FINAL REPORT
Graduation Project
Probabilistic Design of Operations & Maintenance on

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Preface

The report in front of you is the master thesis of K. Neutink with as subject the probabilistic design of operations and maintenance on offshore wind energy conversion systems. It is the obligatory and final part of the Civil Engineering study at the Delft University of Technology. The report was written in co-operation with Hydronamic, Royal Boskalis Westminster’s engineering department, who I would like to thank for giving me the opportunity to graduate at their company.

The committee consisting of the following people supervised the project:

Prof. Drs. Ir. J.K. Vrijling, Chairman
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Mr. Ir. M. Van der Meulen
Dr. Ir. P.H.A.J.M. van Gelder

I would like to thank all of them for their involvement, enthusiasm and advice.

Of course my gratitude also goes out to my family, Sifu, and friends, for their support and innumerable things they have done for me. I could never have completed this without you.

Delft, March 2001,

Kjell Neutink
Summary

The demand for energy is still increasing, together with the desire to create more durable solutions. Wind energy is currently one of the most promising ways to provide both. A shortage of suitable land sites was the main reason for considering the location of the wind farms offshore, which also offers higher wind speeds. A problem however is formed by the low accessibility during periods of high wind speeds. This low accessibility could lead to a decrease in availability of the system and high O&M cost, both unfavourable for the levelised production cost and thus the profitability of the system. The levelised production costs have long been used as the main criterion in the evaluation of a farm design. In a private energy market, the system however should be optimised to maximise profit. At present energy prices the difference this gives for the optimisation of the farm and its O&M can be neglected.

The goal of this thesis is the optimisation of operations and maintenance on Offshore Wind Energy Conversion Systems with a probabilistic model. A number of previously executed studies were used to determine what input parameters should play a role. This showed that all subsystems contribute significantly to the initial capital cost, O&M cost and the unavailability of the system.

The model should take into account that periods of low accessibility coincide with periods of high energy potential. The model is based on a state-space model of each component. A component can find itself in the states "Failed", "Corrective Maintenance", "Preventive Maintenance" or "Available". Each component in the system is part of the chain connection that transports the produced energy to shore. If this chain is broken by a failure the loss in production capacity is determined by the place of the component in the chain. The failure of a component is determined by a Monte Carlo simulation. The reliability of components decreases in time according to a certain decline rate. After the execution of PM or CM the initial reliability will be restored.

Accessibility of the wind farm and produced energy are determined by the wind speed, which is also determined by a two seasonal Monte Carlo simulation. By changing two parameters a production function has to be fit on a data series obtained from the turbine manufacturer. The wave height is build-up of swell and wind-waves. A two seasonal Monte Carlo simulation also determines the swell waves. A deterministic relation is used to calculate the wind-waves. By superpositioning the two wave heights the in-field wave conditions are determined.

By bookkeeping the revenues and costs that result from the states of the components, the overall costs and revenues are calculated.

The program, written in visual basic, shows results according to predictions by hand calculations and results from other studies. It can be used to optimise the system. A simulation of the base case showed that the turbines are the main cause of unavailability and cost. The main cost drivers of ICC are turbines and their support structure. As expected the main O&M costs are caused by the turbine and in particular the rotors. The turbines are also the main cause of unavailability: 7 % compared to around 2 % for the shore- and grid connection.

There is a relationship between unavailability of the system and the occurrence of high wind speeds. It shows a decline in availability of about 5 % for wind speeds higher than the wind limit of used O&M tools. This results in a loss of revenues of about 2 % per year.

The relationship between PM interval, failure- and decline rate has been investigated. The first results indicate a trend towards a decreased need for PM than the intervals used in the base case. The influence of the decline in reliability can be neglected for decline rates up to 25 %. The program can be further improved by accounting for the availability of spare parts and crew or enabling more decision rules for the execution of O&M.
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List of Symbols and Abbreviations

MW = Mega Watt, $10^6$ Watts
KWh = Kilo Watt Hour, $10^3$ Watts during one Hour
Mln = Million, $10^6$
LPC = Levelised Production Cost
ICC = Initial Capital Cost
ICE = Initial Capital Expenditure
O&M = Operations and Maintenance
PM = Preventive Maintenance
CM = Corrective Maintenance
HV = High Voltage, referring to the high voltage used to transport produced energy to shore
MV = Medium Voltage, referring to the medium voltage to used collect to produced energy
AC = Asynchronous Current
DC = Di-Synchronous Current
p.d.f. = probability density function
p.m.f = probability mass function
OWEC = Offshore Wind Energy Converter
OWECS = Offshore Wind Energy Conversion System
1 Introduction

background
Since the seventies' oil crisis many western countries have searched for new ways of energy production. More and more emphasis is being put on renewable energy. Not only because of shortage in supplies of traditional sources, but also by a growing demand for more durable and environment friendly ways of energy production. Wind energy is one of these renewable energy sources. It has a long history and is one of the most promising to produce cost effective and clean energy on a large scale in the future. In recent years a significant cost reduction and improved reliability of the turbines strengthened the case for wind energy. Between 1991 and 1995 the Netherlands Agency for Energy and Environment (NOVEM) conducted research for the Dutch government on the Application of Wind energy In the Netherlands (TWIN). This showed promising results and was therefore continued in the TWIN 2 program. One of the goals of the program is to install 100 MW of wind energy production capacity per year. Furthermore, the program contains plans for a near shore demonstration project and allocation studies for offshore locations.

advantages of offshore locations
A shortage of suitable land sites, as exists in most of Western Europe’s densely populated countries, was the main reason for considering the location of the wind farms offshore.

