

# O&M Cost Reduction of Offshore Wind Farms - A Novel Case Study

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## Acknowledgement

This report is written in the context of the “*Operation and Maintenance Cost Estimator (OMCE)*” project by ECN. Within the OMCE approach, a methodology has been devised and subsequently software tools are being developed to estimate and control future O&M costs of offshore wind farms more accurately taking into account operational experience. In this way it can support owners and operators of offshore wind farms to optimise their O&M strategies.

Further development and validation of the OMCE is carried out in the context of the Dutch Far and Large Offshore Wind (FLOW) innovation programme. Within the FLOW programme, a baseline model of the OMCE is being set up by developing software and working procedures using data and feedback from the Rhyl Flats wind farm of project partner RWE. This baseline model is to be implemented and validated in an operational offshore wind farm.

In addition to FLOW, ECN would like also to thank project partner RWE for their assistance and investing time and resources in further development of the OMCE.



## Abstract

This report gives a summary of the FLOW “*Operation and Maintenance Cost Estimator (OMCE)*” project. In this report first a short introduction to operation and maintenance (O&M) of offshore wind farms is given and then, the tools which are further developed through this project for O&M cost estimation are discussed. Furthermore, an O&M study for RWE’s Rhyl Flats offshore wind farm is demonstrated and the results are discussed.

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# Summary

Compared to onshore wind energy, offshore wind is more expensive because of high capital expenditures and high Operation & Maintenance (O&M) costs. With ECN's Operation and Maintenance Cost Estimator (OMCE) approach, historical operational data of the wind farm can be applied to estimate and optimise the O&M costs and downtime for the forthcoming years.

The Dutch government has promoted the Far and Large Offshore Wind Programme (FLOW). The FLOW research programme aims to reduce the costs and risk of far offshore wind energy by 15 to 20%. In 2011 ECN and project partner RWE Offshore Wind Nederland started a FLOW research project with the objective to further develop ECN's OMCE approach using data and feedback from an existing RWE wind farm.

The OMCE approach comprises the Event List, the O&M Data Analyser and the O&M Calculator. Within the FLOW OMCE project three months of operational data of RWE's Rhyl Flats wind farm was manually structured in the Event List resulting in a refined Event List format. The ECN O&M Data Analyser modules 'O&M', 'Logistics' and 'MetOcean' are further developed using this Event List data. Additionally, the O&M Calculator is further developed where its functionality is extended based on feedback from industry.

To demonstrate the OMCE approach, an O&M optimisation study is performed for RWE's Rhyl Flats wind farm. First, a baseline O&M Calculator model is created based on generic assumptions. Next, the Data Analyser tools were applied on the O&M data in the Event List. This showed that component reliability was higher than initially expected and an updated O&M Calculator model is created. The updated model is used to perform a theoretical optimisation study. By reducing the number of workboats and technicians and by improved scheduling of preventive maintenance, the production losses and repair costs can be decreased significantly. Compared to the updated O&M model, the Levelised cost of energy can be reduced by 2.77%.

The next step in the project is to implement the OMCE approach in an operational wind farm for a longer period and to validate the potential cost reduction in more detail. Upon request, ECN can assist the offshore wind industry in applying the OMCE knowledge and tools.



# 1

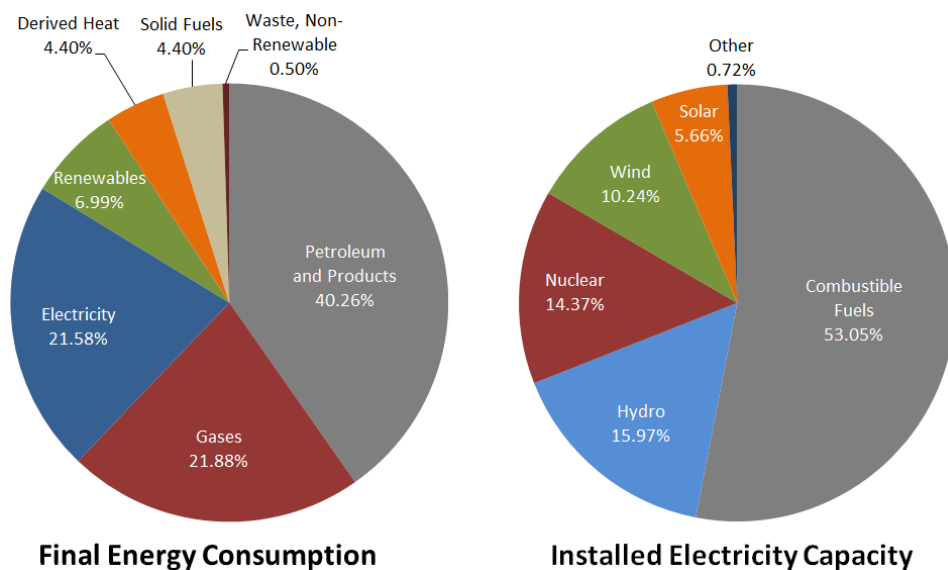
## Introduction

### 1.1 Energy in Europe

The total energy consumption of twenty seven European countries in 2011 was 1103.3 Mtoe<sup>1</sup> or 12.8 PWh [1]. As illustrated in **Figure 1**, still only 7% of the energy demand in Europe is generated by sustainable energy sources and the rest are generated by traditional energy sources with high emissions and environmental impacts.

In 2009, the Renewable Energy Directive of the European Commission established a European framework for the promotion of renewable energy, setting mandatory national renewable energy targets for achieving a 20% share of renewable energy in the total energy consumption by 2020 [2]. Therefore, at least 220.6 Mtoe or 2.56 PWh of energy consumption in Europe should be generated by renewables before 2020.

**Figure 1:** Total energy consumption and installed electricity capacity of 27 EU countries in 2011 [1].



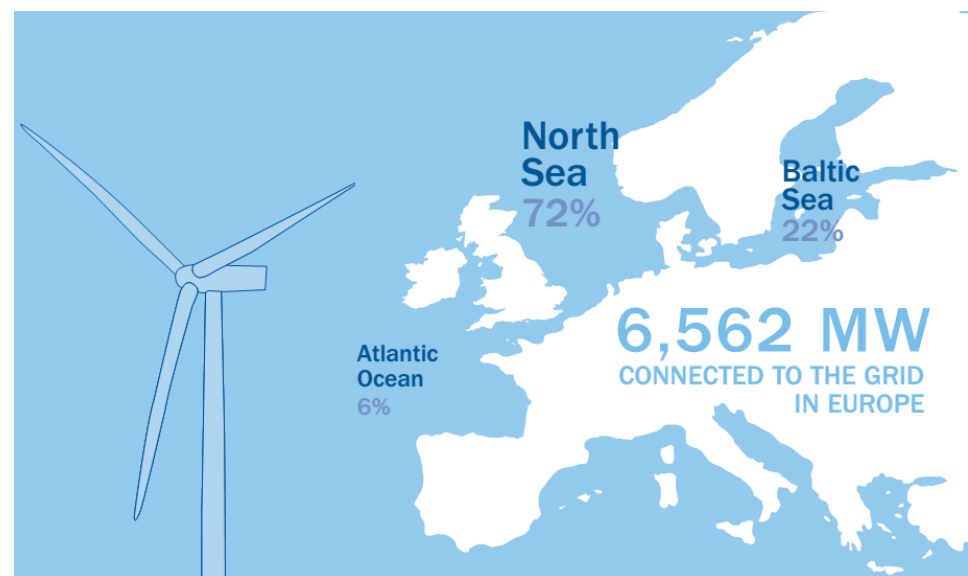
1 Million tonnes of oil equivalent

## 1.2 Offshore Wind Energy

As illustrated in **Figure 1**, wind energy is one of the fastest growing and most promising renewable energy sources in Europe. According to the European member state plans, wind capacity is expected to reach 169 GW onshore and 44 GW offshore by 2020 [2].

By the end of 2013, more than 2000 offshore wind turbines were installed in Europe, achieving a cumulative total of 6.5 GW in 69 offshore wind farms [3]. It means that during the next seven years about one hundred new offshore wind farms (with average capacity of 375MW) should be installed in Europe to cover the planned 44 GW of offshore wind energy by 2020.

**Figure 2:** Distribution of 6.5 GW installed European offshore wind capacity in 2013 [4]



Compared to onshore wind turbines, offshore turbines receive more undisturbed wind and have less visual impact, but they are more expensive because of the following reasons:

1. High Capital Expenditures (CAPEX) caused by sea bed preparation, foundation, electrical infrastructure and installation;
2. High Operation and Maintenance (O&M) costs caused by:
  - more downtime and revenue loss due to the harsher weather conditions
  - expensive offshore vessels and technicians

Currently there are several ongoing national and European projects aiming to increase the reliability of offshore wind turbines, but unfortunately limited attention has been paid to the optimal O&M planning of offshore wind farms.



## 1.3 O&M of Offshore Wind Farms

Wind farm components are deteriorating constantly due to mechanisms such as fatigue, corrosion, wear and erosion. As depicted in **Figure 3** two scenarios can happen:

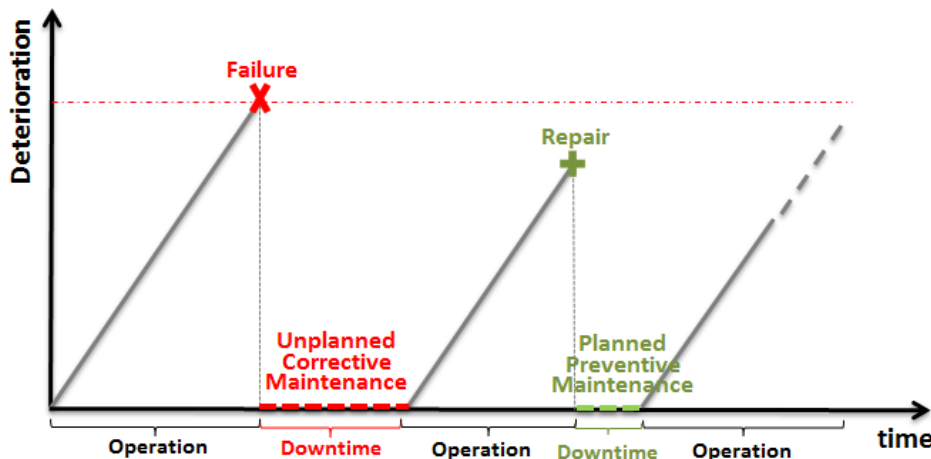
### 1. The component is not maintained in time

In this case the component will fail and corrective maintenance should be scheduled. Normally downtime during unplanned corrective maintenance is high because of the long lead time of vessels and waiting time for a good weather window to sail to the wind farm.

