed | 95 m/s |
| | |
| Shaft tilt angle | 6 deg |
| Rotor pre-cone angle | -4 deg |
| Blade pre-bend | 4 m |
| | |
| Blade mass | 65 t |
| RNA mass | 1017 t |
| Tower mass | 860 t |
| Tower diameter at base | 10 m |

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[1] HAWC2 is an aeroelastic code intended for calculating wind turbine response in time domain (https://www.hawc2.dk/)

### 1.1.2 Substructure technologies

Floating offshore wind concepts emerge as a need to locate new installations further out, and in deeper waters. At depths ranging from approximately 40 m to 60 m, the cost of bottom-fixed and floating wind foundations are comparable, but at depths greater than around 60 m, installing bottom-fixed foundations becomes prohibitively uneconomical and technically challenging [3], so better and more economical solutions must be developed to meet this challenge. The substructure technologies to be developed in the Corewind project are WindCrete and ACTIVEFLOAT floaters. They are based on spar-buoy and semi-submergible concepts, respectively.

**WindCrete** is a monolithic concrete spar platform including both the tower and the floater in a unique concrete member. The use of this monolithic characteristic allows to drive out weak points since joints between the tower and the floater are avoided. The whole structure is in compression state by the use of active reinforcement, and it is designed to avoid traction at any point during the life span of the platform.

The **ACTIVEFLOAT** floater is based on a semisubmersible-type configuration, which means that it has enough waterplane area inertia to face tilting angles with large righting moment. This is reached thanks to three separated columns piercing the water surface, which are the main contribution to the platform stability. A central column supports the wind turbine generator tower while three prismatic pontoons link all the system together below the sea level.

The basic designs for both technologies are described in D1.2 [4]and the advantages and disadvantages for both concepts are summarised in Table 2.

**Table 2. Advantages and disadvantages of the Spar-buoy and Semi-submersible concepts [5].**

| Concept | Advantages | Disadvantages |
|---|---|---|
| Spar-buoy | A relatively simple design for which production is highly scalable, giving potential cost savings through serial fabrication. The design has reduced maintenance requirements as the structure encompasses fewer moving part, due to the absence of an active ballast system. Due to the deep draft and comparatively lightweight top section, the system has excellent stability and buoyancy. | The large draft constrains deployment is shallow waters, and also limits the structure's ability to be towed back to port to undergo maintenance. Furthermore, this requires that the structure be towed out to the deployment area where it will be installed. This requires specialist equipment such as heavy lift cranes and other dynamic positioning vessels, thus increasing deployment cost and risk. |
| Semi-submersible | Can be fully assembled onshore and so it is logistically less challenging. This also means that it can be easily deployed at sea with only basic vessels, such as a tug boat being required. Additionally, the shallow draft gives flexibility of application as it is able to be deployed at shallow depths. The platform can be towed back to port for repairs, reducing the magnitude of risk during maintenance. | The complex nature of the platform means that there are many complex procedures which must be completed to fabricate it, thus increasing deployment costs and risk of defects. The shallow draft of this design requires a high mass in order to give adequate stability and buoyancy to the structure. This system may require an active ballast system, which adds cost and complexity to the construction, along with an increased operation and maintenance burden. |

### 1.1.3 Sites

Different locations with different depths are considered in Corewind project as defined in D1.2. These potential wind farm sites are:

- West of Barra Island, Scotland (UK), 100-meter depth. 20 km off Barra, 100 km off Great Britain. Rocky (basalt) soil.
- Gran Canaria Island, Canary Islands (Spain), 200-meter depth. Distance to shore: 10 km. Sandy soil.
- Morro Bay, California (USA), 870-meter depth. Distance to shore: 60 km. Sandy soil.

The characteristics of these locations and additional information are sourced from previous projects as LIFES50+ and ELICAN, as well as FIHAC partner. They are also summarized in the D1.2, and will be taken into account in the FowApp. The app will be as flexible as possible to provide accurate results and conclusions based on the selected sites.

Both the depth and the characteristics of the seabed are assumed to be the same at each site, therefore varying from site to site but not inside them, for a practical analysis. This consideration will reduce the complexity of the later layout optimisations and allow more generic conclusions.

### 1.1.4 Wind farm capacity

Both LCOE and LCA calculations have to be referred to the same unit, which is defined as 1 MWh of electricity produced. Consequently, the capacity in terms of MW of the floating wind farm must be defined.

According to a *Wind Europe* report [6], Europe's floating wind fleet is the largest worldwide (70%) with a total of 45 MW installed by the end of 2019. This includes Hywind Demo (2.3 MW), SeaTwirl S1 (0.3 MW), Hywind Scotland (30 MW), Floatgen (2 MW), Kincardine Pilot (2 MW) and the Windfloat Atlantic Phase 1 (25.2 MW). The capacity is expected to be significantly increased in the next three years with the installation of projects in the UK, France, Norway and Portugal, ranging between 24 MW to 88 MW [6]. With these ranges and considering the rated power of the turbine in this project (15 MW), a first short-term scenario is defined with a capacity of 60 MW (4 turbines).

Currently, most of the deployed offshore wind farms are based on bottom-fixed turbines. They are located in shallow waters (<30 m) and close to shore (<30 km), generally in less challenging environmental conditions than those found further offshore [5]. The average size of commercial wind farms has been almost doubled over a decade from 313 MW in 2010 to 621 MW in 2019, although significant increases were achieved in 2011, 2017, 2018 and 2019 [6]. The average size of the European offshore wind farms in operation by the end of 2019 was 200 MW, but if non-commercial farms were not considered, the figure would increase. On the other hand, with the growth of installed bottom-fixed capacity, future installations will need to be located further out and in deeper waters [3,7], where the floating technology is likely to be the only choice. Based on this and the mentioned capacity ranges and references, a second scenario is defined with 300 MW (20 turbines).

The Corewind project aims to reduce the costs of the floating technology, and a potential factor to achieve them are the economies of scale. Furthermore, that behaviour is expected by the offshore wind market and already happened with the bottom-fixed technology. Two examples are East Anglia (714 MW) and Hornsea One (1,218 MW), the largest offshore wind farms already supplying electricity to the grid [6]. For that reasons, a FOWF in the long-term scenario is also defined with 1200 MW (80 turbines).

### 1.1.5 Wind farm layouts

In the initial reference layouts, the platforms will be linearly arranged to form a rectangular matrix (Figure 1). This approach will allow a simple starting point to perform initial calculations and establishing a baseline for further works.

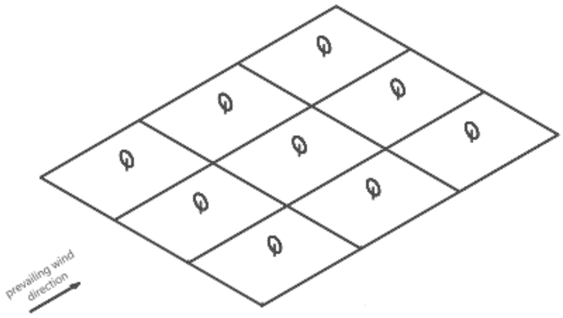


Figure 1. Rectangular layout for the floating wind farm.

The separation for the West of Morro Bay site and WindCrete substructure is set to 9 rotor diameters (2160 m) between both rows and columns. That is the minimum (rounded) distance required to avoid mooring footprint overlapping, if the footprint is defined as a convex polygon where the vertices are the anchors. For the rest of scenarios, the separation is set to 7 rotor diameters (1680 m), a rule that is considered general practice; in these scenarios, the mooring requirements are less restrictive.

A generic wind farm layout is proposed for each wind farm capacity defined, with a distance between rows and columns as per the previous paragraph. Consequently, the initial layouts are site-independent except for the West of Morro Bay site with WindCrete substructures, and are shown in Table 3.

**Table 3. Generic wind farm layouts associated to reference wind farm capacities (rows are perpendicular to prevailing wind direction).**

| Reference capacity | Number of turbines | Number of rows | Number of columns |
|---|---|---|---|
| 60 MW | 4 | 1 | 4 |
| 300 MW | 20 | 4 | 5 |
| 1200 MW | 80 | 8 | 10 |

Both the regular matrix arrangement and separation are likely to change after the optimisation depending on costs, refined (and less restrictive) mooring requirements and wind distribution. Actually, it is expected the evolution experienced by the arrangement of the first (bottom-fixed) offshore wind farms, which was a line or regular layout: the recent wind farms are often characterized by a more erratic layout as a consequence of their optimisation [8].

The layout optimisation model will be defined later, and will take the reference layouts as a baseline. At this stage, it is expected that the model will use the LCOE metric and the impact caused on the energy production and the costs derived from its modification. A reference that may be used for that purpose is the study of Jorge Izquierdo-Pérez et al. [9].

### 1.1.6 Electrical grid connection

The offshore wind farm electrical grids may be divided in two general groups:

- Inter-array cables and grids, which connect the different elements of the wind farm between them.
- Transmission (export) cables and grids, which connect the wind farm to shore.

On the other hand, although not all of them are always used, the elements that integrate the electrical system of FOWFs are:

- Generators, located inside the wind turbines.
- Cables.
- Connection nodes, to allow multiple cable joints.
- Substations, equipped with switchgear, transformers and/or converters.

Due to the high-power nature of FOWFs, the grid voltages are increased to reduce the power losses in the conductors; when the voltages are greater than 30 kV, two technologies are available:

- High Voltage Alternating Current. HVAC is the best choice up to 300 MW, unless very long distances are considered (> 200 km) [10]. That is the reason why in the past, most of offshore wind farms were connected to the onshore grid via HVAC, taking advantage of the low AC substation cost [11].
- High Voltage Direct Current (HVDC). Most of studies found in literature show the HVDC transmission offers higher advantages from technical and economic point of view for long distances (>50 km) [12,13].

The previous information explains why inter-array grids are usually AC, as the power and length requirements do not economically justify the utilisation of DC. On the other hand, according to the deliverable D3.1, the inter-array cables voltage is set to 66 kV. For that reasons, the inter-array grid of the FOWFs of reference scenarios are defined as 66 kV HVAC.

Regarding the connection to shore, the technology selection must be assessed. Offshore wind power plants continue to increase in scale and distance from shore, thereby designs with HVDC transmission potentially become optimal because of those longer distances and higher power levels [14]. Studies on forward-looking designs compare three different transmission topologies: HVAC, HVDC with a Line-Commutated Converter (HVDC-LCC) and HVDC with a Voltage Source Converter (HVDC-VSC) [15].

These studies show that for a distance to shore of 150 km and a power plant capacity of 117 MW, HVAC transmission loss can be 12% higher than HVDC [16]. For a wind farm capacity between 500 MW and 1000 MW and 200 km of distance to shore, the HVDC-LCC has slightly less losses compared to the HVDC-VSC, but both have around 66% less losses than HVAC [15]. However, these studies must be validated and updated using data of power plants in operation.

On the other hand, the investment cost may be considered as a decision threshold. For example, considering a 300 MW power plant, a scenario where the investor for the transmission infrastructure and the wind turbines is a different party (the most common scenario), HVAC is preferable for cable lengths shorter than 80 km and a HVDC-VSC for longer cables. Otherwise, if the investor for the transmission infrastructure and the wind turbines is the same entity, HVDC-VSC is chosen for 35 km and higher cable lengths [17].

According to the details provided, the choice of the configuration for the grid connection to shore is subjected to the wind farm capacity, the distance to shore and the associated costs. The export cables of the West of Barra and Southeast of Gran Canaria wind farms would be shorter than 25 km, therefore HVAC is considered for any wind farm size in both sites. On the other hand, the Morro Bay site is located further (around 60 km), therefore HVAC is considered but the HVDC approach may also be analysed for the 1200 MW farm.

For the 4-turbine farms, offshore substations would represent a high relative cost compared to the wind farm cost. Moreover, the distance to shore is not very high for any site. For that reasons, it appears to be more realistic assessing that farms without offshore substations, connecting the turbines directly to the onshore substation.