Equally important, however, is the fact that wind speeds are often significantly higher offshore. An increase of about 20 percent at some distance from the shore is not uncommon. Furthermore, the offshore wind resources are enormous: Wind energy resources in the seas of the European Union, with water depths up to 50 metres, are easily several times larger than the total European electricity consumption.

A third argument in favour of offshore wind power is the generally smooth surface of water. This means that wind speeds do not decrease as much with the decrease in height above sea level as they do on land. This implies that it may be economical to use lower (and thus cheaper) towers for wind turbines located offshore.

A last advantage of offshore locations is the lower air turbulence and thus longer lifetime of the turbines except the support structure. The temperature difference between the sea surface and the air above it is far smaller than the corresponding difference on land, particularly during the daytime. This means that the wind is less turbulent at sea than over land. This, in turn, will mean lower mechanical fatigue loads on rotor, blades and shaft and thus longer lifetime for turbines located at sea. Waves however, will cause heavier loading of the support structure, which will have to be designed for heavier ultimate and fatigue loads.

Fig. 1.1 Inside a Turbine
challenges

The primary reason delaying development of offshore wind farms has been cost. Although the price of wind turbines has been falling some 20 per cent per kW installed power over the past few years, and installation cost per kW installed on land have declined due to up-scaling of turbines, installation costs offshore have remained more or less stable. This due to the fact, that offshore foundations and grid connections add significantly to the project costs.

A number of challenges arise from moving wind energy offshore. Further up-scaling of wind turbines, which are already the largest rotating machinery on earth, and adapting them to the offshore environment, will be challenges to manufacturers. Other challenges can be found in mass production of cheap foundations and improving the logistics of installation.

Another important challenge, that is the subject of this thesis, will be to economically optimise the availability of energy production of the wind farm, through an efficient operation and maintenance strategy. A number of studies indicate that remote surveillance of offshore farms will be even more important than it is on land. It may be economical to install e.g. extra vibration sensors, a technology, which is well known in the industry to ensure optimum maintenance of machinery. Since bad weather conditions may prevent service personnel from approaching the wind turbines, it is important to ensure a high availability rate of offshore wind turbines (similar to the 98 to 99 per cent average achieved by onshore turbines). Preventive maintenance check programmes may need to be optimised for remote offshore locations.

thesis' reader guide

Because this thesis' subject, the design of O&M on OWECS, cannot be treated separately from the entire system, a description of the system is made in chapter 3. Economic aspects of wind energy production are discussed in chapter 4, together with the build-up and sensitivity of initial, operational and maintenance cost as investigated in other reports. The reliability of the system, with respect to energy production, together with an O&M strategy leading to availability and revenues, is treated in chapter 5. As stated before, the optimisation cannot be made by optimising single subsystems alone, therefore a simulation of the entire system is made to determine the effect of design and strategy choices. The simulation is described in chapter 6. Results and their consequences for O&M decisions are discussed in chapter 7. Conclusions from the simulation and recommendations for further studies are presented in chapter 8.
2 Problem Statement and Objectives

2.1 Problem Analysis

general

Although considerable experience exists with wind energy onshore, the changes implied by the transfer offshore are uncertain. The goal will be to produce energy from offshore wind in a reliable and cost efficient way. In order to do so, not one turbine but an entire Offshore Wind Energy Conversion System (OWECS) is required. Such wind farms comprise a large number of turbines, a grid connection system and infrastructure facilities for operation and maintenance (O&M). The optimum design of the OWECS is ultimately determined by the profit gained from energy production. One of the main aspects herein is optimising investment versus O&M cost. This however cannot be reached by the optimisation of single subsystems alone. Other aspects that need optimisation are the reliability of the system and the adaptation to economies of scale of the single OWECS units.

Due to the changed scale and the transfer offshore, new failure mechanisms may arise and others are estimated to have an increased frequency. Another major difference to the onshore wind farms is the infrastructure needed for O&M; where the turbines onshore can be easily reached for either preventive or corrective maintenance, this is not the case for the OWECS. This can lead to a low availability and high O&M cost, both unfavourable for the feasibility of the offshore wind farms.

model Schöntag

The Institute for Wind energy (IvW) of the Delft University for Technology currently uses the model of Schöntag [1] for the simulation of O&M on the turbines. With this model the LPC and a number of system parameters can be calculated. The calculation is made with constant, weather independent, failure rates, a two-seasonal model of the wind and a number of other assumptions e.g. used O&M tools. Cost drivers of O&M and influences hereon are reported in [1]. The sensitivity of the levelised production cost to the distribution of initial investment and O&M cost should be determined in order to come to a well-balanced overall design.