### 2. The component is maintained in time

In this case, preventive maintenance is scheduled before the component fails. In this scenario, maintenance is planned preferably during periods of low wind speeds and the vessels are ordered in advance. Therefore, waiting time for a good weather window is zero. The downtime for preventive maintenance is significantly less than the downtime for unplanned corrective maintenance.

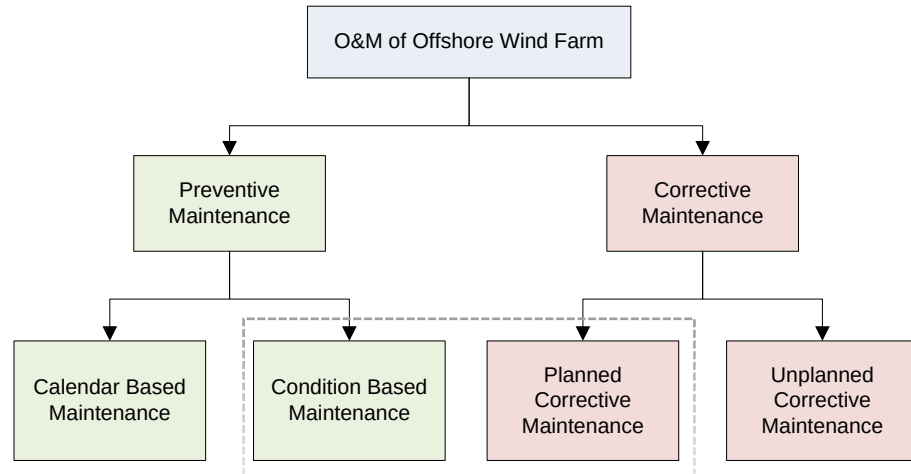
**Figure 3:** Simple deterioration model of a wind turbine component



Clearly planned maintenance is a better maintenance strategy. However, it is difficult and costly to obtain accurate information about the damage state of all wind farm components and to predict their failures before they occur. The information about the damage state of components could be obtained by periodic inspections and Condition Monitoring Systems (CMS) data, but it can't be done for all wind farm components because of the high costs. Therefore, the optimal maintenance strategy is a trade-off between condition monitoring and preventive maintenance costs and the reduction in corrective maintenance costs.

In **Figure 4** the maintenance effort of an offshore wind farm is categorised in four groups.

**Figure 4:** Maintenance effort categorisation for an offshore wind farm



**1. Preventive maintenance:**

- Calendar Based: one or two fixed inspections/repairs per year planned by wind turbine manufacturer regardless of the damage state of components.
- Condition Based: when based on the observed degradation of a component the failure is expected, but is not known when it happens.

**2. Corrective maintenance:**

- Planned: when based on the observed degradation of a component the failure is expected in due time and the maintenance can be planned at a suitable moment.
- Unplanned: when a component fails without any prior knowledge and the turbine is shut down until the component is maintained.

Both condition based preventive maintenance and planned corrective maintenance are initiated based on the observed status or degradation of a component. The main difference between these two categories is that condition based preventive maintenance is foreseen in the design, but it is not known in advance when the maintenance has to be carried out, while the occurrence of planned corrective maintenance is not foreseen at all. This is illustrated by the following examples [10]:

- **Example condition based preventive maintenance**

The oil filter has to be replaced several times during the lifetime of a wind turbine. The oil filter is monitored and the replacement will be done depending on the pollution state of the filter. So it's not the question **if** this maintenance has to be carried out, but **when** it has to be done.

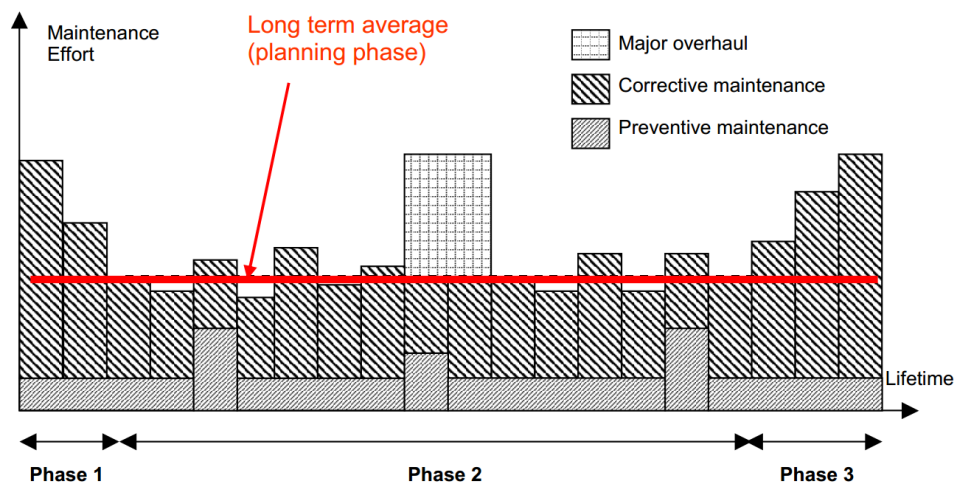
- **Example planned corrective maintenance**

During the lifetime of the turbine it appears that the pitch motors show unexpected wear out and have to be revised in due time to avoid complete failure. Until this revision the pitch system is expected to function properly. On contrary to the example above this maintenance was initially not foreseen, but as it is not necessary to shut down the turbine, the maintenance can be planned such that it can be carried out at a suitable moment.

Considering the limited differences between condition based preventive maintenance and planned corrective maintenance, the planning and execution of both categories will probably be similar in practice.

In **Figure 5** a schematic overview of the maintenance effort over the lifetime of a wind turbine is given. It can be observed that at the beginning of the turbine's lifetime corrective maintenance costs could be higher because of manufacturing errors and teething troubles. Furthermore, corrective maintenance costs are high because of the deterioration of components at the last years of the turbine's lifetime. Therefore, it can be clearly seen that the amount of corrective maintenance effort for a wind turbine follows a so called bath-tub curve. On top of the regular corrective maintenance costs, one or two times per lifetime, major overhauls such as the replacement of the gearbox or pitch drives could be expected.

**Figure 5:** Schematic overview of the maintenance effort over the lifetime of a wind turbine [7]



During the past decades several tools have been developed to estimate the maintenance costs and plan for preventive actions. In 2007 ECN developed the '**ECN O&M Tool**', which is an Excel based tool to estimate the corrective and preventive maintenance costs of offshore wind turbines [7].

The ECN O&M Tool is a well-known tool in the industry for long term O&M planning of offshore wind farms. In this tool results are being calculated using an average value method and no simulations in the time domain are performed. Therefore, as illustrated in **Figure 5** by the red line, the ECN O&M Tool results in long term averages of corrective and preventive maintenance costs. However, the tool cannot provide accurate short term O&M cost estimations based on available operational data. The latter is part of ECN's Operation & Maintenance Cost Estimator (OMCE) approach. With the OMCE approach, historical operational data of the wind farm is applied to estimate and optimise the O&M costs and downtime for the forthcoming years. This will be further explained and demonstrated in this report.

## 1.4 Outline of the Report

This report provides the reader an overview of ECN's OMCE approach and a demonstration of results obtained through the FLOW OMCE research project.

In Chapter 2, the Dutch FLOW research programme is introduced. The OMCE approach is further explained in Chapter 3. By using the procedures and tools which are further developed within the FLOW OMCE project, an O&M study for RWE's Rhyl Flats wind farm is demonstrated and the results are discussed in Chapter 4. Conclusions and recommendations for future work are finally given in Chapter 5.

# 2

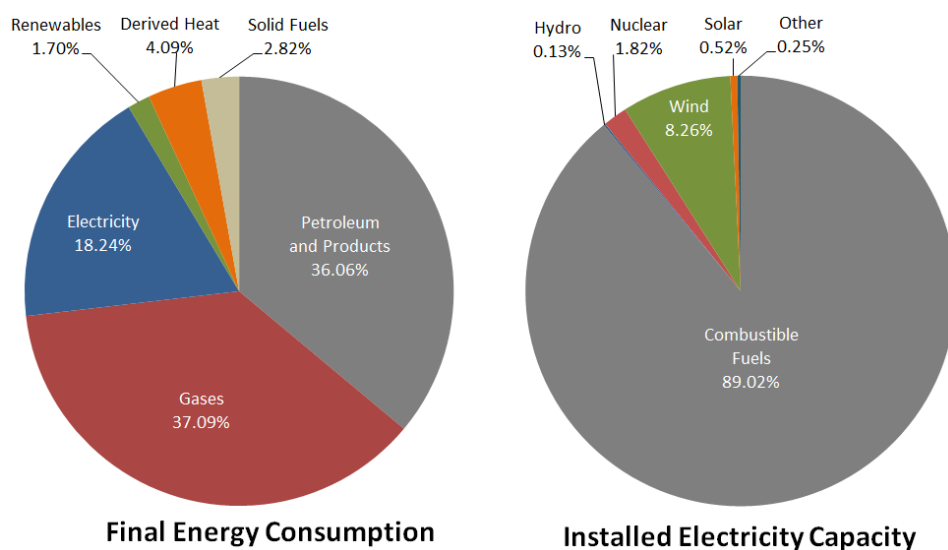
## Dutch FLOW Programme

In the following sections an introduction to offshore wind energy in the Netherlands is given and the Dutch FLOW research programme and OMCE project are described.

### 2.1 Energy in the Netherlands

In **Figure 6** the total energy consumption and installed electricity capacity sources for the year 2011 are depicted. In comparison to Europe, the Netherlands is less focused on using renewable energies. The share of renewables in the total energy consumption is only 2% (7% for Europe) and the share of wind energy in installed electricity capacity is only 8% (10% for Europe) [1].