For the 20-turbine farms, a 300 MW substation may represent a smaller relative cost, therefore it is considered for Barra and Morro Bay sites. However, the distance to shore in Gran Canaria is relatively small, and the strings may be directly connected to the onshore substation. 5 strings of 4 turbines would ensure a clean cable layout.

In the case of the 80-turbine farms, two 600 MW offshore substations are considered for all scenarios, as their high power justifies their placement regardless of the distance to shore. In this case, 16 strings (8 per substation) of 5 turbines each would also ensure a clean and consistent cable layout.

## 1.2 Reference scenarios

The characteristics defined in section 1.1 are grouped in 17 reference scenarios (Table 4). These scenarios define baselines that will be compared and optimised later in this project.

**Table 4. Reference scenarios for the LCOE and LCA assessment.**

| Scenario | Location | Separation | Capacity | Grid connection |
|---|---|---|---|---|
| 1A | W of Barra | 7D | 60 MW<br>4 WT | Single string to onshore substation |
| 2A | | | 300 MW<br>20 WT | 5 strings to single offshore substation, plus export cable to onshore substation |
| 3A | | | 1200 MW<br>80 WT | 16 total strings to 2 offshore substations, plus export cable to onshore substation |
| 4A & 4W | SE of Gran Canaria | 7D | 60 MW<br>4 WT | Single string to onshore substation |
| 5A & 5W | | | 300 MW<br>20 WT | 5 strings to onshore substation |
| 6A & 6W | | | 1200 MW<br>80 WT | 16 total strings to 2 offshore substations, plus export cable to onshore substation |
| 7A | W of Morro Bay | 7D | 60 MW<br>4 WT | Single string to onshore substation |
| 7W | | 9D | | |
| 8A | | 7D | 300 MW<br>20 WT | 5 strings to offshore substation, plus export cable to onshore substation |
| 8W | | 9D | | |
| 9A | | 7D | 1200 MW<br>80 WT | 16 total strings to 2 offshore substations, plus export cable to onshore substation |
| 9W | | 9D | | |
| 10A* | | 7D | | 16 total strings to 2 offshore substations, 2 cables to offshore converter substation, plus HVDC export cable to onshore substation |
| 10W* | | 9D | | |

A: ACTIVEFLOAT, W: WindCrete, 7D & 9D: rotor diameters of separation, WT: Wind Turbine, (*): Additional scenarios that eventually may be considered out of scope

Relevant notes:

- The IEA 15 MW reference wind turbine will be used in all scenarios, as the optimisation of wind turbines is out of the scope of the project.
- Scenarios are referenced by a number and a letter, which identifies the substructure used (ACTIVEFLOAT or WindCrete). The WindCrete spar cannot be used in the West of Barra due to its draught.
- The wind farm layout (relative turbine positions) of the reference scenarios depends on the wind farm capacity according to Table 3.
- A 66 kV HVAC inter-array grid is considered for all scenarios.

The LCOE and LCA of the reference scenarios will be compared using the new FowApp. Some of the scenarios will also be used by other work packages for the optimisation of specific farm parameters, procedures or components.

## 2 The Floating Offshore Wind Assessment Tool: FOWAT

The FOWAT was developed during the European H2020 Lifes50+ project as a MATLAB-based tool to perform LCOE, LCA and Risk assessments of the reference FOWFs of that project. In the Corewind project, a new app has been developed (allowing the calculation of the same parameters for the Corewind scenarios, but with many new features and improvements) based on such tool. To allow a comparison between the original tool and the new app, the former is described in this chapter (based on Lifes50+ D2.2 [18]).

### 2.1 Description of the FOWAT

The tool is made of three main modules:

- Economic evaluation. This module includes LCOE calculations, as well as its variation due to uncertainty ranges introduced in some of the inputs.
- Environmental evaluation module. It includes LCA analysis using three indicators (Global Warming Potential, Non-fossil abiotic depletion potential, Primary Energy consumption).
- Risk evaluation module. Performs technology risk assessments.

The tool includes two additional modules based on the results of the previous modules:

- Multicriteria ranking generator using the following weighting factors:
    - LCOE: 70%
    - Risk Assessment: 20%
    - LCA: 10%
- KPI report generator. It evaluates the quality of the LCOE and LCA input data using a KPI table.

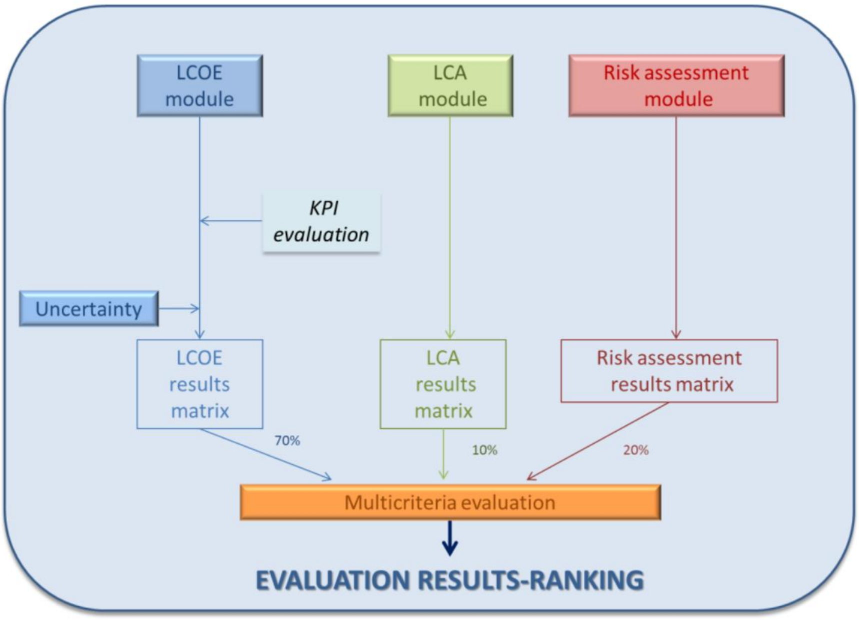


Figure 2. FOWAT structure.

#### 2.1.1 LCOE module

Lifetime energy production and LCC are calculated to obtain the LCOE of the different concepts. The LCC includes information of the different phases of a project (CAPEX, OPEX and DECEX), in particular:

- Development & design. It includes all activities up to the point at which the official orders for production and purchasing are made.
- Manufacturing & acquisition. Includes the wind turbines, the floating substructures, mooring lines and anchors, offshore transformer substation, onshore substation and cables. Transport costs to shipyard (for the substructure) or port (for all the other components) are included in this stage.
- Transport. Includes the costs of transportation of the different components between the shipyard, the port and the offshore site during the construction stage. It is the sum of the port activities cost plus the offshore transportation cost.
- Installation. Includes the installation costs of turbine + substructure, anchor + mooring, electrical system, commissioning and insurance.
- O&M. Includes fixed costs that occur annually for operating the FOWF as well as costs related to maintenance activities.
- Decommissioning. Includes disassembly and transportation of turbines + substructures, anchor + mooring, power cables and offshore + onshore substation. Moreover, it considers the final treatment of the components and the site clearance.

On the other hand, the energy produced by the farm is calculated as the available wind energy minus the sum of losses, to obtain the net energy delivered to the grid annually. The available wind energy is obtained using probabilistic data of the wind speeds. On the other hand, the considered losses are as follows:

- Turbine aerodynamic mechanical losses due to cut-in wind speed, power coefficient for different wind speeds and cut-out speed.
- Wake losses caused by the wake effects from the neighbouring wind turbines. The wake loss coefficients must be introduced in the tool as it is not designed for their calculation.
- Grid connection losses in the collection grid, transmission grid and substations. The HVAC power loss calculation is performed using a simplified equivalent circuit for both collection and transmission grid. Additionally, dielectric loss is considered for transmission grids (negligible for the collection grid voltage). Finally, the substation loss is calculated using an efficiency.
- Availability losses due to farm downtime, expressed as an efficiency rate.

Some of the inputs also have an upper and lower bound to deal with uncertainties and perform a sensitivity analysis. The tool calculates 750 simulations for each concept, with the aim of obtaining a distribution curve describing its LCOE behaviour. The statistical analysis of these distribution curves determines the concept design ranking based on economic aspects.

### 2.1.2 LCA module

In the FOWAT, the goal of the LCA assessment is to quantify and compare the environmental impacts of the developed concepts. For this purpose, a unit of structure is considered as functional unit. The function of this substructure is to support 10MW turbine during 25 years. Three environmental impact assessment categories are quantified:

- GWP Climate Change, measured in $CO_2$ equivalents.
- Abiotic Depletion Potential, measured in Antimony (Sb) equivalents.
- Net Primary Energy, measured in MJ equivalents.

The considered life cycle stages in the LCA are:

- Manufacturing. It considers the raw materials consumption and handling, as per the required material types and quantities. 12 materials are available.

- Transport. For the transport from the material supplier to the manufacturing facility, the impacts are calculated depending on the distance, the weight and the type of transport. However, the distance and type are predefined for three suppliers: local, European or world. On the other hand, the impact of transports between the shipyard, port or offshore site are calculated according to the vessels consumption.
- Installation. The environmental assessment of the installation stage is based on the energy consumption of the vessels and equipment used to install the structure.
- O&M. Fuel consumption of the vessels and auxiliary means used in maintenance operations are considered.
- Decommissioning. On the one hand, the impacts related to the decommissioning process are calculated considering the fuel consumption of the vessels and auxiliary means used. On the other hand, the same quantities and types of materials specified in manufacturing phase are considered to be managed during their end of life and their impact depends on their destination (incineration or landfill).

### 2.1.3 KPI analysis

One purpose of technical KPIs is to complement the LCOE analysis and provide quantitative information on aspects of platform performance that are not considered or not fully accounted for in the cost calculations. In combination with the LCOE tool, they would help trace back any differences in costs to differences in technical characteristics, including assumptions and operating conditions. The different KPI types used are:

- Collection of values chosen for key design parameters.
- Basic configuration and sizing.
- Outputs from the numerical simulations of the Design Load Cases.

The farm properties analysed are grouped in categories, each one with many KPIs associated to one of the previous types. The categories are:

- Static stability performance.
- Loads, reserve factor and survivability. These include scantling loads for the site, partial material properties, corrosion, thickness of walls and plates, resonance issues, mooring and platform fatigue life.
- Turbine operating conditions. These include the following subcategories: heel angle at nacelle, horizontal acceleration at nacelle, max total bending moment at tower base, tower mode excitation and rotor-nacelle assembly load variations
- Power production.
- Use of marine space.

### 2.1.4 Multicriteria analysis

This module reads the results of the LCOE, LCA and risk modules and provides a final concept design ranking. The results of the source modules are converted from their units to scores ranging 1 to 4 (except for the risk module, which already has scores as output). Each score is given a weighting factor: 0.7 for the LCOE, 0.2 for the risk and 0.1 for the LCA. The final score of each concept is the sum of the weighted scores, and the ranking is proposed being the best concept the one with the highest score.

## 2.2 Tool structure

The tool has two modes of operation:

- **Single Mode** for the assessment of a FOWF at a specific location. LCOE, LCA and Risk assessments may be conducted, and KPI report can be produced. In this case, a single LCOE value is obtained, therefore uncertainty is not considered.
- **Evaluation Mode** to compare all designs and locations. In this mode the ranking may be obtained. For the LCOE, no breakdown of costs nor energy is produced, but uncertainty is considered.

### 2.2.1 Single mode

Before reaching the mode menu, the user must select a location, a substructure and a wind farm capacity. Once there, the user can:

- Edit general data and wind conditions related to the selected location.
- View and edit some of the wind farm definition elements. The wind turbine and selected substructure can be seen, as well as the predefined layout. Also, grid connection parameters and a scheme of it are shown.
- Calculate the LCOE of the defined wind farm. A section is dedicated to energy production parameters view and edit, another section has a guided process to input the different life cycle costs, and a third section is for results visualisation.
- Calculate and view the three environmental parameters as per the LCA.
- Calculate and view the four commercial risk values for the defined farm.
- Generate a report with all KPI parameters.