The existing model currently does not incorporate the influence of the joint probability of high wind speed and thus possible high energy yield and low accessibility. This because the weather simulation makes use of a Weibull distribution to determine the storm length and interval, storm being defined as a wind speed above 7 Beaufort. Turbines are defined inaccessible for a period of 2.5 times this storm length to compensate for build-up of the storm and calming down of the sea. The number of turbines that is unavailable is updated per time step in the simulation. A Monte Carlo simulation determines the prevailing wind speed and occurrence of failures. The availability is calculated afterwards and annual energy yield is determined based on this overall availability and average annual wind speed. This could discard the longer duration of O&M during strong winds, underestimate lost revenues, penalty cost and overestimate energy yield.

A new model will therefore be made to account for the joint probability of high wind speeds and low accessibility and to investigate the influence of the different sea states on the choice of O&M tools, the influence of preventive maintenance on the failure rates and the consequences this has for the distribution between PM and CM efforts.
2.2 **Problem Statement**

The problems are:

a) The relations between the main cost drivers, investment and O&M, and their combined effect on the systems profitability are uncertain.

b) Wind and wave simulation is currently period based which can lead to overestimation of energy yield and underestimation of O&M cost.

2.3 **Objectives**

The goal of this study will be to optimise the offshore wind energy cost by:

- Determining the main cost drivers and their relationship to the farm layout.
- Simulating these main cost drivers with an improved model of the sea states.
- Implementing the improved sea state simulation in the model from Schöntag.

2.4 **Limitations**

- Availability of data will limit the possibilities of verifying the model.
- Limitations on workability of O&M tools will affect the definition of sea states thus possibilities of maintenance and the LPC.
- Furthermore, a number of limits affect to what extend the O&M strategy and farm layout can be freely chosen and thus also affect the LPC, these are:
  - Government regulations on used materials and methods.
  - Prices of produced energy from other sources.
  - Environmentally protected areas.
  - Conflicting interest from other energy suppliers (locations close to oil or gas fields)
  - Shipping routes.

2.5 **Assumptions**

Several locations for the wind farm have been investigated in previous studies. Although the allocation of the farm is not the subject of this study, it will greatly affect the all conditions in which the farm is to be placed. Distribution of wave height and wind speed will therefore be variables in the model to develop. The same goes for local currents and the distance to the harbour, which will affect the time span that is needed to reach the site. As a starting point for the system’s model, a base case will be used as a reference in this study.

The base case is an OWECS consisting of 40 Nordex N80, 2.5 MW turbines located at 8 km of the coast of Egmond aan Zee

Distribution of wave height is seasonal with a summer and a winter period and is stationary during these seasons.

Because the layout of the farm is determined by the wake created behind the turbines, the distance between the turbines has to be at least eight times the rotor diameter. This is greater than the required space for maintenance or repairs so these can be done independently to each turbine.
3 System Description

3.1 System Definition

The system that is the subject of this thesis is an offshore wind farm. To give a description of the system first its limits must be determined. Most important characteristic of the system is that it is situated offshore. This implies differences for the exerted loads on the system and for the ways the system can be controlled, maintained and repaired. Furthermore, the purpose of the systems’ model will be to determine and optimise its output. The system’s limits will thus be taken to include all components offshore that determine the systems cost and revenues.

The system and its subsystems can be modelled as:

![System Diagram]

*Fig. 3.1 System Model*

In which the Offshore Wind Energy Converter can be modelled as:

![OWEC Diagram]

*Fig. 3.2 OWEC Model*
In the system the following subsystems and components are present:

- **A Medium Voltage Network (MV-net):** The turbines give a production in low voltage, which eventually has to be connected to a high voltage network ashore. Because the produced power is too large to collect at low voltage and direct transformation to high voltage is expensive, a medium voltage network connects the low and high voltage networks. There are no principle differences between on- and offshore grid connection and farm layouts, but magnitude and distribution of individual cost components may lead to a different optimum design solution. For submarine power transmission cables the fundamental choice lies between AC and DC. The first gives difficulties with the three phase cabling and capacity losses, the second by the cost of converters. For distances up to 60 km offshore the AC option is to be preferred [4]. Connection to the grid of the Nordex N80/2500 kW is established through an IGBT converter based on the principle of the asynchronous generator. For the reliability of the system, the main parameters are the length of the cables, the number of switches in the grid and the choice for either a chain circuit or star connection. A physical limit exists on the number of turbines that can be connected in one circuit as a result of both the capacity of the cables and the voltage drop along their length. The maximum number of turbines is therefore a function of the turbines’ rated capacity and the spacing of the turbines. Generally the farm will consist of \( m \) clusters or strings with \( n \) turbines. If and how switches or redundancy in the network can improve the reliability will be discussed further on.

- **The Transformer** collects the power from the AC grid and changes the medium voltage to a high voltage to reduce the energy losses of the produced power during transport ashore. The probability of failure in the transformer will be derived from that of a land based transformer.

- **A High Voltage Network (HV-net):** For most farms a single connection to shore is sufficient to transport the produced power. With greater distances from the coast the probability of failure will increase in this connection, the cost to build redundancy in this connection will too. The revenues from the increase in availability resulting from the redundancy will have to be compared to the cost of this redundancy. The cost of the redundancy will not only be determined by the length of the connection but also by the approach to shore and the type of coast.