**Figure 6:** Total energy consumption (left) and installed electricity capacity of the Netherlands in 2011 [1].



Currently the Netherlands has two offshore wind farms, the first one is the 108 MW **Offshore Wind farm Egmond aan Zee (OWEZ)** consisting of 36 Vestas V90-3MW turbines located 10 km far from the Dutch North Sea coast and the second one, 120 MW **Princess Amalia Wind Farm** consisting of 60 Vestas V80-2.0MW turbines located 23 km far from the Dutch North Sea coast. These wind farms were commissioned in 2007 and 2008 respectively.

In addition to the current operational offshore wind farms, multiple farms are in the planning and construction phase, such as:

1. **Gemini Offshore Wind Farm** to be constructed in 2015 with a total capacity of 600 MW consisting of 150 Siemens SWT-4.0MW turbines located 85 km offshore in the North Sea.
2. **Luchterduinen Wind Farm** to be constructed in 2015 with a total capacity of 129 MW consisting of 43 Vestas V112-3MW turbines located 23 km offshore in the North Sea.

The construction of new Dutch offshore wind farms is promising, but in order to meet the European targets by the Dutch government more offshore wind farms need to be developed in the near future.

## 2.2 FLOW Programme

In order to bridge the gap between the Netherlands and Europe in share of renewables, the Dutch government has promoted several research programs such as FLOW, which is devoted to offshore wind energy.

Far and Large Offshore Wind (FLOW) is a research programme of thirteen Dutch companies and knowledge institutions that collaborate on innovation with the aim of accelerating the deployment of offshore wind energy and reducing costs [5].

One of the main objectives of FLOW is to reduce the costs and risk of far offshore wind by 15 to 20%. The programme consists of the following R&D themes:

1. Wind farm design
2. Support Structures
3. Electrical systems and grid integration
4. Turbine development
5. Societal R&D lines

Since 2010 the FLOW programme is running with a total budget of approximately EUR 40 million (half government subsidy) and it is expected to be finished by 2015 [6].

## 2.3 FLOW OMCE Project

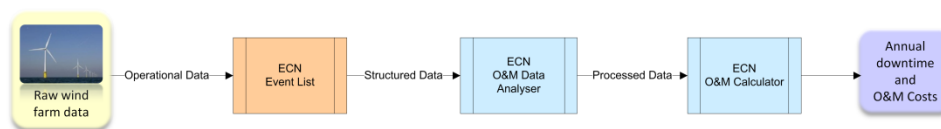
In 2011 ECN submitted several research proposals to FLOW in order to contribute to the cost reduction of offshore wind farms. Since ECN has in depth knowledge in the field of O&M of offshore wind farms, ECN together with industry partner RWE Offshore Wind Nederland submitted a project proposal titled “Development and demonstration of the Operation & Maintenance Cost Estimator (OMCE) to estimate the future O&M costs”. The project proposal was approved by the FLOW executive board in November 2011 and the project is expected to be finished in 2015.

The FLOW OMCE project is being executed through five work packages by ECN as project coordinator and by RWE as project partner. The main project objectives are:

1. Further development of tools and working procedures using data and feedback from an existing RWE wind farm to develop a baseline model.
2. Make developed OMCE baseline model available to other offshore operators.
3. Apply the model for an analysis of expected O&M costs for an operational offshore wind farm.
4. Validate the model by implementation of the OMCE approach in an operational offshore wind farm.

In **Figure 7** a summary of the Operation & Maintenance Cost Estimator approach is illustrated.

**Figure 7:** Summary of the OMCE approach



The main idea behind the OMCE approach is to define data capture procedures to obtain wind farm operational data (Event List) and then process the data to get information on weather, equipment, crews, spare parts and failures rates of wind farm components (ECN O&M Data Analyser). Later on the processed historical operational data can be used to calculate amongst others annual downtime and O&M costs for the forthcoming years (ECN O&M Calculator).

In the next chapter the structure of the OMCE approach is explained in more detail. Furthermore, a limited O&M study conducted for the Rhyl Flats wind farm is demonstrated in chapter 4.



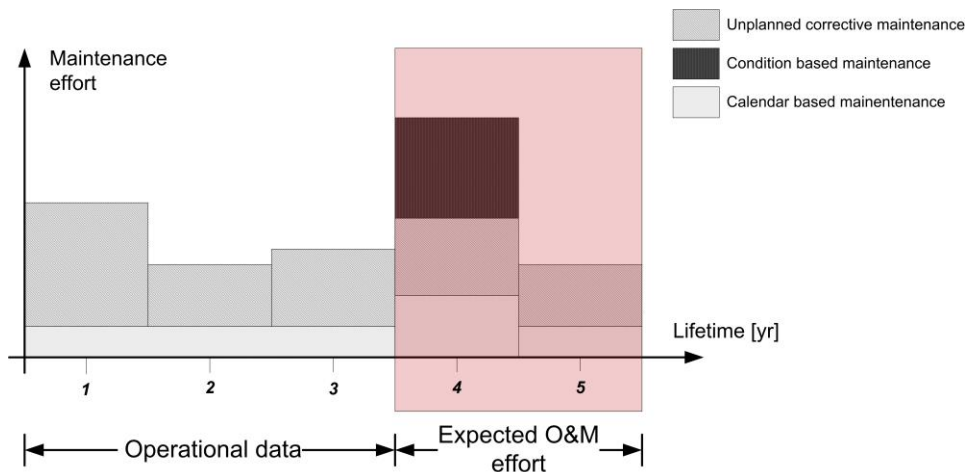


# 3

## Operation and Maintenance Cost Estimator (OMCE)

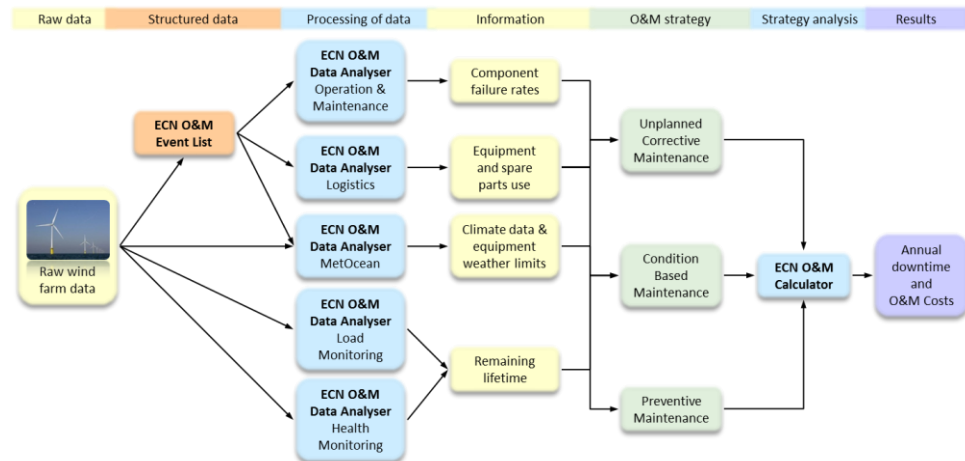
For the initial O&M planning of offshore wind farms the 'ECN O&M Tool' gives a good estimation of averaged long term maintenance costs and downtime. But during the operational years of the farm it is essential to make use of the historical operational data of the farm and update the O&M cost estimations. In **Figure 8** an example of this approach is given. In this example, the operational data of the first three years of the wind farm are used to estimate the expected O&M effort of the next two years.

**Figure 8:** Estimation of O&M effort for forthcoming years based on the historical operational data



The aim of the OMCE is to provide the industry with accurate tools and procedures to implement this approach. Through the FLOW OMCE project, the 'ECN Event List' and the ECN O&M Data Analyser are further developed to obtain and process the historical operational data of the farm and the ECN O&M Calculator is further developed to estimate the O&M effort for the forthcoming years. In **Figure 9** the complete structure of the OMCE approach is depicted.

**Figure 9:** Structure of OMCE approach showing the steps from structuring operational data in the Event List format through data processing with the Data Analyser tools and modelling O&M strategies and performing analyses with the O&M Calculator.



In **Figure 9** the ECN O&M Data Analyser and the ECN O&M Calculator are depicted in the blue boxes. The ECN O&M Data Analyser consists of five modules:

- 1. Operation and maintenance (O&M)**
- 2. Logistics**
- 3. MetOcean**
- 4. Load monitoring**
- 5. Health monitoring**

The first three modules are further developed within the current FLOW OMCE project and the last two modules, load and health monitoring, are being developed within other ECN research projects such as ‘Blade Load Monitoring based on Fibre Optic Measurements (BLM-FO)’ and ‘Fleet Leader concept for cost-efficient load monitoring and O&M optimisation’.

In the following sections, the components of the OMCE approach are further described.

### 3.1 Event List

The ECN Event List is used to collect and structure wind farm operational data from various data sources. The Event List first was first defined based on the maintenance data of the 109 MW Dutch OWEZ wind farm. Within the FLOW OMCE project it was used to structure maintenance data of the RWE’s Rhyl Flats wind farm. In the next phase of the OMCE project, the Event List will be used to obtain a larger set of operational data of for the validation phase of the project.

Within the context of the OMCE, a maintenance event is considered as a (sequence of) maintenance action(s) to prevent or correct turbine malfunctioning. Maintenance

actions can be, for example, remote resets, visits with technicians only, or the replacement of large components. The location of the Event List within the OMCE approach is in between the raw wind farm data and the ECN O&M Data Analyser, see **Figure 9** [8].

Within the FLOW OMCE project three months of operational data of RWE's Rhyl Flats wind farm was structured in the Event List format. The 90 MW RWE's Rhyl Flats wind farm consists of 25 Siemens SWT-3.6MW turbines located 8 km offshore in the Irish Sea. In the following sections an example of this operational data collection with the ECN Event List is given.