### 2.2.2 Evaluation mode

The evaluation mode menu allows:

- Viewing the wind farm layouts and wind conditions of the wind farms.
- LCOE comparison using uncertainty assessment. It provides graphical representations of the LCOE distribution values and ranks the farms as per ANOVA and Tukey tests.
- Calculating and ranking the LCA impacts for all concepts at once.
- Calculating and ranking the risk values for all concepts at once.
- Providing different KPI reports based on concept developers and locations.
- Performing a multicriteria evaluation and ranking according to the LCOE, LCA and Risk modules results and the defined weighting factors.

## 2.3 Limitations of the FOWAT

The following characteristics of the FOWAT limit its functionality and the possibilities of its adaptation to evaluate additional wind farms and designs.

### 2.3.1 Internal structure

Limitations related to the tool internal design and operation.

- The data used by the tool is stored in Excel workbooks. The tool access that information directly, using predefined ranges and worksheet names that may have to be changed to fetch the same information of different concepts. This limits the maximum number of projects and concepts to be stored.
- 736 files and 110 folders are required to run the application, which adds complexity if the tool needs to be modified.
- Some figure structures are repeated, adding more complexity to the program edition.

- Developed with MATLAB GUIDE (deprecated).

### 2.3.2 Usability and appearance

Limitations related to the user-friendliness.

- The window size change from figure to figure.
- The window location changes from figure to figure, an important drawback when working with a large screen or more than one screen.
- Some information is defined before reaching the mode menu.
- The information is visualised in a linear way, requiring more steps to reach the desired window.

### 2.3.3 Wind farm definition

Limitations related to the inputs that can be added or modified.

- The tool has a high degree of hard coding, which means each concept included cannot be edited without altering the program.
- The program itself cannot cope with additional designs. For example, it does not expect any number of wind turbines when the farm is defined, it only expects 1, 5 or 50 turbines. New projects cannot be added.
- One offshore substation is mandatory. Two grids are required: collection and transmission.

### 2.3.4 Lifetime energy production calculation

Limitations related to the energy production evaluation.

- The wake losses are not calculated by the tool. Hence, an external tool is required to perform that calculation.
- The grid losses are estimated using average power and the grid configuration must follow a specific pattern in order to calculate them.
- The cable properties must be defined for each connection.

### 2.3.5 LCOE

Limitations related to the cost evaluation.

- Discount rate and wind farm lifespan are fixed parameters.
- There is little flexibility on the project lifetime processes definition.

### 2.3.6 LCA

Limitations related to the environmental evaluation.

- The LCA module code cannot be edited due to the requirements of its developer.
- The substations impact is not considered.

# 3 The Floating Offshore Wind Assessment app: FowApp

In the Corewind project proposal it was stated that the FOWAT was going to be adapted in order to assess the wind farms defined in the project. The expected works of the adaptation were introducing the new information in the same format as the existing information, and modifying the tool programme to deal with that information and provide similar results. However, having observed the tool limitations after a deep examination (see chapter 2.3), the responsible team decided creating an assessment app, in contrast to the modification of the FOWAT. While the original tool and the new app share the same objective, the internal structure and the way the information is introduced has been deeply changed.

## 3.1 Core changes

Next, the key and main changes are described.

### 3.1.1 App designing

The FowApp has been developed using the MATLAB App Designer [19]. It allows more functionalities and is more suited for app creation than its predecessor. Each figure of the app is a class; therefore, the scripts are mainly object oriented.

A great effort has been made to give the FowApp a standard application appearance, similar to any commercial app. This has been made to increase the user friendliness, as a considerable amount of information is managed by the app. Improvements such as the window size and location fixing during transitions have been done for the same reasons. For both data input and output, the window arrangement has been completely modified.

### 3.1.2 Data storage

The only data stored in folders are pictures; other folders contain program files, input .xlsx templates or the user guide, but nothing that is modified by the user through the app. The reason is that the data is stored into an SQLite database [20]. It allows storing the data used by the app in a more organised and solid way, as well as using its engine to manage errors and relate data. Furthermore, SQLite is open source and the information stored may be used and modified by any other app to perform any other type of assessments. Compared to other databases its functionality is limited, but it has been selected due to its simplicity and portability.

One of the new features of FowApp is that the user can create new projects (wind farms) and define new components and their properties. Actually, almost any part of the wind farms may be edited by the user, which would not be possible without a linked database. In fact, such flexibility is the main difference between the FOWAT and the FowApp.

The fact that the data is stored into a database has allowed the distinction between the projects and the app library:

- The app library contains generic information that may be used in different projects, such as environments, FOWF components (turbines, substructures, etc.) and auxiliary means.
- Each project contains specific information, such as the wind farm layout, the grid connection or the construction process definition. References to the library are done when necessary.

### 3.1.3 External applications

No inputs from external applications are required to run the FowApp, which means all the process to obtain, for example, the LCOE of a FOWF, may be developed exclusively in the app environment. However, at some stages it may be useful or faster importing data from other apps than introducing the data manually in the app. To that end, some .xlsx templates have been produced.

The MATPOWER software [21] is used and completely integrated within the FowApp. This software is a MATLAB based toolbox for power flow analysis that accurately estimates the energy losses by the electrical collection and transmission systems given the power produced by the turbines and the connection layout. The details of the grid losses determination using MATPOWER can be seen in section 3.2.8.

## 3.2 Specific changes related to energy production

### 3.2.1 Wind climate definition and visualisation

A wind climate may be associated to each defined environment and is required to perform energy calculations. Wind climates are introduced in the app by importing a predefined .xlsx template with information about the wind height, directions, speeds and probabilities.

The defined wind climate is now visualised in a wind rose, according to common practice.

### 3.2.2 Wind turbine performance

Wind turbine performance data is imported using a .xlsx template. The thrust coefficient may be now visualised in both the table and graph.

### 3.2.3 Cables

As previously stated, the cables definition is now in the library of the FowApp as a cable catalogue, decoupled from the connection definition for each wind farm. While the cable parameters are the same, the following can now be estimated:

- Inductance: based on conductor section and distance between conductors.
- Capacitance: based on conductor section, distance between conductors and insulation relative permittivity.
- tan(δ): dielectric loss factor, based on insulation material.

### 3.2.4 Substation definition

Four different types of substations may now be defined and integrated into the electrical grid of any wind farm project:

- Offshore transformer substation (OTS). These substations only include reactance and reactive compensation as an option. The substation reactance may be estimated using the following transformer parameters: VA rating, primary voltage and short-circuit voltage.
- Reactive compensation substation (RCS). The only electrical parameter of these substations is the reactive compensation.
- Offshore converter substation (OCS). These substations are electrically defined by its efficiency and possible reactive compensation.
- Onshore substation (ONS). Electrical parameters: efficiency and possible reactive compensation (ignored in the case of a DC transmission grid).

### 3.2.5 Electrical system definition

The power system is divided by grids as follows:

- Any number of AC grids, with the same frequency but different voltages.

- None or a single low frequency transmission grid. If an offshore converter substation is assigned to the project, then the low frequency grid is considered, and its frequency and voltage must be defined. The grid frequency must be set to 0 for DC grids.

The electrical system of each project is defined by a graph. The graph nodes can be:

- Any number of generation units, each connected to a single grid.
- Any number of submarine connection nodes, also none. Each node must be connected to a single grid.
- Any number of OTS, also none. These substations must be connected to two grids, with the same frequency but different voltages.
- Any number of RCS, also none. These substations are connected to a single grid.
- None or a single OCS. These substations must be connected to two grids, with different frequencies and different voltages.
- A mandatory onshore substation, connected to a single grid (mainland grid omitted).

On the other hand, the graph edges represent the connections and include the following parameters:

- The grid to which the connection belongs.
- Origin and end nodes.
- Connection (cable) length.
- Connection (cable) model.
- Connection (cable) average operating temperature.

The electrical system may be visualised in a table with customizable sorting order. Additionally, it can also be visualised as a graph, with a variety of display options.

The defined power system may be automatically checked. In particular, the elements checked are:

- Connections between the wind farm elements.
- Assignment of cables to all connections.
- Defined connections for all grids.
- Internal connection of grids.
- Grids interconnection.

### 3.2.6 Wind data extrapolation

The wind turbine power curve depends on the wind speed at hub height, therefore the wind data provided during the environment definition needs to be extrapolated. According to ROM.04-95 [22] and the Coastal Engineering Manual [23], the vertical wind profile can be separated into three regions:

- Constant shear region: from 0 to 100 m height.
- Ekman region: between the constant shear region and the geostrophic region.
- Geostrophic region: starts at 200-1000 m height ($z_g$), depending on the surface roughness.

The wind speed variation with height may be represented by a logarithmic spiral which depends on the surface roughness [24]. However, in the ROM it is stated that an empirical profile is better for the Ekman region. Consequently, the wind speed at a certain height can be calculated using the equation 1.

$$v = \begin{cases} v_{ref} \cdot \frac{\ln\frac{z}{z_0}}{\ln\frac{z_{ref}}{z_0}}, \; z, z_{ref} \le 100\,m \\ v_{ref} \cdot \left(\frac{z}{z_{ref}}\right)^{\beta}, \; z, z_{ref} \ge 100\,m \end{cases}$$

equation 1

Where $z_0$ is the roughness height and β depends on the roughness. In the cases where $z$ and $z_{ref}$ belong to different regions, an intermediate step needs to be carried on at a height of 100 m.

The following table is a relevant subset of table 2.1.2.2.1 in the ROM [22]:

**Table 5. Parameters required to extrapolate the wind speed at different heights.**

| Surface | $z_0$ [m] | β | $z_g$ [m] |
|---|---|---|---|
| Open seas | 0.001 – 0.01 | 0.12 | 200 |
| Sea with large waves | 0.01 – 0.3 | 0.16 | 300 |

The intermediate values $z_0$ = 0.01 and β = 0.14 are selected, as lower values would give more accurate results for weak winds (related to calm seas), but these winds are not common at the wind farm locations and may be under the cut-in wind speed. On the other hand, higher values would give more accurate results for strong winds (rough seas), but the effect would be only relevant for the cut-out wind speed, which is not a usual working zone of the turbine; in all other cases the wind turbine would be working at rated power, regardless of the wind speed.

### 3.2.7 Wake model

Wake losses are now calculated by the app, therefore a wake model has been developed and implemented.

Average power losses due to wind turbine wakes are of the order of 10 to 20% of total power output in large offshore wind farms [25] therefore they play a relevant role when it comes to compute the LCOE. Several wake models have been developed to estimate these losses, each one with different purposes, accuracy and complexity [26]. As the aim of the tool is calculating the AEP (Annual Energy Production) of the wind farm, a simple wake model may estimate the losses with acceptable accuracy.

The implemented wake model is based on the Jensen/Katíc (Park) model [27], where mass conservation is applied (equation 2):

$$\begin{cases} \pi r_0^2 v_0 + \pi (r^2 - r_0^2) u = \pi r^2 v \\ r = r_0 + kx \end{cases}$$

equation 2

Where:

- $r_0$ is the rotor diameter.
- $v_0$ is the velocity behind the rotor.
- $r$ is the radius of the wake at a distance $x$ from the generator.
- $u$ is the ambient wind velocity.
- $v$ is the velocity in the wake at a distance $x$ from the generator.
- $k$ is the wake decay coefficient.