- **The Offshore Wind Energy Converters:** As stated in the design assumptions of this thesis, the Nordex N80, 2.5 MW turbines will be used. They are state of the art and therefore contain all components that can play a role in the further analysis of the system. These turbines are controlled by a programmable logic controller, analysing the data from the sensors of the turbine and environment, and generating the control signals for the wind turbine. Data can be read from a display-board. Parameter settings for the turbine can be changed accordingly, if required. The wind turbine is prepared for remote monitoring and control, connected by a telephone-line. From a Personnel Computer a range of data can be read from the turbine, such as energy production, wind speed, wind direction, temperatures, hydraulic pressure, etc. Moreover, certain basic functions of the wind turbine can be activated this way. In case of an error, the turbine controller automatically reports the event, and the data in the controller is stored so that it is possible to see what happened just before, and when the error occurred.

The turbines operate fully automatically. This means that the turbine automatically starts when the wind speed reaches 3.5 m/s (Cut-in wind speed). When the rotor/generator gains speed, the generator is connected to the grid via an IGBT converter. The turbine supplies electricity to the grid, as long as the wind speed is between 3.5 and 25 m/s. At wind speeds higher than 25 m/s (Cut-out wind speed), the turbine will be shut down for safety reasons. The turbine will automatically re-start after any shut down if no error is present. If the turbine has an error, this has to be analysed and reset or fixed before the turbine starts up again.

A more detailed description of the Nordex N80 turbine can be found in Appendix 7.
3.2 System Functions

Now that the physical layout and the boundaries of the system have been determined, the functioning of the components should be examined. This to see what might influence the system and what are the limits to the functioning of the components.

For the examination of the functions the components have to fulfil, the path of the energy and its conversion through the system, including the supporting functions, will be followed.

**rotor**

The input from the wind is transferred into rotation of the rotor blades. This causes a horizontal load on the entire structure, forces from turbulence and changing gravitational forces on the blades themselves. Further cause of loads can be the cover of the rotor and blades with ice. The excitations from these forces and response and resonance hereto are the main parameters in the fatigue and ultimate state analyses of the turbine. The fatigue life will be longer when the number of productive hours increases due to aerodynamic damping.

**nacelle**

The blades are placed in the optimum position with respect to the wind by the pitch system. This pitch system is also used as primary brake system. The hub connects the three blades to each other and to the main shaft. Here, the drive train is connected to the generator via a gearbox. The current will then be converted by the IGBT converter and transmitted to the MV net. The gearbox, generator and converter are housed in the nacelle, in which switchgear, control systems and maintenance equipment will also be present. The nacelle is turned into the wind by the yaw system.

**support structure**

The nacelle and its rotor blades are supported by the tower, which in its turn is supported by the foundation. Acting loads on the tower are those from above laying structures, wind and waves. Furthermore there can be forces from mooring or colliding vessels. Plans exist to equip the tower with a winch to be able to lift all parts of the turbine, including the rotor and blades, without the need for offshore cranes.

**electrical infrastructure**

The grid of the MV net starts in the tower, e.g. at the IGBT converter, and ends at the transformer. The number of switches in the grid connections determines the dependency of the wind turbine on the other turbines in the grid. The circuits or strings are then connected to the central transformer where the current is converted for transport to shore.

**control system**

The OWEC is controlled by a programmable logic controller, analysing the data from the sensors of the turbine and environment and generating the control signals for the wind turbine. The data can be used for remote monitoring if a telephone connection to shore is made. This connection can be integrated with the MV and HV networks.
The matrix below shows the relationships between the physical components and the functional aspects of the OWECs.

<table>
<thead>
<tr>
<th>Physical Subsystems</th>
<th>Functional Subsystems</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy conversion</td>
<td>Load carrying</td>
<td>Conversion support</td>
<td>Energy transport</td>
</tr>
<tr>
<td>Rotor blades</td>
<td>●</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitch system</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaft &amp; Coupling</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Gearbox</td>
<td>●</td>
<td></td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Generator</td>
<td>●</td>
<td></td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>IGBT Converter</td>
<td>●</td>
<td></td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Yaw system</td>
<td></td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>Control system</td>
<td>●</td>
<td></td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Mechanical brake</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Tower</td>
<td>●</td>
<td></td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Foundation</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>MV net</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Transformer</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>HV net</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

*Table 3.1 Aspect Systems in OWECs*
3.3 *In- and Output of Subsystems and Components*

The input to the system is formed by the wind. The intended output is a HVAC current on shore. Each component or subsystem has its role in completing this task. For the inventory of failure mechanisms and calculation of the reliability, insight is needed in the in- and output of the components. Furthermore, influences on the processing within the subsystem and components is required. An overview is given in the table below.