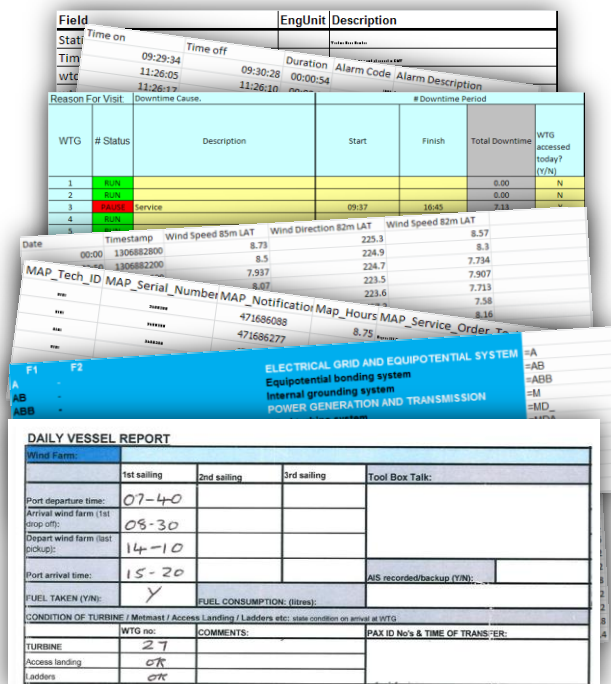
### 3.1.1 O&M Data Sources for Rhyl Flats Wind Farm

The operational data provided by RWE contained the following data sources:

- List of SCADA parameters
- Alarm list
- Meteorological and wave data
- Monthly downtime summary reports
- Daily work reports
- Turbine breakdown in RDS-PP coding
- Daily vessel reports

The inventory of available data sources revealed that O&M data are stored in many different sources at independent locations, see **Figure 10** [9].

**Figure 10:** Examples of operational data stored in different uncorrelated formats



### 3.1.2 Event List for Rhyl Flats Wind Farm

The operational data from Rhyl Flats were analysed initially to determine whether the fields of the existing Event List format (defined based on the Dutch OWEZ wind farm operation data) could be filled or should be updated. This analysis has proven to be a manual step since:

- The relations between an event and the underlying maintenance actions had to be determined.
- The components on which maintenance was performed were often not described or only specified in a free text-format forcing the data analyst to make assumptions.
- It was difficult to determine the start and cause of an event.
- Information on logistic times of spare parts and stock control was not supplied by the wind turbine manufacturer.

Based on the analysis some of the fields of the Event List format have been updated to match the available on-site data. Examples of such fields are the travel time of access equipment and the number of hours of weather downtime. An example of the updated Event List format is presented in **Figure 11**.

**Figure 11:** Example of updated Event List format showing an event consisting of two maintenance actions in columns (white fields) as part of a single corrective maintenance event (yellow fields) [9].

|                             |                    |                              |                              |
|-----------------------------|--------------------|------------------------------|------------------------------|
| Event nr.                   |                    | 1                            |                              |
| Start event                 | [date/time]        | 15/02/2013 09:33             |                              |
| Event type                  |                    | Corrective maintenance       |                              |
| Turbine ID or BOP ID        |                    | 1. Turbine A                 |                              |
| Nr. maintenance action      |                    | 1.1                          | 1.2                          |
| Start                       | [date/time]        | 15/02/2013 09:33             | 16/02/2013 08:30             |
| End                         |                    | 15/02/2013 14:33             | 16/02/2013 17:00             |
| Duration                    | [h]                | 1.05                         | 8.50                         |
| Downtime                    | [h]                | 5.00                         | 8.50                         |
| Type of maintenance         |                    | Inspections                  | Replacement (finalisation)   |
| Weather downtime            | [h]                | 4.00                         | 0.00                         |
| Scada alarm code            |                    | 0001                         | 0010                         |
| Scada description           |                    | Temperature error            | Turbine stopped by operator  |
| Reported labour hours       | [h]                | 2.00                         |                              |
| Crew size                   |                    | 2                            |                              |
| Access equipment            |                    | Access vessel                |                              |
| - travel time (heading out) | [h]                | 0.75                         |                              |
| - travel time (return)      | [h]                | 1.00                         |                              |
| - fuel consumption          | [dm <sup>3</sup> ] | 200                          | 225                          |
| Second equipment            |                    | n.a.                         | n.a.                         |
| - travel time (one way)     | [h]                |                              |                              |
| - mobilisation time         | [h]                |                              |                              |
| Third equipment             |                    | n.a.                         | n.a.                         |
| - travel time (one way)     | [h]                |                              |                              |
| - mobilisation time         | [h]                |                              |                              |
| Explanations                |                    | Pitch motor overheated       | Replaced pitch drive blade A |
| Main system_ID              |                    | MDC Blade adjustment         |                              |
| Component ID                |                    | GL001 Pitch drive assembly A |                              |
| Work carried out            |                    | Replacement                  |                              |
| Spare part in stock         |                    | Yes                          |                              |
| Logistic time spare part    | [h]                | 2                            |                              |
| Consumables                 |                    | n.a.                         |                              |
| # consumables               |                    |                              |                              |
| Total labour hours          | [h]                | 27.50                        |                              |
| End event                   |                    | 16/02/2013 17:00             |                              |
| Duration event              | [h]                | 31.44                        |                              |
| Downtime event              | [h]                | 31.44                        |                              |

In the following sections the processing of the Event List data by the ECN O&M Data Analyser tools is further described.

## 3.2 O&M Data Analyser

The structured operational data in the Event List format can be processed by the ECN O&M Data Analyser tools to get information on weather, equipment, crews, spare parts and failures rates of wind farm components. The processed data can later on be used as inputs for the ECN O&M Calculator.

The specifications and demonstration versions of the ECN O&M Data Analyser tools were developed within the Dutch Offshore Wind Energy Services (DOWES)<sup>2</sup> and We@Sea<sup>3</sup> projects by name of the OMCE Building Blocks [10]. As part of the FLOW OMCE project goals, the existing modules are updated and new features such as a reporting function and the Module MetOcean are developed using the Event List created for RWE's Rhyl Flats wind farm.

The ECN O&M Data Analyser consists of five modules of which the first three modules are further developed in context of the FLOW OMCE project:

### 1. Operation and Maintenance (O&M)

Generates information about the observed maintenance and failure behaviour of components by evaluation of maintenance events and downtime and an analysis of failure rates and failure modes.

### 2. Logistics

Generates information about applied equipment, spare parts and repair strategies for the recorded maintenance events.

### 3. MetOcean

Generates information on the weather conditions on-site and determine the weather limits for different types of equipment applied for maintenance.

In the following sections a summary of these three modules is given.

### 3.2.1 Module O&M

The purpose of the Module O&M is to process and analyse the maintenance data from the offshore wind farm stored in the Event List format [11]. The Module O&M consists of three parts, ranking analysis, trend analysis and reporting:

1. **Ranking Analysis** to create a general overview of wind farm performance in terms of downtime and number of maintenance events for different event types.
2. **Trend Analysis** to determine (updated) failure frequencies of components.
3. **Reporting** of (selected) analysis results in PDF and Word formats.

<sup>2</sup> DOWES website: <http://dowes.nl>

<sup>3</sup> We@Sea website: <http://we-at-sea.org>

The outputs of the Module O&M are:

- **Wind farm performance assessment** to obtain a general overview of the performance and health of the offshore wind farm in terms of number of maintenance events and downtime per event.
- **Inputs for the O&M Calculator** such as failure frequencies or Mean Time To Failure MTTF [h] and number of preventive maintenance events for each component.

### 3.2.2 Module Logistics

Similar to the Module O&M the main purpose of the Module Logistics is to process and analyse the maintenance data from the offshore wind farm stored in the Event List format [11]. The Module Logistics consists of four parts:

- **Equipment Analysis** calculates characteristics of different types of equipment used for maintenance in terms of travel time, mobilisation/demobilisation time, the number of technicians transported and amount of fuel used.
- **Spare Parts Analysis** calculates spare parts characteristics for different types of maintenance, number and type of spare parts used, the logistics time involved for (re)ordering and transport of spare parts to the wind farm, stock size and components maintained.
- **Repair Class Analysis** calculates the classification of repair activities in repair classes for different types of maintenance, where for each maintenance event the following information can be obtained: the number of mission phases (i.e. successive activities such as remote reset, inspection, replacement, repair etc.), the time to organise the repair activity, duration of each activity, number of technicians required, equipment used and components maintained.
- **Reporting** of (selected) analysis results in PDF and Word formats.

The outputs of the Module Logistics are the wind farm logistics assessment and inputs for the O&M Calculator:

- **Wind farm logistics assessment** to obtain a general overview of characteristics of different types of equipment, spare parts characteristics and classification of repair activities.
- **Inputs for the O&M Calculator** such as equipment, spare parts and repair class data.

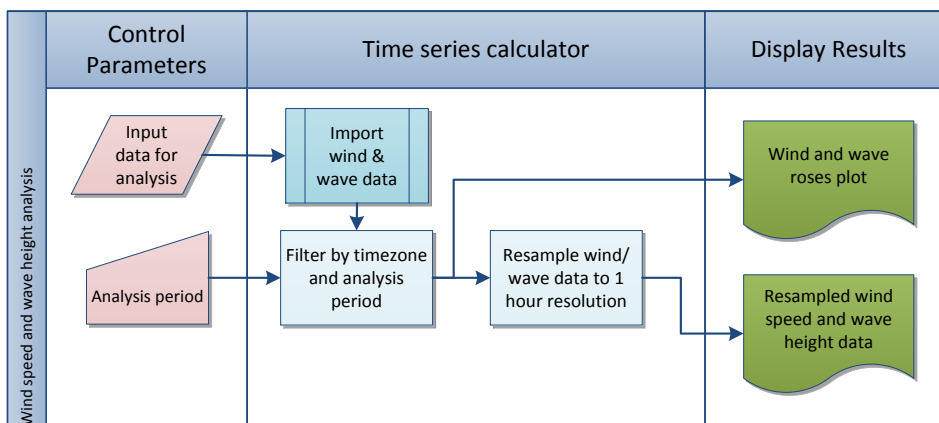
### 3.2.3 Module MetOcean

The purpose of the Module MetOcean is to process and analyse the meteorological and oceanographic measurements at the location of the wind farm and combine those with (updated) maintenance data from the offshore wind farm stored in the Event List format [11]. The outputs of the Module MetOcean are:

- **Additional output for wind farm performance assessment:**
  - o Assess the validity of the long term wind and wave data derived from hind cast models in the planning phase of a wind farm. This includes plotting the time series of measured wind speeds and wave heights and creating wind and wave roses, histograms and probability distribution fitting.
  - o Analysis of production losses during downtime using the wind turbine power curve and the observed wind speed profile(s).
  - o Extend the weather limits analysis with current, tide, visibility, wave period, wave direction and wind direction.
  - o Verify the alignment of wind directions measured at different heights on a met mast (superimposed wind direction measurements).
  - o Analysis of disturbed wind sectors using wind speed and wind direction measurements.
  - o Determine wind shear dependency on atmospheric stability by distinguishing between day and night time operations.
  - o Generate scatter diagrams for combinations of wind speed, wind direction, wave direction, wave period and significant wave height.
  - o Detect possible wave buoy drift (e.g. caused by broken mooring line) using the buoy GPS data.
- **Inputs for the O&M Calculator** such as:
  - o Wind shear model parameters
  - o Time series of the wind speed and significant wave height
  - o Operational limits (wind speed and wave height) for each equipment type.