Solving for v using the equation 3:

$$v = u\left[1 - \left(1 - \frac{v_0}{u}\right)\left(\frac{r_0}{r_0 + kx}\right)^2\right] \qquad \text{equation 3}$$

Jensen assumed the wind speed behind the rotor is equal to 1/3 of the speed in front of it ($v_0/u = 1/3$), which corresponds to the optimal working point of an ideal wind turbine. However, that is not accurate and, if used, it only works between the cut-in and the rated wind speeds. Nevertheless, wind turbine manufacturers provide the thrust coefficient ($C_t$) for each working point, and the relation between the wind speeds in front of and behind the rotor can be expressed in terms of it [28], as shown in equation 4 :

$$\frac{v_0}{u} = \sqrt{1 - C_t(u)} \qquad \text{equation 4}$$

The previous relation is valid for the full working range of the turbine and gives more accurate results, therefore the wind velocity in the wake may be expressed as in equation 5:

$$v = u\left[1 - \left(1 - \sqrt{1 - C_t(u)}\right)\left(\frac{r_0}{r_0 + kx}\right)^2\right] = u(1 - \delta) \qquad \text{equation 5}$$

Jensen used a value k = 0.1, but further research and experience indicates that for offshore applications a lower value of k = 0.04 is recommended [29]. On the other hand, $\delta$ is known as the speed deficit, and it gains importance when wake interaction occurs. In that regard, Katic assumes a kinetic energy deficit equilibrium per equation 6.

$$\delta_i = \sqrt{\sum_{j=1}^{n} \delta_{ij}^2} \qquad \text{equation 6}$$

Where:

- $\delta_i$ is the speed deficit of turbine *i*.
- *n* is the number of turbines.
- $\delta_{ij}$ is the speed deficit only caused by turbine *j* over turbine *i*.

There are several ways to compute the wake superposition effect in the literature, although no general agreement has been reached [30,31]. Is for that reason that the original Katic assumption (quadratic) is followed.

Jensen noted that if the presence of the terrain (or sea) surface is not considered, the rate of recovery would be overestimated after a certain distance. For the 10 MW and 15 MW reference turbines, the lowest height reached by the blades is 30 m. Using a wake decay coefficient of 0.04 implies that such effect starts 750 m behind the rotor (approx. 4D and 3D respectively), although the distance should be larger to observe a relevant effect. Conversely, Steen Ole et al. [31] suggest that the wake reflection should not be considered because it would require high wake decay coefficients to match experimental measurements, and the procedure would not be consistent according to CFD analysis. Moreover, it has been stated that overlapped wakes increase the turbulence intensity, which increases the wind speed recovery [30]. This may compensate the wake reflection omission, as both effects are only relevant for far wakes. In this situation of uncertainty, it is preferred keeping the model simple, which in turn speeds up the calculations, therefore wake reflection is omitted.

The wind data at a wind farm location is usually given for a number of speed and direction bins. It has been checked that relatively wide direction bins increase the model accuracy [26], which is the case of the tool as it requires only 16 wind direction bins. Consequently, the speed deficits are calculated as the average of the speed deficits changing the wind speed direction by a rate of 0.9º (25 calculations per bin) between the upper and lower direction bin limits. This solves the problem of using the top hat wakes instead of a gaussian distribution.

### 3.2.8 Grid losses

The grid losses are calculated using power flows for improved accuracy. This is achieved by integrating the MATPOWER in the FowApp. The assumptions made are:

- Wind turbines are considered PQ nodes with Q = 0 Mvar.
- The offshore transformer substations only have reactance, no resistance.
- If a low-frequency transmission grid is considered, a separate power flow is calculated for it (as MATPOWER does not support hybrid grids).
- There can only be one onshore substation (slack node).

The grid losses are calculated for each combination of wind speed – wind direction. To obtain the annual average, each combination is weighted according to the statistical wind data of the site.

For additional information on how the MATPOWER works, refer to its documentation [21].

## 3.3 Specific changes related to the LCC

### 3.3.1 Auxiliary means

The used auxiliary means have also been migrated to the app library, avoiding its definition for each project and stage. Four types are considered:

- Heavy equipment: includes cranes, etc.
- Land transport: includes trucks.
- Vessels: includes all vessels used during the wind farm lifetime such as crew transfer vessels, floating drydocks, tugboats, etc.
- Air transport: includes helicopters and drones.

A fuel type must be indicated for each auxiliary mean. The average fuel consumption in operation is defined depending on the auxiliary mean type:

- For trucks, the average fuel consumption per 100 km must be introduced.
- For the other means, the fuel consumption is stored as l/h. It can be introduced directly, or estimated according to the fuel type, the man engine(s) total rated power and the main engine(s) efficiency.

The rates may include fuel consumption costs, and they also depend on the auxiliary mean type:

- For trucks, rates are defined as €/100 km.
- For the other means, the rates are specified as €/day.

### 3.3.2 Generation units

Generation units are defined for each project by the following components:

- A wind turbine from the library.
- A substructure from the library.
- A tower from the library, if it is not included with the substructure.
- A mooring line from the library, the number of mooring lines per generation unit and its length.
- An anchor from the library and the number of anchors per generation unit. Allowing a different number of anchors to the number of mooring lines opens the door to layouts with shared anchors.

### 3.3.3 Construction process

The user interface figures required to define the construction process have been reduced to two. In them, any number of stages can be included to represent land transport, storage, assembly, loadout, sea transport, installation or commissioning activities. The construction process is sequentially defined, therefore for each stage the previous stage(s) must be indicated. In each stage the following elements may be defined:

- Expenses: area leasing, labour, light equipment and indirect cost percentage.
- Auxiliary means assignment: indicating the mean, quantity, rental days, operating hours per day, distance to cover and mobilisation / demobilisation costs. Some fields may not be relevant, depending on the selected auxiliary mean type.

Stages may be defined as overall or to be repeated for each generation unit.

### 3.3.4 Maintenance activities

The information related to maintenance activities is the same as for the construction stages, but defined by groups and not sequentially. These activities may correspond to preventive or corrective maintenance, and are also grouped by component type.

### 3.3.5 Decommissioning

A study has been carried out to ensure the data collection on FowApp corresponds with the current decommissioning procedures for oil platforms, as there is no experience on the field directly related to FOWFs. Some guidelines have been obtained from [32], although floating platforms are not mentioned. A more detailed report has been consulted for further detail [33].

The decommissioning has been structured in three parts:

- Pre-decommissioning: including planning and other costs previous to mobilisation.
- Dismantling and transport. This part is structured like the construction process and may include the following stages: site preparation, disconnection / disassembly, retrieval, sea transport, site clearance, unload, storage and land transport.
- End of life. See chapter 3.4.3.

## 3.4 Specific changes related to the LCA

The specific main changes at FowApp level are described from the section 3.4.1 to 3.4.3. However, the detail description of the LCA module is performed in section 3.5.

### 3.4.1 Component materials assignment

All components of the wind farm may be subdivided in parts. One or more materials may be assigned to each part, indicating its family, name, weight and generic supplier (source).

### 3.4.2 Auxiliary means

See chapter 3.3.1.

### 3.4.3 End of life

The end of life defines what is eventually done with the components of the wind farm at the end of the project. According to the parts and materials assigned to each component when it was defined (see chapter 3.4.1), the options considered in this stage are landfill, incineration, sale/reuse, recycling and leave on site.

## 3.5 FowApp LCA module development

This section is dedicated to describe the framework of the FowApp LCA module to evaluate the potential environmental impacts considering the entire life cycle of the FOWF. The LCA is the tool applied in the Corewind project in order to provide a multicriteria analysis to select the best concept design from environmental point of view. The LCA methodology and how the LCA is performed to support the assessment is described in the next sections. Then, the structure of the LCA module is also described to understand its working in the FowApp.

LCA is an analysis tool which quantifies environmental impacts of a project, product, service or process, throughout its lifecycle, from raw material acquisition to end-of-life (EoL) management. The entire life cycle for a man-made product goes from obtaining everything needed to make the product, through manufacturing it, using it, and then deciding what to do with it once it is no longer being used. Returning to the natural life cycles described above, this means going from the birth of the product to its death. As such, this kind of view is often called a "cradle to grave" view of a product, where the cradle represents the birthplace of the product and the grave represents what happens to it when we are done with it [34].

LCAs have many uses, such as providing a means to systematically compare impact of inputs and outputs of two projects, products or processes, identifying which stages of a life cycle have the greatest environmental impacts, establishing a comprehensive baseline to which future research can be compared, providing guidance in the development of new products; to verify a product's environmental claims, and to provide information to decision makers in industry, government and non-governmental organizations [35]. LCA guidelines have been established by the International Organization for Standardization (ISO) 14040 family of standards [36,37].

### 3.5.1 Methodology

The life cycle assessment applied in Corewind project follows the life cycle stages specified in the mentioned standards as showed in Figure 3. These stages are described in the next sections aligned to the project.

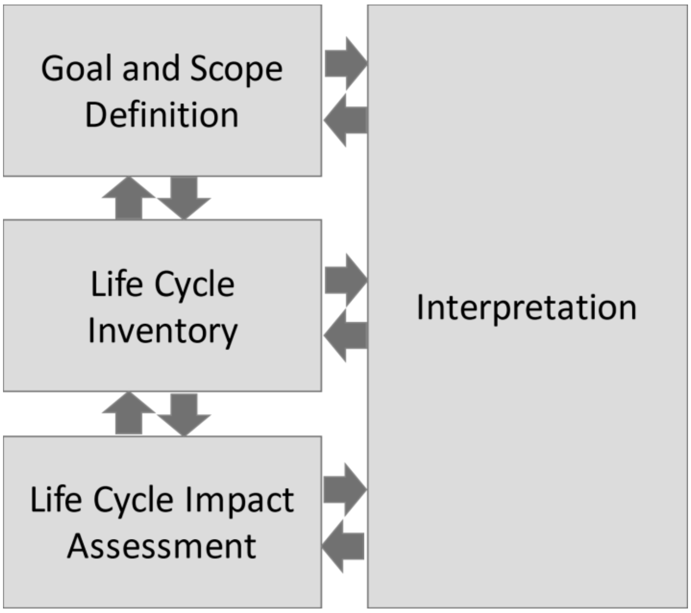


Figure 3 Phases of an LCA study (ISO 14040/44:2006) [34,35].

#### *3.5.1.1 Goal and scope definition*

The goal addresses for what the study is intended and the audience. The scope is defined considering the functional unit (FU) that provides the quantified description of the performance of a system. The FU defines as the amount of product, material, or service to which the LCA is applied. It is used to put the data on a common basis for direct comparison. On the other hand, the system boundaries, data quality, flow reference and the methodological considerations are stablished in this stage.

In this light, the objective of this study is to quantify the emissions of an offshore floating wind farm designs by conducting an LCA. In this step we identify which are the most relevant environmental criteria concerning the adoption of green practices for the floating offshore wind farm designs of the Corewind project. The LCA is aimed to:

- Find suitable environmental metrics to quantify the environmental impacts.
- Locate those components/sub-components or sub-processes responsible of the highest environmental impacts.
- Have useful information in order to reduce the environmental impacts and to improve plant's performance.

**Functional Unit:** the FU is defined as 1 MWh of electricity generated and delivered to the onshore electricity grid during the lifetime of the wind farm. This FU is easily comparable to the performance of the other power generation technologies used in Europe. This allows the impacts associated with the measured performance to be comparable. According to the industrial experts involved in the project, the lifetime is different for each technology developed in the project. For the WindCrete approach, the lifetime could be between 50 to 60 years, while 25 of operation for the ACTIVEFLOAT. For the LCA application in the FowApp, we have decided to take the lower limit (50 years) for the WindCrete.

**Reference Flow:** in this project, a reference flow is characterized by a single, complete wind farm inclusive of turbines, floating substructures, mooring lines, anchors, inter-array cables, export cables, and three substations. Furthermore, the reference flow includes the complete operational lifetime.

**System Boundaries:** the system boundaries follows the cradle to grave approach as shown in Figure 4 including raw material extraction and energy as inputs and emissions and waste outputs for all stages in the life cycle: component production, installation, use phase (maintenance) and decommissioning of the FOWF.