<table>
<thead>
<tr>
<th>Input</th>
<th>Component or Subsystem and influences hereon</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>Pitch and yaw angle</td>
<td>Rotation speed</td>
</tr>
<tr>
<td>Wind turbulence</td>
<td>Brakes Control system</td>
<td>Torque</td>
</tr>
<tr>
<td>Air density</td>
<td><strong>Rotor blade</strong></td>
<td>Vibrations</td>
</tr>
<tr>
<td>Control system</td>
<td>Lubrication</td>
<td>Horizontal load</td>
</tr>
<tr>
<td></td>
<td><strong>Pitch system</strong></td>
<td></td>
</tr>
<tr>
<td>Variable rotation speed</td>
<td>Brakes Control system Lubrication</td>
<td>Constant rotation speed</td>
</tr>
<tr>
<td>Variable torque</td>
<td><strong>Transmission</strong></td>
<td>Constant torque</td>
</tr>
<tr>
<td>Constant rotation speed</td>
<td><strong>Generator</strong></td>
<td>Rotation speed dependent</td>
</tr>
<tr>
<td>Control system</td>
<td>Lubrication</td>
<td>AC power</td>
</tr>
<tr>
<td></td>
<td><strong>Yaw system</strong></td>
<td>Yaw angle</td>
</tr>
<tr>
<td>Horizontal loads from</td>
<td>Tower stiffness</td>
<td>Overturning moment</td>
</tr>
<tr>
<td>- wind</td>
<td>Tower dimensions</td>
<td>Horizontal forces</td>
</tr>
<tr>
<td>- waves</td>
<td>Number of excitations</td>
<td>Vertical forces</td>
</tr>
<tr>
<td>Vertical loads</td>
<td>Corrosion protection</td>
<td>Vibrations</td>
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<td><strong>Tower</strong></td>
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<td>Soil Characteristics</td>
<td>Soil stresses</td>
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<td>Horizontal loads</td>
<td>Erosion</td>
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<td>Vertical loads</td>
<td><strong>Foundation</strong></td>
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<td>Rotation Speed</td>
<td><strong>Control System</strong></td>
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<td>Power Output</td>
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<td>Yaw Angle</td>
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<td>Current</td>
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<td>Power</td>
<td><strong>MV net</strong></td>
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<tr>
<td>Voltage</td>
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<td>Current</td>
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<tr>
<td>Power</td>
<td><strong>Transformer</strong></td>
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<tr>
<td>Voltage</td>
<td>Voltage</td>
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<tr>
<td>Current</td>
<td>Current</td>
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<tr>
<td>Power</td>
<td><strong>HV net</strong></td>
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</tbody>
</table>

*Table 3.2 In- and Output of Components*
3.4 Design Limits of the System

To determine the reliability of the system, the design limits of its subsystems and components should be known. Limits exist for the expected loads exerted by the systems surroundings, or by components on each other. The design limits can be divided in serviceability state limits and ultimate state limits.

serviceability limits

- Cut in wind speed of the turbine is 3.5 m/s
- Cut out wind of the turbine speed is 25 m/s
- Number of rotations for lubrication
- Total hours of operation before necessary maintenance
- Number of blade rotations before necessary maintenance
- Number of pitch corrections before necessary maintenance
- Number of gear changes before necessary maintenance

ultimate design limits

- Short circuit voltage / current and allowed phase differences in the different nets
- Survival wind speed of the rotor and nacelle is 70 m/s (IEC) 65 m/s (GL1)
- Fatigue of support structure and rotor blades
- Maximum turnover moment at foundation
- Maximum horizontal loads at foundation
- Maximum depth of scour holes.

As far as these limits can be quantified, or probability of occurrence of failing components can be estimated, they can be taken into account in the calculation of the systems reliability or simulation of the systems availability
3.5 Operations, Maintenance and Tools

3.5.1 Operations and Maintenance Tasks

All maintenance procedures to be carried out are influenced by weather, waves and wind. The allowed wave height and wind speed will differ depending on the used equipment. Furthermore the visibility, waves and wind will play a role in the time needed for the execution of maintenance operations. To reduce the number of trips to the site, the offshore wind turbines can be equipped with remote control and reset capabilities where possible.

Maintenance operations and inspections can be divided in:

- **turbines**
  The inspection and maintenance procedures on offshore turbines have to be derived from those onshore because no sufficient data on offshore wind turbines is available. Preventive maintenance is estimated to involve the following tasks:
  - Visual inspection of the unit, both in and out of service
  - Lubrication of mechanical components such as blade bearings and links
  - Replacement of worn items e.g. brake pads, oil filters etc.
  - Inspection of hydraulic system
  - Gas pressure test of accumulators
  - Re-torquening of bolts on critical components
  - General inspection of electrical components

  These tasks are normally due at six month intervals. A more detailed inspection of the blades, generator and gearbox is made once a year and every five years these components have to undergo a major overhaul. After ten years the following components will have to be exchanged.
  - Generator bearings
  - Yaw pads
  - Pitch linkage bearings
  - Pitch cylinder
  - Friction clutch
  - Transmission shaft gear
In [4] the following overview is given on preventive maintenance on the turbine.