The technical description of the described outputs for the Module MetOcean and limited demonstration software are developed within the FLOW OMCE project. A full software implementation was beyond the scope of this project. For example, the general procedure to create the required time series of wind speed and wave height measurements as input for the O&M Calculator is depicted in **Figure 12**.

**Figure 12:** Flowchart for wind speed and wave height resampling using the Module MetOcean [11].



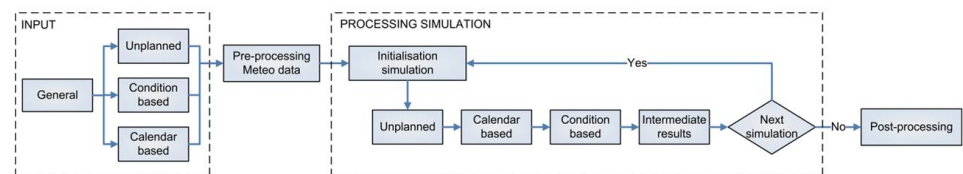
As explained in the previous sections the output of the O&M Data Analyser tools can be used as input for the O&M Calculator. In the following section an overview of the O&M calculator is given.

### 3.3 O&M Calculator

The ECN O&M Calculator is the tool within the OMCE approach to estimate the O&M effort of the offshore wind farm for the coming years by using the output of the O&M Data Analyser.

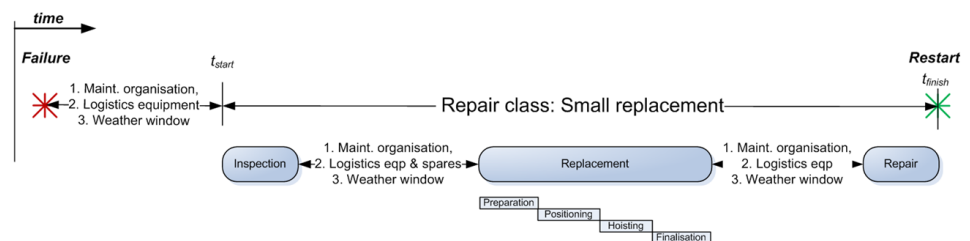
The O&M calculator is a time domain simulation tool developed in MATLAB. The structure of the time domain simulation process is given in **Figure 13**. In this process, performed simulations will provide results with respect to the uncertainty in the failure and wind/wave distributions.

**Figure 13:** Simulation process of the ECN O&M Calculator [12].



In **Figure 14** an example of the repair modelling for corrective maintenance is given. Once a failure has occurred it will require some maintenance organisation followed by logistics time for the equipment and crew to be ready. It is then possible that vessels will have to wait for a suitable weather window to access the wind farm before the actual maintenance event can start. In between the inspection, replacement, and repair phases it is possible that organisational time, logistics time, and waiting time occur again due to e.g. not having required equipment or spares directly available. The total downtime is defined as the time from turbine failure to restart.

**Figure 14:** Example of repair strategy modelling - planning a small replacement in time[12].



The O&M Calculator consists of four separate modules, see **Figure 13**:

#### 1. Input

In this module the maintenance model is set up and the required input data are imported (e.g. manually from the O&M Data Analyser). The maintenance model and the corresponding input data are stored in a number of so called libraries, i.e. MAT-



files, in such a way that the other three modules can extract all required information from these libraries straightforwardly.

## 2. Pre-processor

To facilitate the simulation process a pre-processing step is executed in which a number of MAT-files are generated, which can be loaded in the simulator module. An important part is the processing of the weather data.

## 3. Simulator

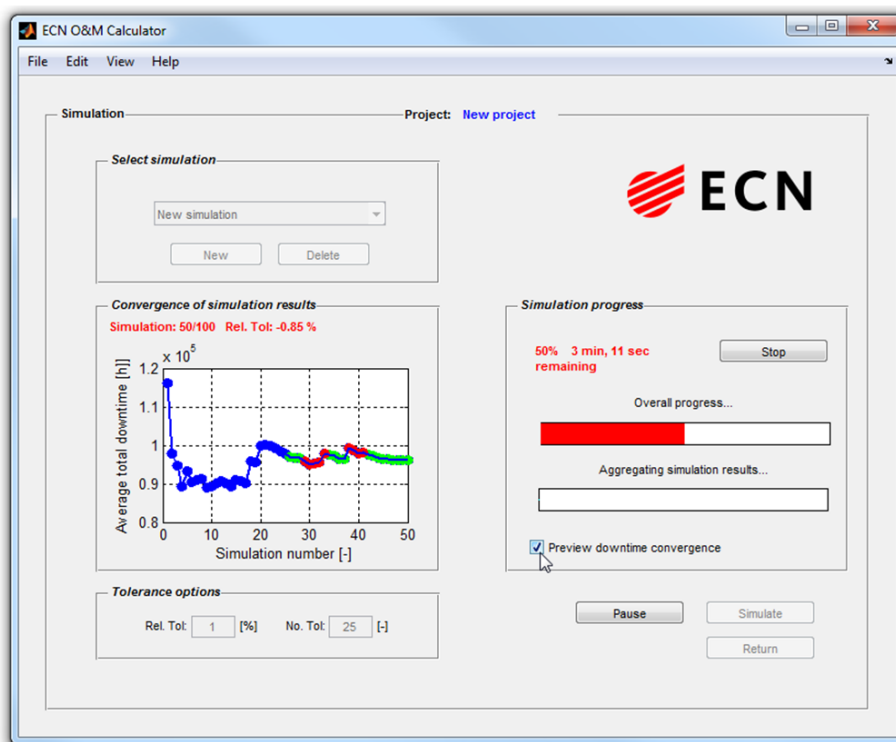
The simulation process is part of this module. The results of the simulations are stored in a number of MAT-files which can be loaded in the post processing module. At the start of a simulation, a number of control parameters have to be specified such as number of simulations and length of simulation period.

## 4. Post-processor

After the simulations are finished, the results can be post-processed to obtain the required output in tables and graphs. At the start of the post-processing a number of control parameters to define the required output have to be specified.

The execution of these four modules is organised by a graphical user interface (GUI), where it should be noted that these modules can be executed independent of each other. In **Figure 15** the interface of the simulation module is given.

**Figure 15:** Graphical user interface of the O&M Calculator for simulation process [13].



The demonstration version of the O&M Calculator was developed within the Dutch Offshore Wind Energy Services (DOWES) and We@Sea projects by name of the OMCE-Calculator [10]. As part of the FLOW OMCE project goals and based on feedback from the industry, the tool is further developed and its functionality is extended. A number of

new key functionalities of the O&M Calculator developed through the FLOW OMCE project are highlighted below [14]:

**Variable feed-in tariff for costs per kWh calculation**

In previous versions of the O&M Calculator, the price of energy used for the calculation of revenues and revenue losses was assumed to be constant over the lifetime of the wind farm. However, it is observed that having a variable electricity price (€/kWh/year or €/kWh/month) is a better proposition to make the definitions in accordance with (inter)national subsidy programs and feed-in schemes.

Within the FLOW OMCE project, the tool is modified to multiply the monthly production and losses and by the corresponding monthly electricity price put in by the user, thereby providing total revenue (and revenue loss) over the simulated period for the wind farm.

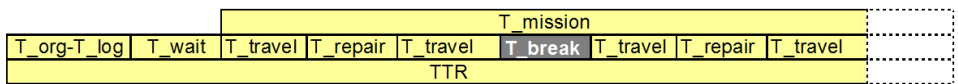
**Working shifts per season**

In previous versions of the O&M Calculator, it was possible to specify only a single shift for technicians which was valid throughout the year. Within the FLOW OMCE project, the tool is vastly improved to allow the definition of working shifts for up to four user-defined seasons. In this way replacements, which are usually also performed during night time periods, can be modelled more realistically.

In the O&M Calculator a replacement may take a number of days and the work has to be carried out in one period of consecutive days (i.e. uninterrupted mission in one weather window). In this situation the crew will travel back to the harbour or hotel ship at the end of the working day and will travel back to the turbine the next morning. This is depicted schematically in **Figure 16**, where T\_break denotes the period the crew stays overnight.



**Figure 16:** Uninterrupted mission with a single shift [14].



The O&M Calculator model is now further refined when the technicians are working in e.g. two or three shifts a day. An example of the refined model considering two working shifts is depicted in **Figure 17**. Depending on the number and length of the shifts T\_break can be equal to 0 hours. For modelling purposes, the working shifts are assumed to have the same length each and in between shifts the access equipment will travel back to the harbour or offshore accommodation to load/unload technicians for the new working shift.

**Figure 17:** Uninterrupted mission with 2 working shifts [14].

|                     |        |          |          |                 |          |          |          |                 |          |          |          |
|---------------------|--------|----------|----------|-----------------|----------|----------|----------|-----------------|----------|----------|----------|
| T_mission           |        |          |          |                 |          |          |          |                 |          |          |          |
| T_wrkday = 24 hours |        |          |          |                 |          |          |          |                 |          |          |          |
| Working shift 1     |        |          |          | Working shift 2 |          |          |          | Working shift 1 |          |          |          |
| T_org-T_log         | T_wait | T_travel | T_repair | T_travel        | T_travel | T_repair | T_travel | T_break         | T_travel | T_repair | T_travel |
| TTR                 |        |          |          |                 |          |          |          |                 |          |          |          |

For the maintenance phases which can be split up in a number of separate missions (Inspection or Repair phases), the work is assumed to only be performed during the first working shift. Depending on periods of daylight the number of shifts and the start of the first shift may vary in different seasons throughout a year.