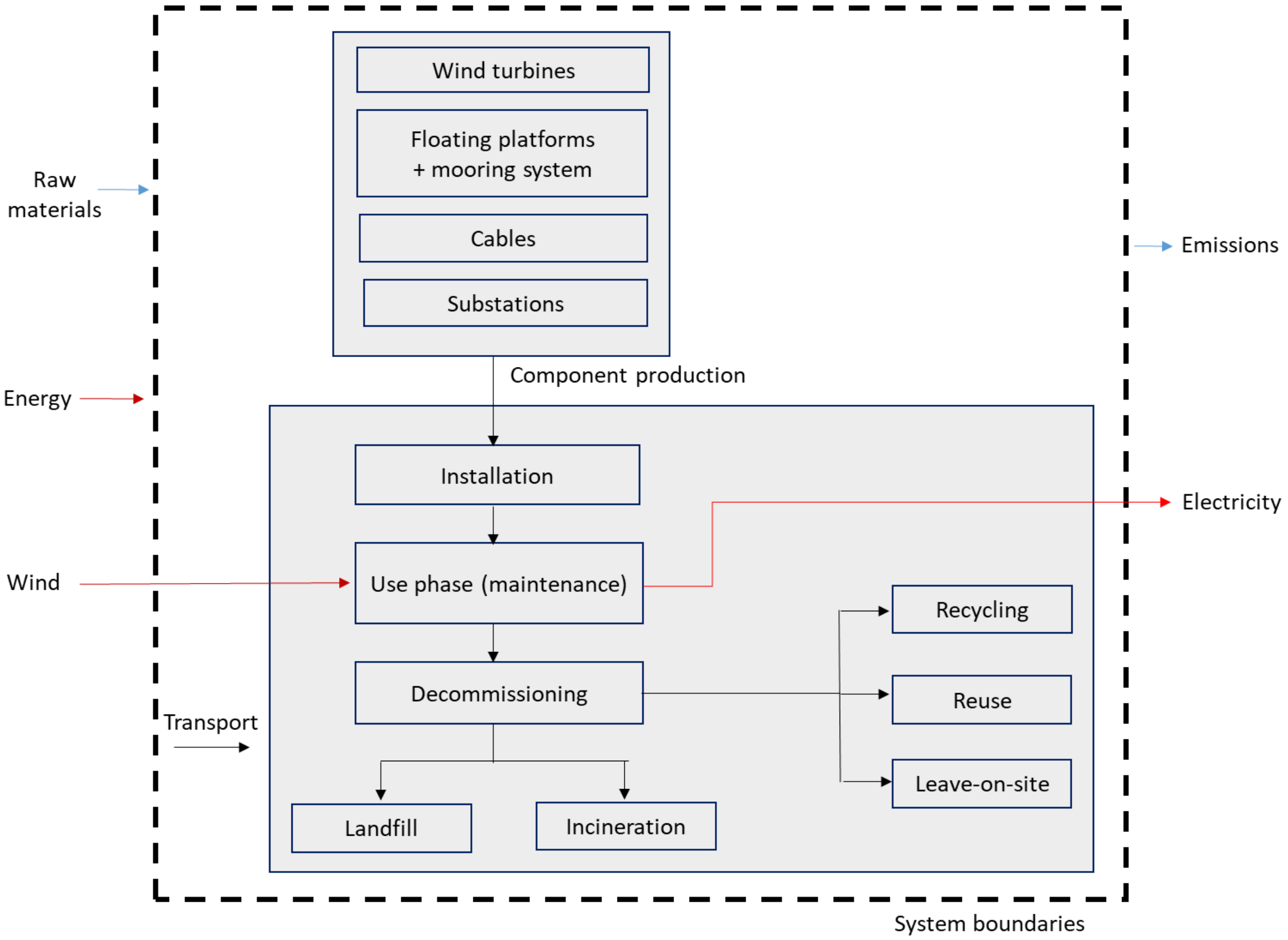


Figure 4 System boundaries of the Corewind LCA study.

### *3.5.1.2 Life cycle inventory (LCI) analysis*

This phase involves the collection of all data required to characterize the system including flows in terms of materials and energy for the product under the study. The data collected in this phase consider all the environmental and technical quantities for all relevant unit processes within the system boundaries.

The LCI is the critical phase to conduct a reliable and representative LCA since it depends of the data quality. In this sense, data gathering for LCA studies can represent a difficult task, thereby IREC prepared a data gathering protocol for the LCA of the FowApp as internal document. This document was shared with the partners involved in WP6. It is focused on the steps to collect data to manufacture the floater technologies developed in Corewind project.

Figure 5 shows basic steps that are recommended during LCI stage to be aligned with the rest of stages of the LCA. The activities of sub-task task 6.1.3 involves the step 1 (identification of required data), thereby the identification of partner’s contacts, who are working on the technical WPs involved in Corewind project, was firstly done. Then description of the project technologies (new and conventional technologies) with their materials, energy (inputs) and product, emissions and wastes (outputs) are carried out. Based on the description, data gathering charts/templates with the adequate information, which would be in accordance with the real processes, were generated and sent to the partners to starts the life cycle inventory data for the turbine, substation, cables, substructures (ACTIVEFLOAT and WindCrete) and the mooring system.

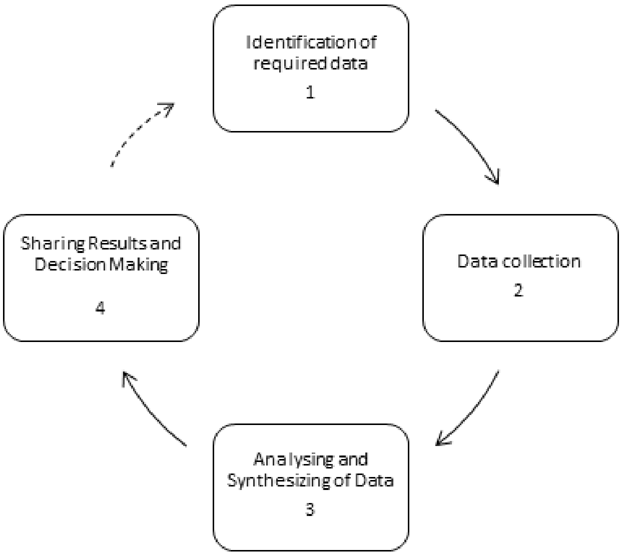


Figure 5 Data gathering protocol that was followed the LCI.

The data acquired through the LCI templates are used along with the data from the literature to complete the LCI of the wind farm in order to identify and collect the data pertaining to the various materials comprised within the different components/sub-components of the various parts of the wind farm.

Based on the above, the construction of the LCI take into account the life cycle stages that have an influence in the LCA assessment. This process has been started in task 6.1 to be continued in task 6.2, since the collection data will be carried out during the execution of this last task.

Under this scenario, the following paragraphs describe the approach taken into account by the tool to quantify the environmental impact of each them in next steps of the project.

**Component production:** the impact of the component production is calculated while considering the raw materials consumption and handling. Types and quantities of materials are the parameters needed for the assessment, which are also required for the environmental impact calculation of transports. During the analyzing and synthesizing of the inventory data, the environmental impacts per kg of material are calculated to be incorporated in the database of the FowApp.

Table 6 shows a summary of the main materials by components.

Table 6 List of main materials considered in the component production LCI

| Component | Material |
|---|---|
| Cables | Lead |
| | Copper |
| | HDPE |
| | LDPE |
| | Reinforcing Steel |
| WINDCRETE Foundation | Slag (by-product) |
| | Concrete |
| | Reinforcing Steel |
| ACTIVEFLOAT Foundation | Concrete |
| | Reinforcing Steel |
| Tower (ACTIVEFLOAT) | Reinforcing Steel |
| Tower (WindCrete) | Concrete |
| | Reinforcing Steel |
| Mooring System | Hot Rolled Steel |
| | Reinforcing Steel |
| Turbine | Glass Fiber |
| | Polyurethane |
| | Epoxy Resin |
| | Carbon Fiber |
| | Cast Iron |
| | Reinforcing Steel |
| | Copper |
| | Steel (low alloyed) |
| | Magnet |

| | |
|---|---|
| | Steel (Chromium) |
| Substations | Steel (low alloyed) |
| | Glass Fiber |
| | Rubber |
| | Aluminum |
| | Paint |
| | Cellulose |
| | Porcelain Enamel |
| | Oil |
| | Copper |
| | Concrete |
| | Reinforced Concrete |
| | Polypropylene |
| | Epoxy Resin |
| | Polyvinylchloride |
| | Polyester Resin |
| | Sulphur hexafluoride |
| | Tetrafluoro ethylene |
| | Silver |
| | Tin |
| | Zinc |
| | Corrugate board box |
| | Brass |
| | Flat Glass |
| | Polycarbonate |
| | Cast Iron |
| | Wood |

**Installation:** there are a series of activities that take place in preparing a site and manufacturing components for installation. This leads to energy consumption mainly associated with the transport (vessels and equipment used to install the structure), which will be taken into account for the environmental assessment in this stage.

**Use (Maintenance):** the approach for calculating the impacts of this phase is the same as used for the installation phase, this means that the fuel consumption of the vessels and auxiliary means used in maintenance operations are considered.

**Transport: l**argely, eight different kinds of transportations can be identified considering the whole life cycle of the FOWF, such as shown in Figure 6.

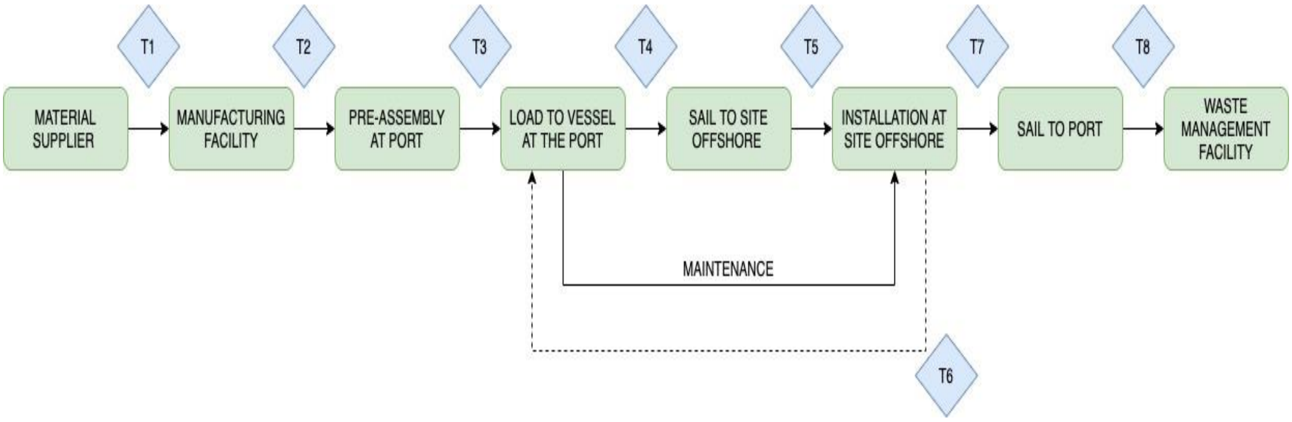


Figure 6. Transportations within the life cycle structure of the wind power system.

An initial scenario is assumed where the erection and assembly of the floating substructure with the turbine will be done at the Port.

During the transportation stage, the environmental impact is associated to the energy used to transport the different parts of the floating offshore wind farm [38]. The way to calculate the impact depends of the transportations shown in Figure 6 and described as follows.

Transport T1:

This stage corresponds to the transportation of raw materials from the supplier to the manufacturing facility.

*Parameters considered*

- Distance from supplier to manufacturing facility, km.
- Weight of material to be transported, kg.
- Type of transport (lorry or freight ship/barge).

*Default data*

In most of cases the user of the tool will not know the specific location of the raw materials supplier nor the specific type of transport, therefore, we have decided to use three transport scenarios as defined in Life50+ project [18].

Table 7 . T1 transport default scenarios.

| Scenario | Acronym | Distance, km | Transport type |
|---|---|---|---|
| Transport from local supplier | FLS | 50 | Lorry |
| Transport from European supplier | FES | 2000 | Freight ship |
| Transport from rest of the world supplier | FWS | 8000 | Transoceanic freight ship |

*Modifiable data in the tool*

This information will be introduced by the user during the manufacturing phase definition.