<table>
<thead>
<tr>
<th>Component</th>
<th>Elements</th>
<th>Action yearly</th>
<th>Action five yearly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blades</td>
<td>Outer Surface V</td>
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<td>Bolt Connection V</td>
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<td>T</td>
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<td>Pitch System</td>
<td>Blade Bearings VG</td>
<td>P</td>
<td></td>
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<tr>
<td></td>
<td>Pitch Cylinders V</td>
<td>F</td>
<td></td>
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<tr>
<td></td>
<td>Cylinder Bearings P</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Valves etc. V</td>
<td>F</td>
<td></td>
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<tr>
<td>Main Shaft</td>
<td>Thrust Bearing G</td>
<td>P</td>
<td></td>
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<tr>
<td></td>
<td>Oil Distribution Box V</td>
<td>F</td>
<td></td>
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<td>Slip-ring Unit V</td>
<td>FR</td>
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<tr>
<td>Gearbox</td>
<td>Mechanical Parts V^2</td>
<td>V^2F</td>
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<tr>
<td></td>
<td>Lubrication System V</td>
<td>F</td>
<td></td>
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<td>Cooling System V</td>
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<td></td>
<td>Lubrication Oil T</td>
<td>X</td>
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<td>Filter FX</td>
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<td></td>
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<tr>
<td>Generator</td>
<td>Shaft Bearings G</td>
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<td></td>
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<td></td>
<td>Windings V</td>
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<td>Emergency Stop F</td>
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<td>Mechanical Brake F</td>
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<td></td>
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<td></td>
<td>Brake Linings X</td>
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<tr>
<td>Yaw System</td>
<td>Gear Mesh VG</td>
<td>P</td>
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<td>Yaw Motors F</td>
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<td></td>
<td>Yaw Bearing VG</td>
<td>P</td>
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<td>Hydraulics</td>
<td>Pump VG</td>
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<td>Hydraulic Oil T</td>
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<td>Valves etc. V</td>
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<td>Switchgear</td>
<td>V</td>
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<td>Transformer</td>
<td>V</td>
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<tr>
<td>Control System</td>
<td>Wind Logging V</td>
<td>F</td>
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<td>PLC F^4</td>
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<tr>
<td>Power Supply Unit</td>
<td>Motor and Generator VF</td>
<td>G</td>
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<td>Fuel R^5</td>
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<tr>
<td>Cables</td>
<td>V</td>
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<tr>
<td>Platforms and Ladders</td>
<td>V</td>
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<td>Fire Extinguishers</td>
<td>V</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Nacelle</td>
<td>Bed Plate and Hub V</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nacelle Cover V</td>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3 Preventive Maintenance on Turbine

In which:  
V = Visual Inspection  
T = sample Test  
X = eXchange of component when necessary  
F = Functional test, vibration finger print  
P = measurement of bearing Play  
R = Refurbishment  
G = Greasing  

^1 = repair from platform  
^2 = only from outside  
^3 = inside through inspection holes  
^4 = continuously tracking itself  
^5 = filling
- **electrical infrastructure**
  A large part of the maintenance on this sub-system will be corrective. Failures will mainly consist of cable fractures in the connections inside the farm. When fractures occur in the cables, they will be located with echo-impulse measurements. At the location the cable will then be dug up for 20 to 50 m on both sides of the failure. Part of the cable will have to be removed due to corrosion, the remainder will be reconnected with muffs. Five yearly inspections of certain parts however will also be necessary.

- **foundation**
  The steel mono pile foundations will be protected against corrosion with a cathode protection. Instead of the metal of the construction, a block of a base metal corrodes. Maintenance of the support structure will therefore consist of an annual inspection / maintenance for the proper functioning of the navigation equipment.
  A large inspection or major overhaul is carried out every five years to discover early metal fatigue or major mass displacements. This inspection is necessary to obtain or renew offshore and navigation certificates for another five years. During the inspection, the depth of scour holes will be checked. Painting of the structure is also part of this five yearly maintenance.
  Further maintenance must be carried out in case of accidental damage, caused by ships, fishery, vandalism or recreation.

The question whether a maintenance base is necessary and what tools to use for O&M tasks, depends on the number of installed turbines, occurring failures and distance to shore. Executing O&M will bring the components back to their initial state and reliability. Whether and how a decline in reliability affects the optimisation of the system will be investigated later on.

### 3.5.2 Tools and their Workability

The O&M tasks will be performed under varying weather conditions. The characteristics of the tools used for O&M determine the workability during these weather conditions. A sea state is a combination of environmental conditions e.g. wind and waves. The duration of a sea state will depend on the time window in which the wind speed and wave characteristics are within predefined limits. These limits can be derived from workability limits of O&M tools. Depending on the sea state, decisions on the execution of O&M tasks will be taken.

When performing O&M tasks offshore, accessibility and workability are determined by characteristics of vessels, offshore cranes and working platforms. Horizontal and vertical movements are of importance for lifting operations and for transferring personnel on and off the turbines.

Horizontal movement is divided in sway, surge and yaw motions [31]. The components sway and yaw are most important for determining the required manoeuvring areas. Wake effects, leading to distances between turbines of 8 to 10 times the rotor diameter, determine the layout of the wind farm. In case of the Nordex N80 this means distances of 640 to 800 meter between turbines. This hardly forms a restriction on manoeuvrability. These components, together with sway motion, however, are important for mooring operations. Roll can be an additional component in locating fenders on the support structure.