### Number of available technicians

One of the main modelling assumptions in previous versions of the O&M Calculator was that the number of available technicians would match the crew capacity on all user-defined vessels to be used for access. Within the further development of the O&M Calculator, the number of technicians is considered as a separate limiting factor to improve the model for far offshore scenarios. By assigning downtime due to a lack of available technicians, trade-off studies for the number of technicians with respect to the downtime/production losses can also be performed.

### Additional equipment weather limits options

In the new version of the O&M Calculator it is now possible to specify an additional maximum wind speed limit for calendar based maintenance and to set infinite values for equipment weather limits. The calendar based maintenance wind speed limit can be used to maximise power production during periods of high wind speeds. This will enable trade-off studies between the required maintenance in a specific period and lost revenues.

### Mean Time To Failure per turbine

In previous versions of the O&M Calculator, the Mean Time To Failure (MTTF) was specified in hours for each component as input for the simulation of unplanned corrective maintenance. In the new version of the O&M Calculator, the option is added to specify the MTTF separately for each wind turbine. In this way, failures can be modelled more accurately for turbines which are considered to fail more often due to e.g. higher loading of components.

In the following chapter an O&M case study for the Rhyl Flats wind farm is presented. In this study first a baseline O&M scenario is defined and then the OMCE approach is implemented to update and optimise the baseline O&M scenario. Furthermore, the results are discussed and a conclusion is given.



# 4

## O&M Study of Rhyl Flats

In the planning phase and early operational life of the wind farm limited field data is available. Therefore, an initial O&M strategy will usually be set-up based on assumptions and best estimates using generic data.

Later on, the results of the initial expected O&M effort and costs can be validated when operational data becomes available and the data analysis tools are applied. This will result in more accurate input data such that the expected O&M effort and associated costs can be interpreted with much more confidence compared to the situation where only historical generic data and assumptions are used.

Based on the updated predictions, the operator of a wind farm can investigate whether the current O&M strategy is still optimal or improvements are possible by means of running scenario studies with the O&M Calculator.

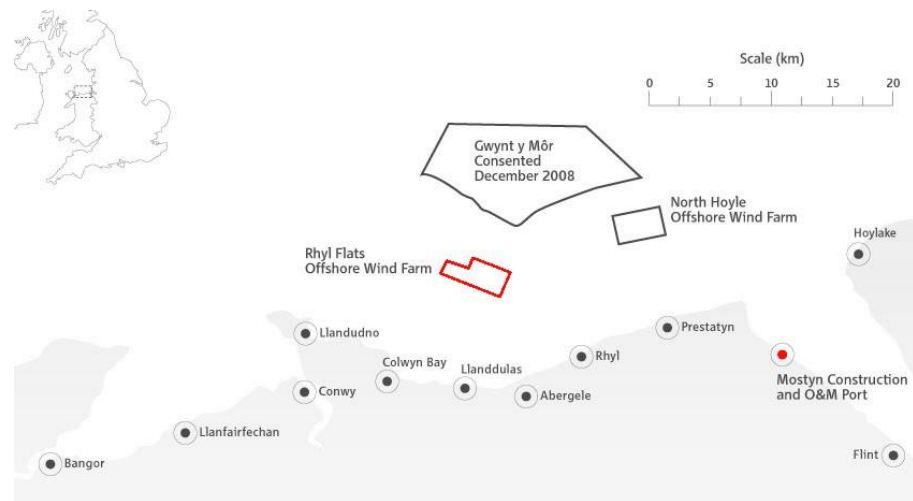
In order to demonstrate this approach, an O&M study is performed for RWE's Rhyl Flats wind farm. The O&M study starts with setting up a baseline model to determine the initial O&M strategy. Next, the baseline scenario will be updated based on the data analysis results of the Rhyl Flats Event List data with the Data Analyser tools. Furthermore, an optimisation scenario is presented and a conclusion is given.

In the following sections first the wind farm and its components are defined and then, all three scenarios are described in detail.

## 4.1 Rhyl Flats Wind Farm

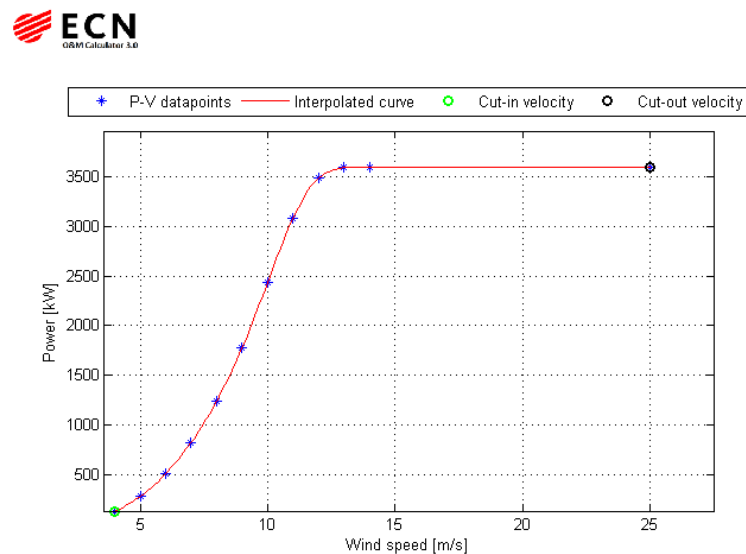
The Rhyl Flats wind farm consists of 25 Siemens SWT-3.6 MW turbines with a total capacity of 90 MW. The wind farm is located 8 km offshore in an area of shallow water of the Irish Sea. Construction of the farm was conducted from the Port of Mostyn starting in 2008 and was completed by December 2009. The location of the farm is illustrated in **Figure 18**. The turbines are placed in three rows with 6, 10 and 9 turbines on each row and are connected to the grid through an onshore substation.

**Figure 18:** The location of the Rhyl Flats wind farm in the Irish Sea [15].



The Siemens SWT-3.6-107 turbines used in Rhyl Flats are pitch regulated with total capacity of 3.6 MW. The hub height of the turbine is 80 m with 107 m rotor diameter. The power curve of the Siemens turbine is given in **Figure 19**.

**Figure 19:** Power curve of Siemens SWT-3.6-107 turbine modelled in ECN O&M Calculator [16].



## 4.2 Baseline Model

When an O&M model is first created for an offshore wind farm to estimate the required O&M effort in terms of costs and downtime, the starting point for the analysis is to write a summary of the assumed O&M strategy which is considered to be the baseline O&M scenario.

In section 4.2.1 the main assumptions for a baseline O&M scenario used to model O&M for the Rhyl Flats wind farm are given. A summary of modelling results obtained for the baseline O&M model with the ECN O&M Calculator is given in section 4.2.2.

### 4.2.1 Baseline O&M Scenario

In this section a baseline O&M scenario is defined which is based on ECN's in-house knowledge in the field of O&M modelling. This baseline scenario will be used to set-up a suitable O&M model in the ECN O&M Calculator.

The assumed reliability of wind farm components, available equipment and technicians for maintenance and weather climate of the farm location are explained below.

#### **Maintenance base**

Maintenance is performed from the Port of Mostyn at approximately 21 km distance from the wind farm. Small spare parts are assumed to be stored at warehouse facilities at the harbour.

#### **Component reliability**

The distribution of component failures is derived from the results of the Reliawind project [18] where the overall number of component failures is based on ECN's experience.

#### **Equipment**

The Siemens turbine is equipped with a service crane in the nacelle [17]. It is assumed that the turbine is able to hoist small components with a weight of up to 2000 kg to the nacelle.

Workboat access vessels are applied to transport the maintenance crew and small spare parts from the harbour to the wind turbines. The workboats are able to transport small parts (up to 2000 kg) from the harbour to the turbines. These parts are assumed to be picked up from the vessel with a crane placed on the turbine platform and can subsequently be hoisted to the nacelle using the service crane.

To transport and hoist larger components with weights in excess of 2000 kg a jack-up vessel will be chartered.

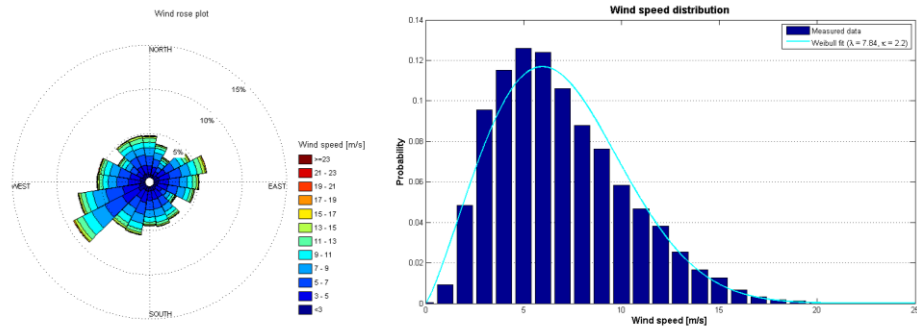
#### **Technicians**

Service technicians will work during daylight periods when the maintenance performed does not require large vessels. On average they are considered to work in a single shift of 10 hours throughout the year. When large vessels are required to perform the maintenance, the technicians are assumed to work in 2 shifts of 10 hours each.

## Weather climate

Given that ECN does not have access to sufficient weather data at the location of the wind farm, a set of weather data for the location 'IJmuiden munitiestortplaats' near the Dutch shore is used. A wind rose and a Weibull fit for these data are given in **Figure 20**.

**Figure 20:** Wind rose and Weibull fit for wind conditions at site 'IJmuiden munitiestortplaats' are created with O&M Data Analyser Module 'MetOcean'



## 4.2.2 O&M Calculator - Baseline Results

By using the modelling assumptions set up for the baseline O&M scenario as input for the ECN O&M calculator it's possible to calculate the initial expected O&M effort for the Rhyl Flats wind farm. For the model described in the previous section, 1000 simulations are performed for a period of one year to take into account the uncertainty in failure and wind/wave distributions.

The calculation results indicate an estimated loss of production of 20,241 MWh and a total energy production of 278,100 MWh, resulting in a yield availability of 93.2%. An overview of key simulation results is depicted in **Figure 21**.