- The weight of the materials to be transported (associated to the material quantities of the different elements of the FOWF).
- A transport scenario from Table 7.

*Example*

For each material, 3 different options exist depending on the supplier. For instance, for the steel reinforcing material:

- Steel Reinforcement (FLS).
- Steel Reinforcement (FES).
- Steel Reinforcement (FWS).

If the user indicates 50 kilograms of "Steel Reinforcement (FLS)", the tool calculates the environmental impacts of the material on the one hand and the transport by lorry of 50 kg of this material along 50 km on the other hand.

Transport T2 and T8**:**

These stages correspond to the road transport of wind farm components and component parts. While T2 refers to the construction phase, T8 is part of the decommissioning phase.

*Parameters considered (all modifiable in the tool)*

- Road distance, km.
- Truck type
- Required number of trucks (may be estimated using the weight of the element to be transported)

Transport T3 and T7:

These stages make use of vessels (barges, tugboats, crane vessels, jack-up vessels, excavators, cable laying vessels, etc.) or air units (helicopters and drones). A common approach is considered for all of them: the assessment is based on the fuel consumption and combustion of the vessels or air units. For this purpose, the tool calculates the fuel consumption of each transport and translates it to impacts based on the information of its database.

That approach is considered more relevant than the distance in this case, as the speed of the transport means is not always constant (tugboats) and may be idle but burning fuel (SOV) or working and moving at the same time (CLV) [39]. Moreover, the required data is more reliable than the consumption per km.

*Parameters considered (all modifiable in the tool)*

- Operating time (or equivalent operating time), h.
- Transport type.

<u>Means of transport and fuel consumption:</u>

Specific means of transport may be defined and stored in the FowApp database as project-independent data as well as the fuel consumption parameters.

*Trucks*

The LCA-related parameters for each stored truck are:

- Fuel consumption in l/100 km (a parameter that can be found for many truck types).
- Fuel type.

*Vessels and air units*

The LCA-related parameters for each stored transport are:

- Fuel hourly consumption during operation.
- Fuel type.

The fuel consumption expressed in l/h is a typical parameter for both vessels and helicopters because it can be measured. However, the tool will be able to make the estimation using other known parameters according to the equation 7:

$$FC = \frac{EC \cdot P \cdot 3600}{(\eta/100) \cdot t \cdot \rho} \qquad \text{equation 7}$$

Where:

- *FC* is the fuel consumption, l/h.
- *P* is the rated main engine power, MW.
- *η* is the engine efficiency, %.
- *EC* is the power specific fuel consumption, kg/MWh
- *ρ* is the density of the selected fuel, kg/l.
- *t* is the duration of the trip in hours, h

*Fuels*

Fuel data is stored in the FOWAT database as project-independent data. For each type of fuel, the following LCA-related parameters are defined:

- Power specific fuel consumption, kg/MWh.
- Impact on each considered indicator per kg of fuel consumed

- Density of the fuel in kg/l.

**Decommissioning:** The decommissioning process of the wind farm is usually the reverse of the installation; removing the electrical structure, the rotor, the nacelle, the tower, then the transition piece and finally removing the foundation. Hence, decommissioning is assumed to be a reflection of installation [20]. After the dismantling and sorting of the decommissioned specific components, materials can be destined to different EoL processes or scenarios. For the FowApp, the EoL process encompasses five types of scenarios:

- Landfill
- Incineration
- Recycling
- Reuse/Sale
- Leave-on-Site

The environmental impacts associated with the dismantling and material sorting account the fuel consumption of the vessels and auxiliary means used in this phase. To do this, the transportation and parameters such as the number, types of vessels and equipment and hours of duration of decommissioning operations are needed.

On the other hand, the same quantities and types of materials specified in component production stage are considered materials to be manage during the EoL of the FOWF. In order to quantify the impact. The user indicates the destination of these materials or components according to the EoL scenarios mentioned above. In a summarized way, the parameters in which the assessment is based are: quantities, types of materials and waste management plan or scenario for each of them.

EoL process description:

The options to manage the waste includes landfill, incineration, reuse/sale, recycling and leave-on-site, are described as follows:

*Landfill*

The cheapest option is landfilling, but since the organic content in most parts of the wind farm is considerable, for example, in rotor blades is around 30 % only [40], this is banned in many countries and the last resort in European countries according to the waste hierarchy. For example, in Sweden it is prohibited to send any organic or combustible waste to landfill and in Germany landfilling is prohibited [41].

*Incineration*

Blade materials and many other materials from the various components of the wind farm may be incinerated for energy recovery. This solution is currently used in Denmark. It has however several drawbacks. Structural composite material, such as the one used in wind turbine blade contain up to 70%wt. of glass fiber. Energy recovery is difficult, as glass fibers are not combustible and will hinder the incineration [42]. It has also been reported that the presence of glass fibre in the flue gas could disturb the gas cleaning system [6]. Finally, the large amounts of fly ashes, which will come from the combustion of large structure such as blade, will remain at the end of the combustion process. This residue also needs to be disposed of or used [43].

*Recycling*

Parts from the system that are not reused for practical or economic reasons should if possible be recycled. The average recyclability for an entire wind turbine (excluding the foundation) is calculated to be around 80 %, where most of the non-recycled material is found in the rotor blades [40]. Most of the wind turbine mass comes from the tower, blades and gearbox, and the main materials are steel and fibreglass. Due to the demand and technological availability for recycling, some materials, for example steel and aluminium, have a higher scrap value. These types of commodity materials do not require a lot of efforts since there are already efficient ways to recover them and a market for demand and supply. Other turbine parts, like blades, which are made out.

EoL best practice scenario

Since the turbine and substructures are constituted by different materials, the entire system to be disposed cannot not treated homogeneously. Therefore, a base case scenario for the EoL by materials should be firstly stablished based on the specific recycling rates of different components depending of the major material they are built from, material purity and easy dismantling.

Table 8 shows the major materials used in the project with the recycling, incineration, and landfilling ratios. These ratios are on previous researches and LCA literature [43–53]. Any other materials obtained from the dismantling process of the wind turbine array, is assumed to be totally landfilled.

Table 8 EoL best case scenario according recycling, incineration, and landfilling ratios.

| EoL - Recycling, Landfilling and Incineration ratios (%) | | | |
|---|---|---|---|
| **Material** | **Recycled** | **Landfilled** | **Incinerated (no energy recover)** |
| Iron | 90 | 10 | 0 |
| Lead | 90 | 10 | 0 |
| Zinc | 90 | 10 | 0 |
| Polymers (TFE, PVC, PP, PE, Polyester, Epoxy Resin, Paint, Carbon fiber) | 30 | 40 | 30 |
| Other Plastics | 0 | 0 | 100 |
| Glass Fiber | 0 | 0 | 100 |
| Lubricants | 0 | 0 | 100 |
| $SF_6$ | 0 | 0 | 0 |
| Steel | 90 | 10 | 0 |
| Aluminum | 90 | 10 | 0 |
| Copper* | 90 | 10 | 0 |
| Concrete | 100 | 0 | 0 |
| Oil | 0 | 0 | 100 |

| | | | |
|---|---|---|---|
| Rubber | 0 | 0 | 100 |
| Slag | 100 | 0 | 0 |
| Magnet | 100 | 0 | 0 |
| Silver | 100 | 0 | 0 |
| Wood (Timber, Cellulose fiber) | 100 | 0 | 0 |
| Glass (Enamel Porcelain/$B_2O_3$, Flat glass) | 100 | 0 | 0 |
| Brass | 100 | 0 | 0 |
| Tin | 100 | 0 | 0 |

(*) According to expert of the technologies, concrete can be as a substitution of gravel in other concrete structures or for bases in streets and roads.

EoL allocation 50-50 approach in the LCA

When LCA involves recycling of materials needs a method for allocation of processes and avoided emissions that fits the goal and scope definition of the assessment. Nevertheless, the issue in LCA is how to allocate the environmental benefits of recycling, with respect to the use of virgin materials, between the process being studied (process A) and another process being out of the system boundaries (process B). Both of them are involved in the flow of secondary materials. To do this, two 'extreme' approaches can be found in the literature: recycled content (also named as cut off approach) and the EoL approach, but there are also options to go in between [49]

The cut off approach takes into account secondary materials that are input to a process have zero attached environmental burden except for energy use and transport for collection, sorting, etc. Secondary materials on the output leave the product system without any further environmental [49].

In the EoL approach, secondary materials that are input to a process have the same attached environmental burden as virgin materials. Here, secondary materials on the output side leave the product system causing extra environmental burden (energy use for melting and transport for collection, sorting) as well as an environmental bonus (avoided burden virgin material production), i.e., the benefit of recycling goes entirely to the process A [47].

We have chosen a combined approach adapted from the 50-50 approach [47]. The approach would divide the 'bonus' over wind farm system and another process being out of the system boundaries. The recycling process (collection, sorting) is not divided being to go the wind farm system and the avoided final waste treatment is assumed to go another process. The 50-50 approach is shown in Figure 7. It is worth noting that environmental burden for recycling process is applied as zero because of the lack of the information.

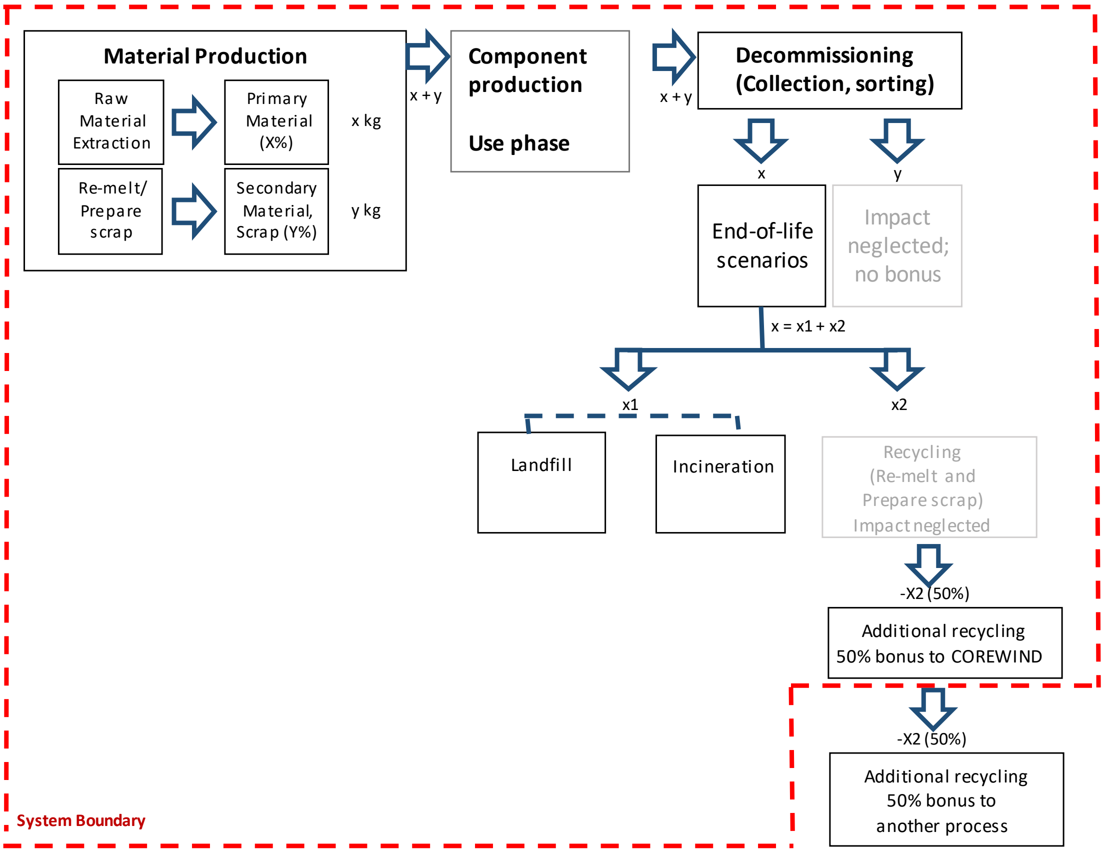


Figure 7 EoL recycling 50-50 approach.