Vertical displacement may be caused by either waves or forward speed in still water. This latter displacement can be split into squat and trim, while waves give rise to pitch, heave and roll. Squat and trim can be neglected since O&M tasks will be performed with very low or no vessel speed.

The wave induced motions depend on the size of the vessel relative to the waves, and their dynamics can be considered equivalent to mass-spring dynamic systems. Each vessel will thus have its own natural or resonant frequency.
When the motion components of a ship are linear, thus directly proportional to wave height, it is possible to determine the total response by superposition of the individual response components.

![Diagram of ship motions](image)

*Fig. 3.3 Pitch, Heave and Roll*

From Fig. 3.3 can be seen that:
- Heave motion is most severe when the wave length equals half the wave length
- Roll motion is peaks when the beam of the ship equals a quarter of the wave length
- Heavy Pitching can be expected when the ship length equals a quarter of the wavelength.

Since the ships' speed can be neglected during O&M, the encountered frequency will be the same as the wave frequency.

![Spectra diagrams](image)

*Fig. 3.4 From Wave Spectrum to Response*

Although wave height, frequency and length thus all play a role in determining ship motion, in normal practice wave height, and for lifting operations also wind speed, are taken to determine workability. This because, unlike wave frequency and length, the wave height can be estimated visually. Wind speed can be easily measured. The effects of this simplification are outside the scope of this thesis, but could be subject of further investigation in the future.
3.6 Offshore Environment

For both determination of the energy yield and the accessibility of the system for the execution of O&M tasks, the environment formed by wind and waves is of utmost importance. An overview of general process modelling can be found in Appendix 1.5. Here the models for wind and wave prediction will be discussed, that will be used in a simulation of the OWECs.

3.6.1 Wind Modelling

The wind can be modelled in several ways. Wind models are needed for determination of ultimate loads, production capacity of a chosen site and for defining weather windows in which O&M tasks can be completed.

The strength of the support structure is standardised in the IEC norms and GL classifications. The Nordex N80 is build to withstand 65 m/s winds (GL class 1) or 70 m/s according to the IEC norm. The variation herein is not known but is assumed small in comparison to that of the wind speed. The ultimate limit state will thus have the same distribution as the distributions of maximums of the wind speed.

For the North Sea, a database was created by the North European Storm Study (NESS). This database contains a hindcast of records for three-hour periods of every winter and two summers from 1965 to 1987. The estimates were checked with known measurements. Storms were not yet part of this database, but were recorded in the NEXT database from 1988 until 1995, containing all data for summer and winter.

Location of the base case is Egmond aan Zee 52°36'36"N 4°08'10"E corresponding to grid point 83-49 in the database. The data are best fit to a two-parameter Weibull distribution:

\[ f(V) = \frac{\beta}{\alpha} \left(\frac{V}{\alpha}\right)^{\beta-1} \cdot \exp\left(-\frac{V}{\alpha}\right)^\beta \]

with \( f(V) \) Probability of occurrence of wind speed \( V \)

\( V \) Wind speed

\( \alpha \) Scale parameter \( \approx 9.4 \text{ m/s} \)

\( \beta \) Shape parameter \( \approx 2.2 \) [-]

In a Monte-Carlo simulation the cumulative distribution is used, to determine the occurred events e.g. the prevailing wind speed. This cumulative Weibull distribution is:

\[ F(V) = 1 - \exp\left(-\frac{V}{\alpha}\right)^\beta \]

with \( F(V) \) Probability of occurrence of wind speeds smaller than \( V \)

For a correct simulation, the variation of the wind in time is needed, to take in account that periods of strong wind coincide with periods when maintenance is not possible. Thus the probability of occurrence of wind speed at time \( t \) as function of the wind at \( t -1 \) is important. This function is called the autocorrelation function, which can be derived when sufficient data is available. Where this is not the case, this function will need to be programmed to represent a correct value of the wind distribution during the year.
3.6.2 Wave Modelling

The offshore environment will affect the ultimate and fatigue loads on the structure and determine the O&M possibilities on the turbines and its electrical network. It is common practice to differentiate between the properties of wave climates as judged in the short- and in the long term. The short term ranges from periods from twenty minutes to three hours and statistical properties are assumed constant. In the long-term non-stationary, seasonal and annual variability are taken into account for the prediction of weather windows, fatigue and ultimate loads. The long-term models rely mostly upon empirical distributions.

Wave height can be modelled in various ways. Any model should however take the physical laws governing waves under consideration. Waves are limited in height by their steepness and the local water depth. These limits are combined by Miche leading to the breaking of a single regular wave at [31]:

\[ H_b = 0.142 \cdot L \cdot \tanh \left( \frac{2\pi}{L} \cdot h \right) \]

with  
- \( H_b \) = Height of braking wave  
- \( L \) = Wave length  
- \( h \) = Local water depth

In reality the waves will not be regular on the site and since wavelength is not part of the weather simulation, the maximum wave height in the simulation will be determined by:

\[ H_b = 0.6 \cdot h \]

Local wave height can be seen as a combination of waves caused by wind and swell. The wind waves are related to prevailing wind speeds at the site and can be calculated deterministically with wind-wave formulas from Phillips and Miles. Swell is propagated across seas and oceans and therefore practically independent of local weather conditions. Wave heights caused by swell will thus be stochastic in nature. The local wave height can be determined by superpositioning local wind waves and a wave height drawn with a Monte Carlo simulation on a distribution of swell waves.

wind-waves

At the initial stage of wave generation, the turbulent fluctuations of the atmospheric pressure induce small waves, called capillary waves. These waves are usually unstable and dissipate due to surface tension, when the wind calms. When wind speed increases, waves grow and gravity forces are sufficient to support wave motion. The starting points of current wave generation models are the pressure fluctuations and variation in shear stresses at the water surface, associated with the airflow over the waves.