**Figure 21:** O&M Calculator key simulation results for baseline O&M model.

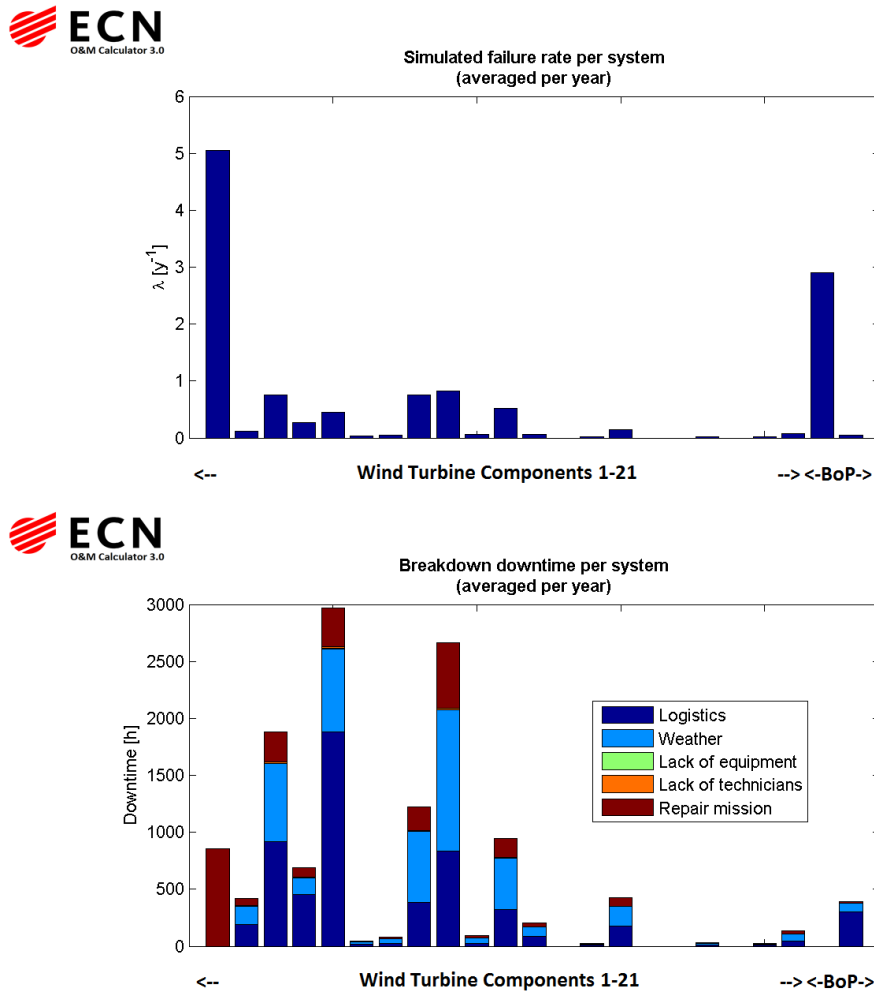
| Summary of downtime & costs     |                     |    |                                  |            |
|---------------------------------|---------------------|----|----------------------------------|------------|
| Project                         | Rhyl Flats baseline |    | Key simulation results (average) |            |
| Installed wind farm capacity    | 90,0                | MW | Availability [time/yield]        | 94 / 93.2% |
| Number of wind turbines in farm | 25                  |    | Costs [c€/kWh]                   | 4,52       |
| Simulation                      | sim                 |    | Repair costs [M€/yr]             | 12,51      |
| Simulation period               | 1                   | yr | Rev. losses [M€/yr]              | 2,63       |
| Start-up period                 | 1                   | yr | Total effort [M€/yr]             | 15,14      |
| Number of simulations           | 1000                |    |                                  |            |

In **Figure 21** it can be observed that the time availability of the wind farm due to downtime is 94%. The low availability of the wind farm and high repair costs may be the result of the conservative estimations made by ECN for the reliability of wind turbine components.



Since the Mean Time To Failure for each component is an input in the O&M Calculator model and the Mean Time To Repair is simulated, the component failure rates are also an output of the model. This graph is depicted in **Figure 22**. Additionally, the newly developed breakdown of downtime per system from the O&M Calculator is also depicted in this figure.

**Figure 22:** Failure rates and downtime per component results from O&M Calculator (anonymised)



In the graphs the component failure rates can be correlated with the downtime. For example, component number 5 has only a low failure rate but a lot of downtime. This is the result of the large replacements assumed to be required for this specific component. For such components the impact is high because  $Risk = Failure\ frequency \times Consequences$ .

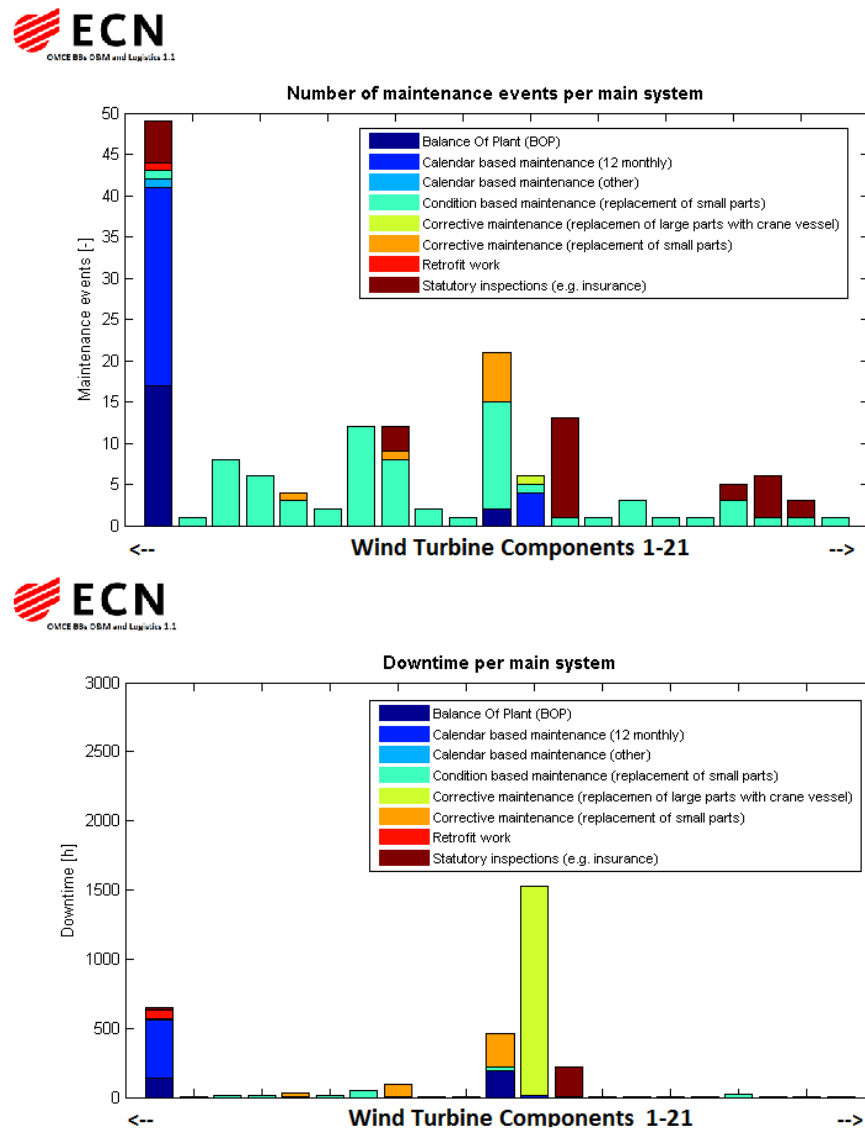
In the graphs it is observed that many components experience a lot of downtime due to logistics (time to organise the repair and arrange equipment) and waiting time for a suitable weather window to actually perform the repairs. Additionally, it is observed that there is virtually no downtime due to a lack of technicians and a lack of equipment.

## 4.3 Updated Model

As explained previously, the results of the initial expected O&M effort and costs can be validated when operational data becomes available and the data analysis tools are applied. In this section the results of the baseline scenario are validated against the actual operational data.

Within the OMCE project ECN obtained operational data for RWE's Rhyl Flats wind farm for a three-month period. As described in chapter 3, first the raw operational data should be structured in the Event List format. The second step is to process the structured data with the O&M Data Analyser to obtain the number of maintenance events and downtime of wind farm components. Some results obtained with the O&M Data Analyser are illustrated in **Figure 23**.

**Figure 23:** Number of maintenance events and downtime per component results from O&M Data Analyser (anonimised)



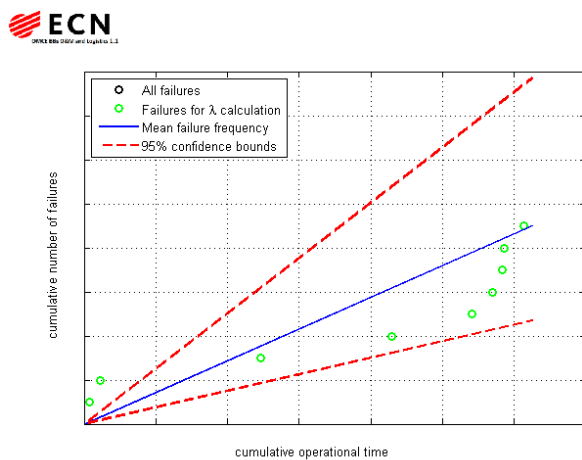
### 4.3.1 Updated O&M Scenario

The baseline O&M scenario is updated based on the O&M Data Analyser observations. In the updated model, only the component reliability estimations are updated, while other modelling assumptions are assumed to remain valid.

#### Component reliability

Based on the analyses results by the Module O&M of the O&M Data Analyser, it was observed that the component reliability was underestimated in the initial assumptions made to set up the baseline O&M model. The O&M Data Analyser provides estimates of the failure figures and the corresponding upper and lower confidence interval limits. An example of the output for the failure frequency analysis is given in **Figure 24**.

**Figure 24:** Example of component reliability estimation with Module O&M of the O&M Data Analyser (anonymised)



The slope of the blue line represents the average failure frequency. It should be noted that this line doesn't represent the trends seen at the start and end of the operational time period since only a limited set of operational data was analysed.

### 4.3.2 O&M Calculator - Updated Results

The baseline O&M Calculator model is updated for the updated O&M scenario (increased component reliabilities). The updated calculation results indicate an estimated loss of production of 12,636 MWh and a total energy production of 285,744 MWh, resulting in a yield availability of 95.8%. An overview of the updated key simulation results is depicted in **Figure 25**.