*Reuse/Sale*

Another option that either the whole plant or parts of it is sold for secondhand use on another location. However, a report carried out by the Swedish Energy Agency and several other Swedish wind power associations [54] concluded that there is no regular secondhand market in place, and that the technical advancements are so rapid that it is difficult to find use for old parts in new projects. The first and simplest EoL solutions for wind turbine blades is to be reused after being decommissioned, this way, their service life is extended.

Reusing wind turbine, wind turbine blades and/or other components of the wind farm may be technically possible. In this case, when the user selects which component can be reused or sold, according to its background, the FowApp assumes to consider the residual environmental performance as a benefit for the system studied. To do this, a factor is used to calculate the impact of the component or part that can be reused by using a factor (FWL/CRL), that takes into account the residual lifetime and the lifetime of the whole wind farm as shown in equation 8.

$$CI = CRI \cdot \frac{FWL}{CRL} \qquad \text{equation 8}$$

Where:

- *CI* is the impact of the component adjusted to the lifetime of the system in units of the environmental category assessed.
- *CRI* is the initial impact of the component to be reused in units of the environmental category assessed.
- *FWL* is the lifetime of the wind farm floating in years.

- *CRL* is the lifetime of the component to be reused in years.

*Leave-on-Site*

During decommissioning post the end of the service life of the turbine, some components are left on-site or buried under the seabed as per the concerned regulatory laws. This is mostly done due to economic reasons, however, there are some environmental benefits too that are associated with this leave-on-site scenario of EoL of some of the components [55]. The environmental risk associated with leaving the foundation in situ can in some cases, be considered as relatively low compared to the environmental impact generated with excavation, breaking, processing, and transporting activities needed to remove it [56]. Scour protection around the foundation, if any, as a general rule, can also be left in situ, as life will have flourished and so it is not disturbed. However, if it is recognised to become a hazard, it will be dredged.

Concerning the electric infrastructure, the subsea cables are usually buried between 1 to 2 meters [57], and therefore could be left in situ. Their complete removal would require excavation and pulling out of the trenches and given their extensive length, this would produce an important marine disruption, as well as notable costs [58].

Similar arguments are found for the substructures. A 'renewables-to-reefs' programme was also proposed, where the environmental and economic benefits of a partial removal were shown, as opposed to complete removal, especially if the habitat created on the left structures has conservation or commercial value [59]. Substructures could definitely become habitats for marine wildlife, such as fish or crustaceans [60].

Despite there is a big debate between the need of a total or partial removal [55], partial removal as more beneficial than complete is also suggested, and it strengthens the idea of turning already existing jackets in artificial reefs, as an example of a green decommissioning. Conclusions on this matter are by studies, where biodiversity enhancement, provision of reef habitats, and protection from bottom trawling are negatively affected by the complete removal of offshore wind farms [58,61]. All the contributions also highlight the strong link between the regulatory framework and the environmental impacts.

Based on this scenario, the environmental impact pertaining to the end of life scenario of the components which were left-on-site is assumed to be zero in the FowApp LCA model.

#### 3.5.1.3 Life cycle impact assessment (LCIA)

This phase calculates the potential for specific environmental burdens each impact category assessed. There are several impact categories that can be assessed, as well as multiple characterization factor models to quantify the categories.

Midpoint impact categories are considered in this study for the impact assessment, which can suitably represent the environmental profile of the floating wind farm according to the goal and scope definition. The impact categories assessed in this study are at midpoint level since they reduce uncertainties associated with assessing the potential environmental damages. They consider the environmental implications that are more important for the system studied, mainly associated to the energy consumption, affecting the climate change and primary energy demand, damage to the soils and ecosystems and harm to human health. On the other hand, the susceptible concern for the natural resource consumption (minerals).

Seven environmental categories to be considered for the LCA model are described as follows:

- **Global Warming Potential (GWP), CML 2001- Jan. 2016 – kg $CO_2$ eq:** this metric describes the emission of greenhouse gases that lead to increased radiative forcing and raise in mean global temperature.

- **Abiotic Depletion Potential Elements (ADPe), CML 2001- Jan. 2016 – kg Sb eq:** abiotic resources are non-living natural resources. The ADPe is a measure of the potential depletion of minerals.
- **Primary Energy Demand from renewables and non-renewables (PED) – MJ:** PED is a measure of the potential primary energy consumption prior any process, i.e., the energy available in primary or natural resources such as fossil fuel.
- **Acidification Potential (AP), CML 2001- Jan. 2016 – kg $SO_2$ eq:** AP measures the increased acidity of soil and water due to proton release from anthropogenic emissions.
- **Eutrophication Potential (EP), CML 2001- Jan. 2016 – kg $PO_4$ eq:** EP measures increased biomass formation and loss of biodiversity due to release of nutrients.
- **Aquatic Toxicity Potential (ATP), USEtox 2.1, Ecotoxicity – CTUe:** ATP is a measure of the potential of a chemical emission to cause adverse impacts on the ecosystem.
- **Human Toxicity Potential (HTP), USEtox 2.1, Human Toxicity, cancer – CTUh:** HTP is a measure of the potential of a chemical emission to cause adverse impacts on humans.

To perform inventory analysis and to classify elementary flows by emissions, we need to know the specific environmental impact of these categories per kg of material. These impacts are obtained using the GaBi software version 10.1 and the values are incorporated in the database of the FowApp.

In this sense, the app will be able to calculate the total impacts ($_T$) for each category. Calculation examples are shown for the following categories:

$GWP_T = \sum_{i=1}^{n} kg\ material_i x\ kg\ CO2\ eq\ per\ kg_{\ i}$

$ADPe_T = \sum_{i=1}^{n} kg\ material_i x\ kg\ Sb\ eq\ per\ kg_{\ i}$

$PED_T = \sum_{i=1}^{n} kg\ material_i x\ MJ\ per\ kg_{\ i}$

### 3.5.1.4 Interpretation

The interpretation phase is dedicated to meet the inventory analysis and the impact assessment to deliver results in consistence with the goal and scope. The impact analysis stage of an LCA takes these data and systematically quantifies the resulting environmental impacts from the material and process data inventoried throughout all life cycle stages within the system boundary. Finally, the improvement analysis stage of the LCA uses the results of the study to identify which processes, underlying materials, or products under investigation can be improved. This can be done by isolating the most harmful or detrimental stages, analyzing the material and energy inputs, outputs, and processes involved in those stages, and identifying methods of reducing related environmental impacts [35]. Evaluating whether a different energy source improves environmental quality and sustainability requires an examination of the entire life cycle of the alternatives [34]. This is in order to make informed decisions, consumer, companies, and government agencies must know the implications of their choices for environmental quality and sustainability [44].

### 3.5.2 Assumptions and limitations of the LCA Study

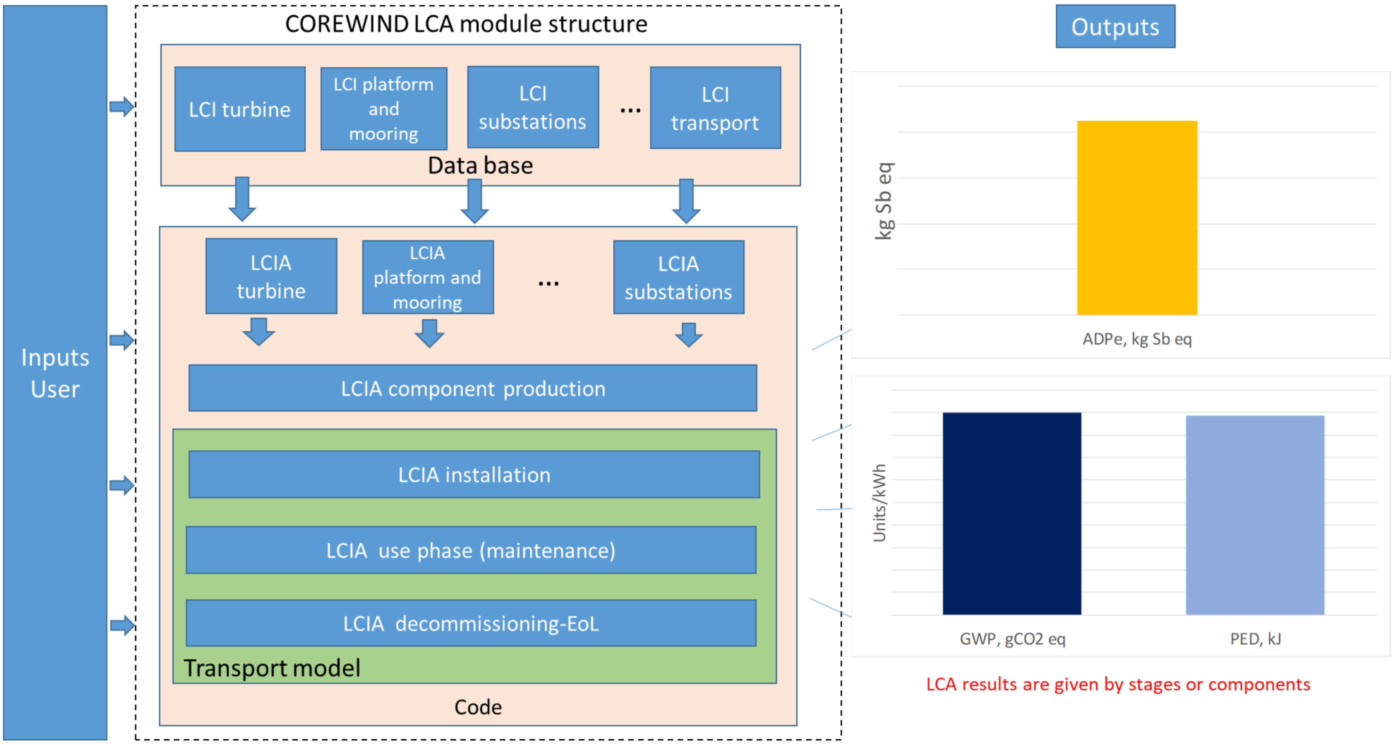
The results of this study are dependent on the availability and quality of data obtained from wind floating farm experts, literature and datasets. Thus, foreground data of components and materials are provided by experts. Background data to calculate the environmental impact per kg of materials are obtained from EcoInvent 3.6, GaBi ts professional Databases and eventually from scientific literature.

Several assumptions are listed as follows:

- This LCA assumes an operational lifetime of 25 years for the FOWF which matches the standard design life. The lifetime of the WindCrete substructure is assumed to be 60 years and that of the ACTIVEFLOAT substructure is assumed to be 25 years.
- The LCA has been developed using a 15MW wind turbine, which is hypothetical due to its non-existence. Therefore, the foreground data has been extrapolated for use in the life cycle inventory with guidance and support from field experts.
- Materials, which were not found in the databases were substituted with materials having similar properties, through consultation from the developers/experts.
- Life cycle inventory consider only materials flows to produce the cables, turbine, mooring system, substation and the substructures. The energy flows to produce the components are not considered. These flows could be considered during the LCI refining process along the project depending of the data availability. In that case, the electricity generation source used in the LCA would be assumed located in Europe as EU-28 mix grid from GaBi database.
- It has been assumed that all the materials which enter the production systems, are sourced as virgin. Nevertheless, some databases from EcoInvent or GaBi st could include secondary materials. In that case, these materials would be considered to get a consistent mass balance in the EoL stage.
- The environmental burden for recycling process is applied as zero because of the lack of the information.
- It is assumed that there are no environmental impacts associated with the EoL scenario of Leave-on-site.
- The life time of components or parts potentially reusable, with higher lifetime than the wind farm life time, is used to calculate the environmental impacts to consider the residual environmental benefits.