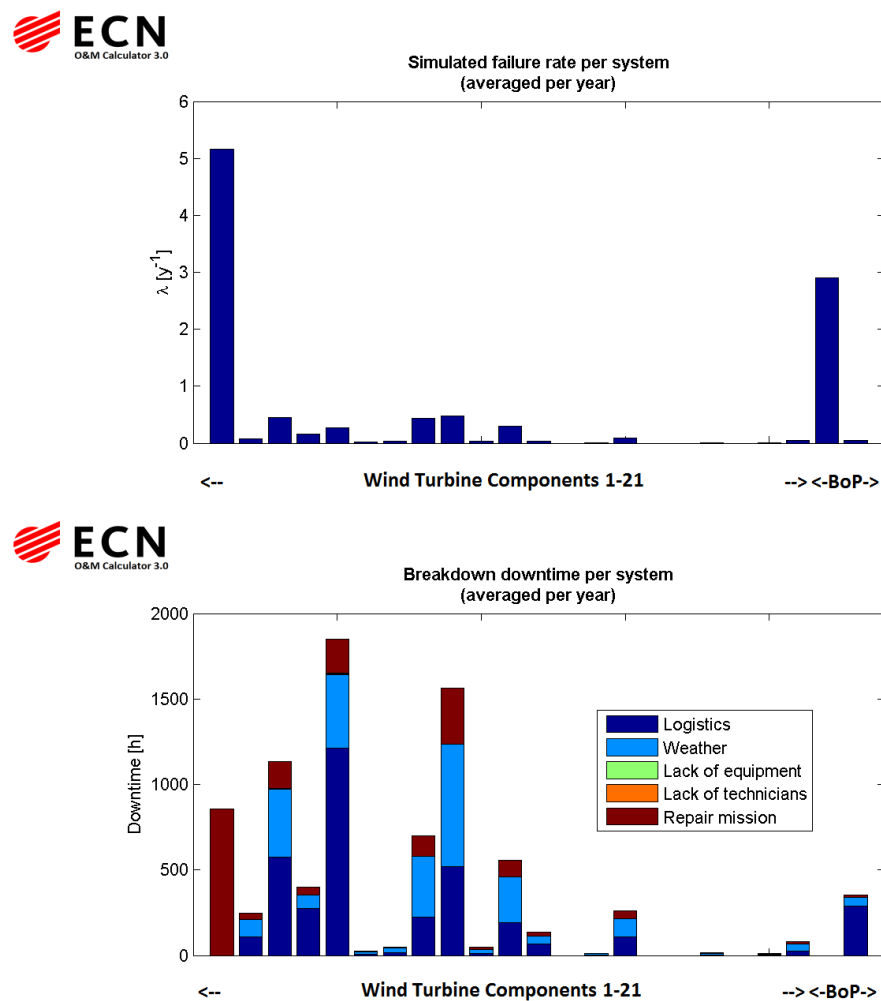
**Figure 25:** O&M Calculator key simulation results for updated O&M model.

| Summary of downtime & costs     |                    |    |                                  |              |
|---------------------------------|--------------------|----|----------------------------------|--------------|
| Project                         | Rhyl Flats updated |    | Key simulation results (average) |              |
| Installed wind farm capacity    | 90,0               | MW | Availability [time/yield]        | 96.2 / 95.8% |
| Number of wind turbines in farm | 25                 |    | Costs [c€/kWh]                   | 3,35         |
| Simulation                      | sim                |    | Repair costs [M€/yr]             | 9,52         |
| Simulation period               | 1                  | yr | Rev. losses [M€/yr]              | 1,64         |
| Start-up period                 | 1                  | yr | Total effort [M€/yr]             | 11,16        |
| Number of simulations           | 1000               |    |                                  |              |

Under the assumption that the long-term wind climate data used as input for modelling is comparable with the Rhyl Flats wind climate during 2011, the total energy production is now very close to the actual power production recorded for the Rhyl Flats wind farm in 2011, which was 286.08 GWh [16].

In **Figure 25** it is observed that the time availability of the wind farm due to downtime is now increased to 96.2%. The repair costs have decreased as well due to less maintenance being required by the reduced component failures observed in practice. Compared to the baseline O&M model, better results are obtained with the updated model. The updated component failure rates and breakdown of downtime per component results from the O&M Calculator are depicted in **Figure 26**.

**Figure 26:** Updated failure rates and downtime per component results from O&M Calculator (anonymised)



It is now observed that the component failure rates and downtime are reduced. As an example, compared to the results of the baseline O&M model, the downtime for component number 5 is reduced by approximately 38%, see **Figure 22**.

In the following section, the updated model is used as input to perform a limited optimisation study to obtain a low-cost maintenance strategy.

## 4.4 Optimised Model

In this section an optimisation of the updated scenario is performed to identify potential solutions to reduce O&M costs. Through this optimisation the maintenance strategy is modified and new results are presented.

### 4.4.1 Optimised O&M Scenario

The following parameters are changed based on the observed results for the updated O&M model:

#### Equipment

In the updated scenario there are two workboats available for maintenance actions, but as illustrated in **Figure 26**, there is no downtime due to the lack of equipment. Therefore, in the optimised scenario the number of workboats is reduced to one to save O&M costs.

#### Technicians

In the updated scenario there are 22 technicians available, 16 for the first shift and another 6 for the second shift in case of major replacements. Similar to equipment, as illustrated in **Figure 26**, there is no downtime due to the lack of technicians. Therefore, in the optimised scenario the number of technicians for the first working shift is reduced from 16 to 10 technicians.

#### Margins for preventive maintenance

In the updated scenario preventive maintenance is defined for the period of May to September where a wind speed limit of 12 m/s is assumed for the workboat to limit access to the wind turbines. In the optimised scenario the wind speed limit is reduced to 4 m/s while the preventive maintenance period is lengthened from January to December to be able to complete all required yearly preventive maintenance. The reduction of the wind speed limit will reduce production losses when turbines are shut down due to preventive maintenance.

### 4.4.2 O&M Calculator - Optimised Results

The calculation results of the optimised model indicate an estimated loss of production of 12,104 MWh and a total energy production of 286,237 MWh, resulting in a yield availability of 96%. An overview of the updated key results is depicted in **Figure 27**.

**Figure 27:** O&M Calculator key simulation results for optimised O&M model.

| Summary of downtime & costs     |                      |    |                                  |            |
|---------------------------------|----------------------|----|----------------------------------|------------|
| Project                         | Rhyl Flats optimised |    | Key simulation results (average) |            |
| Installed wind farm capacity    | 90,0                 | MW | Availability [time/yield]        | 96.2 / 96% |
| Number of wind turbines in farm | 25                   |    | Costs [c€/kWh]                   | 3,00       |
| Simulation                      | sim                  |    | Repair costs [M€/yr]             | 8,53       |
| Simulation period               | 1                    | yr | Rev. losses [M€/yr]              | 1,57       |
| Start-up period                 | 1                    | yr | Total effort [M€/yr]             | 10,10      |
| Number of simulations           | 1000                 |    |                                  |            |

In **Table 1** the costs of the updated scenario and the optimised scenario are compared.

**Table 1:** O&M cost reduction in results of O&M strategy optimisation

|                        | Updated Scenario | Optimised Scenario | Reduction [%] |
|------------------------|------------------|--------------------|---------------|
| Repair Costs [M€/yr]   | 9.52             | 8.52               | <b>10.43</b>  |
| Rev. Losses [M€/yr]    | 1.64             | 1.57               | <b>4.21</b>   |
| Total Effort [M€/yr]   | 11.16            | 10.10              | <b>9.51</b>   |
| Costs per kWh [c€/kWh] | 3.35             | 3.00               | <b>10.58</b>  |

In **Table 1** it is shown that due to the optimisation of the O&M strategy the repair costs are reduced by a factor of 10.43% and revenue losses (because of production losses during periods of downtime) are reduced by 4.21%. Therefore, EUR 1.06 million of total O&M effort is reduced per year.

Assuming that the O&M costs account for 25% of the life cycle costs of an offshore wind farm and assuming the other elements of life cycle costs are constant, it can be concluded that through the optimised scenario the levelised cost of energy can be reduced by **2.77%**, which is an excellent achievement for offshore wind.

Please note that the O&M study presented in this chapter is limited and should be considered theoretical as the feasibility of the proposed adjustments to the maintenance strategy is not further researched. Additionally, only a limited data set for a 3 month period of the Rhyl Flats wind farm was obtained and weather data for the location of the farm wasn't available. In order to validate the OMCE approach in a better way, it is foreseen that at least one year of operational data should be analysed. Furthermore, weather data used in the analysis should be applicable for the location of the wind farm. In this way more confidence is obtained about the observed number of failures and a full yearly preventive maintenance campaign can be recorded.

Also, a more detailed optimisation study can be conducted by exploiting the functionalities of the ECN O&M Calculator. Therefore, the results presented in this chapter should be seen only as a first indication of the added value of the OMCE project.

# 5

## Conclusions & Future Work

As demonstrated in this report, the OMCE approach can provide the wind farm operators with actual wind farm performance assessment and support them in optimising their initial O&M strategies to achieve O&M cost reduction using the available operational data of the farm.

Within the FLOW OMCE project, ECN's O&M tools are further developed to provide the offshore wind industry with a complete O&M package from obtaining the operational data to calculation of the total O&M effort. As demonstrated in the O&M case study for RWE's Rhyl Flats wind farm, the OMCE approach has the potential to reduce the levelised cost of energy by approximately 2.8%, which is an excellent achievement and one the main goals of the Dutch FLOW programme.

The FLOW OMCE project is currently on-going and is planned to be finished by 2015. The next step in the project is to validate the whole approach by implementing the OMCE approach in an operational wind farm for a longer period (e.g. one year). Through this implementation, the potential cost reduction can be validated in more detail.

ECN's O&M tools assist offshore wind farm operators in achieving the most efficient O&M strategy possible over the lifetime of the wind farm. Upon request, ECN can assist the offshore wind industry in applying the OMCE knowledge and tools.

In addition to the knowledge developed in the FLOW OMCE project it is essential to do research on other operational aspects, such as Life Cycle Cost Assessment (LCCA), Operational Risk Assessment (ORA), short term decision support and O&M optimisation by risk and reliability based methods. These research topics are of great interest for the offshore wind industry and may lead to significant cost reduction of offshore wind farms in the future.





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