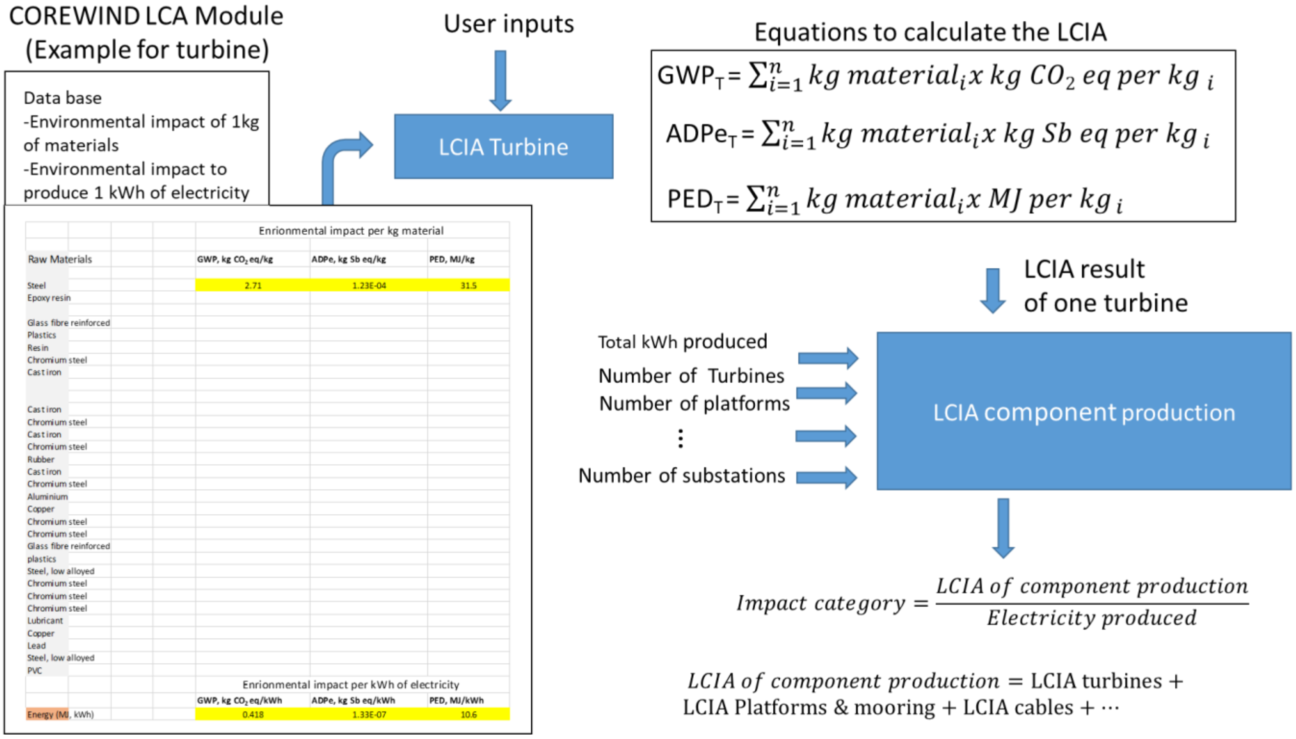
### 3.5.2 FOWAT tool LCA module structure

The LCA model described in the previous section 3.5.1 is used as the framework to construct the LCA module for the FowApp. The LCI parameters related to the life cycle stages, type of the transports and fuels, recycling rates for a best-case scenario in the EoL and environmental impacts per kg, will be introduced in the database of the app. This information and the inputs from the user are organized to perform the LCIA at component level or life cycle stages through the app code and then generate the results for the environmental categories assessed. The user will be able to see the results through charts or tables for the category selected or a group of them, depending the importance to consider on environmental concerns: climate change, use of primary energy, resource depletion, damage to the ecosystem or harm human health. The general scheme of the LCA module can be shown as in Figure 8 and the Figure 9 shows an example on how the LCA module works to calculate the LCIA of the turbine to include it in the LCIA of the component production.



LCA results are given by stages or components

Figure 8 General scheme of the LCA module.



Data base
-Environmental impact of 1kg of materials
-Environmental impact to produce 1 kWh of electricity

| | Enrionmental impact per kg material | | |
|---|---|---|---|
| Raw Materials | GWP, kg $CO_2$ eq/kg | ADPe, kg Sb eq/kg | PED, MJ/kg |
| Steel | 2.71 | 1.23E-04 | 31.5 |
| Epoxy resin | | | |
| Glass fibre reinforced | | | |
| Plastics | | | |
| Resin | | | |
| Chromium steel | | | |
| Cast iron | | | |
| Cast iron | | | |
| Chromium steel | | | |
| Cast iron | | | |
| Chromium steel | | | |
| Rubber | | | |
| Cast iron | | | |
| Chromium steel | | | |
| Aluminium | | | |
| Copper | | | |
| Chromium steel | | | |
| Chromium steel | | | |
| Glass fibre reinforced | | | |
| plastics | | | |
| Steel, low alloyed | | | |
| Chromium steel | | | |
| Chromium steel | | | |
| Chromium steel | | | |
| Lubricant | | | |
| Copper | | | |
| Lead | | | |
| Steel, low alloyed | | | |
| PVC | | | |
| | Enrionmental impact per kWh of electricity | | |
| | GWP, kg $CO_2$ eq/kWh | ADPe, kg Sb eq/kWh | PED, MJ/kWh |
| Energy (MJ, kWh) | 0.418 | 1.33E-07 | 10.6 |

$$GWP_T = \sum_{i=1}^{n} kg\ material_i x\ kg\ CO_2\ eq\ per\ kg_{\ i}$$

$$ADPe_T = \sum_{i=1}^{n} kg\ material_i x\ kg\ Sb\ eq\ per\ kg_{\ i}$$

$$PED_T = \sum_{i=1}^{n} kg\ material_i x\ MJ\ per\ kg_{\ i}$$

$$Impact\ category = \frac{LCIA\ of\ component\ production}{Electricity\ produced}$$

$$LCIA\ of\ component\ production = \text{LCIA turbines} + \text{LCIA Platforms \& mooring} + \text{LCIA cables} + \cdots$$

Figure 9 Schematic example on how the LCA module works to calculate the LCIA of the turbine.

## 3.6 Summary of improvements and new features of the FowApp

All the relevant changes are stated on Table 9.

Table 9. Comparison between the original FOWAT and the new FowApp.

| Item | FOWAT | FowApp |
|---|---|---|
| **Designer** | MATLAB GUIDE | MATLAB App Designer |
| **Input data** | Predefined with limited editing | Add / edit / save / remove capabilities |
| **Inputs from external applications** | Required | Optional |
| **Data storage** | MS Excel and MATLAB files in a structure of 110 folders | SQLite relational database and 10 folders |
| **Appearance** | Specific application | Standard application |
| **Workflow / operation** | • Linear process with coupled project definition / output<br>• Familiarisation required | • Staged process with decoupled library definition / project definition / output<br>• User friendly |
| **Electrical grid nodes** | • >0 turbines<br>• 1 offshore SS<br>• 1 onshore SS | • >0 turbines<br>• Any number of offshore SS<br>• 1 onshore SS<br>• Any number of connection nodes |
| **Grid losses** | Estimated using average power | Calculated using power flows |
| **Component materials** | 1 – 3 | Unlimited |
| **Construction process** | Guided, limited stages | Semi-guided, unlimited stages |
| **Decommissioning** | Summarised | Complete |
| **Environmental metrics** | Concerns to the climate change, primary energy and mineral resources depletion | Concerns to the climate change, primary energy, mineral resources depletion, damage to soil and ecosystems and harm to human health |
| **LCA (EoL)** | Landfill, incineration and sale | Landfill, incineration, recycling, reuse/sale and leave on site, plus best practice definition |

## 3.7 Limitations of the FowApp

The following work may be developed to improve the tool. In some cases, the limitations are on purpose and the reasons are provided.

- The number of wind directions must be 16. The reason is wind data is usually provided in that way, but a different number might be useful. However, narrower wind direction bins (more wind directions) may reduce the wake model accuracy. This could be solved implementing a more accurate wake model. On the other hand, wider wind direction bins (less wind directions) may also reduce the wake model accuracy due to lack of detail in the wind data provided.
- Provided wind speeds and hub heights should be at the constant shear region or at the Ekman region. Although if any of them is in the geostrophic region the application does not crash, the results would lose accuracy. This is only relevant with very large turbines.

- Consider faster wake velocity recover for large wind farms due to increased turbulence [30]. In that case, wake reflection should probably be considered.
- Only one onshore substation is allowed in the model. The reason is that the power flows require only one slack node. If an OPF was performed, then any number of onshore substations would be possible, but the electrical grid optimisation is not the objective of the application at this stage. This is not a relevant limitation for small, medium and most of large wind farms.
- Only one DC grid is allowed. The used PF calculator is MATPOWER, which does not allow hybrid grids, therefore there can only be one connection between AC and DC grids. Although this limitation is not currently relevant, a hybrid solver software, such as MatACDC, may be integrated.
- Offshore substations can only be connected to 2 grids. This is due to the PF calculations and could be solved changing the algorithms or virtually splitting the substations in different substations.
- Only one type of wind turbine is allowed per farm. This may not be a relevant issue.
- Cables ancillary equipment is not considered for dynamic nor static connections.
- Apart from the anchors, mooring ancillary equipment is not considered.
- Rigs to reefs (reefing) is not considered as an option for truss because its impact parameters are not known, but it is a standard practice.
- There is no predefined separation of structure / deck / modules for offshore substations definition.
- Functions for economies of scale for all components may be considered.
- Components with shorter lifetimes than the farm should be replaced, which involves additional materials and intermediate end of life actions (both modifying the LCOE and LCA). There are two options to solve the issue. The first one is automatically adding O&M activities to replace those with shorter lifetimes. An alternative is allowing the user to add components & materials to the O&M activities.
- Uncertainties not considered. Expected in future releases.
- There is no implemented panel to compare farms.

## 4 Final remarks

A general frame has been defined to meet the objectives of task 6.1. On the one hand, a number of reference scenarios have been established. On the other hand, the upgrade of the FOWAT tool (developed in LIFES 50+ project) to the FowApp, with more flexible and intuitive characteristics, has been explained. The main outputs are listed as follows:

- Seventeen reference scenarios for the LCOE and LCA assessment, where the main characteristics describing a wind farm are considered and narrowed down according to the restrictions of the design of the turbine and design basis for both substructure technologies involved in the project. These characteristics (turbine design, substructures, locations, farm capacity, layout and electrical grid connection) are addressed according to the information from the developments from WP1 to WP4.
- Substantial changes of the FowApp compared to the FOWAT tool thanks to the use the MATLAB App Designer to allow more functionalities and the use of an SQLite database for the data storage. The database allows storing the data used by the app in a more organised and solid way, as well as using its engine to manage errors and relate data. Furthermore, almost any data used by the app can be modified by the user. Specific changes have also been conducted for the data input and visualisation, for example for the wind climate or the wind turbine performance. The energy production model has been modified, in particular the substations considered, the electrical connections definition, the wake model and grid losses calculation. Finally, the stages of the wind farm lifetime data input to calculate the LCC have been completely redesigned following flexibility and user friendliness principles.
- A new LCA module considering a cradle-to-grave approach, which activities for its conduction include an identification of materials involving all components of the FOWF to start choosing the most proper database. This allows providing to the app a quality, consistency and completeness model. The LCA module has now several EoL scenarios to give alternatives to the user about the material disposal considering options aligned with of the circular economy, such as the recyclability and reuse/sale to keep the materials in the value chain of the FOWF as much as possible. The environmental impact measurements consider additional categories to take into account environmental concerns related to damage to the ecosystems, the soil and harm to human health.

The next steps include using FowApp to compare the reference scenarios, and extracting relevant information from its outputs to perform the optimisation of the wind farms. Additionally, the application will also be used to provide the final LCOE reduction achieved by innovations during the Corewind project.

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