In determining wave height from wind speed, the fetch length and duration of this wind speed also play a role. The physical processes by which waves are generated by wind are quite complicated and despite considerable research, a full understanding is lacking. It is beyond the scope of this thesis to consider this work in detail.
During the Joint North Sea Wave Project (JONSWAP, Hasselmann et al, 1973) the following empirical relation was developed:

\[ \frac{gH_s}{U_{10}^2} = 1.6 \times 10^{-3} \left( \frac{gF}{U_{10}^2} \right)^{1/2} \]

in which:  
\( g \) = Gravitational acceleration = 9.81 m/s\(^2\)  
\( H_s \) = Significant wave height  
\( F \) = Fetch length  
\( U_{10} \) = Wind speed at a reference height of 10 m.

The previous equation shows an unlimited growth for increasing fetch length. This is clearly unrealistic and an upper limit is observed by Pierson and Moskowitz, it is given by:

\[ \frac{gH_s}{U_{10}^2} = 2.433 \times 10^{-1} \]

The physical reason for the existence can be explained by the fact that an increase in wave height is accompanied with an increase in wave period. As the wave period increases, the speed at which the wave propagate, the phase speed, will also increase. Eventually the point will be reached where wave phase speed equals wind speed and relative wind speed sensed by the waves is zero.

Beside fetch length, the growth of waves is also limited by time. The time \( t_{\text{lim}} \) required for a wave field at fetch length \( X \) to become fetch limited is also found during the JONSWAP project:

\[ t_{X\text{lim}} = 65.9 \frac{U}{g} \left( \frac{gX}{U^2} \right)^{2/3} \]

with  
\( U \) = Wind Speed  
\( g \) = Gravitational Acceleration

In determining wave height from wind speed, both time and direction, since this determines the fetch length, play an important role. Actual in-field wave conditions caused by wind are a combination of waves, from wind of varying speed in different directions and thus varying fetch lengths. For calculation of the build-up of the in-field wave conditions a number of parameters should thus be know. These are the probability of wind speed from all directions, the probability of wind coming from these directions and fetch length from these directions.

The exact calculation is thus beyond the scope of this thesis, furthermore the necessary data is seldom available and calculation is time consuming. In a first approach an estimate for the average fetch length will be taken. Per time step in a simulation, the fully developed wave height can be taken, only limited by the chosen fetch length. The build-up of waves over time will not be taken into account.

This leads to an overestimate of wave height since the time step in the simulation may be too small for the wave field to come to a full development. This can be compensated by adapting the used fetch length.
swell

Short-term statistical properties of swell can, for the greater part, be derived theoretically. These waves can be seen as the sum of a great number of independent spectral components. From the central limit proposition it follows that the waves can be approached with a Gauss process, an approach that is more valid when non-linearities play a less important role (low wave steepness, deep water). This holds for \( h > \pm 1/2 \ L \).

Assuming that the sea surface elevation, \( H(t) \) is a zero mean, stationary and Gaussian random process, it is in a statistical sense completely characterised by its spectral density function, \( \phi_{HH}(f) \). In terms of the autocorrelation function, \( r_{HH}(\tau) = E[H(t)H(t+\tau)] \), \( \phi_{HH}(f) \) can be written as [13]

\[
\phi_{HH}(f) = \int_{-\infty}^{\infty} \exp(-2\pi f t) \cdot r_{HH}(\tau) d\tau
\]

The spectral density function is given for both positive and negative frequencies, the physical realisable spectral density function, \( s_{HH}(f) \) becomes:

\[
s_{HH}(f) = \begin{cases} 
2\phi_{HH}(f) & f \geq 0 \\
0 & f < 0 
\end{cases}
\]

A number of important properties can then be expressed by the moments of this spectrum, the \( n \)th order moment defined as [13]:

\[
m_{HHn} = \int_{0}^{\infty} f^n s_{HH}(f) df 
\quad n = 0,1,2,\ldots
\]

The swell can now be Monte-Carlo simulated by the same process as was used to determine the prevailing wind speed. This time however, the above-mentioned Gauss distribution will be used instead of the Weibull wind distribution.
3.6.3 Correlation of Wind and Waves

There is not only a correlation between waves and wind speed through the wind waves. Swell will also be correlated to the wind speed. This correlation will increase when swell- and wind directions coincide for long periods of time. The probability of this can show when comparing the wind rose of a site with its wave rose. Care should be taken however, in taking the wave rose for swell waves only. When swell wave and wind direction coincide for a longer period of time, the calculated waves from wind will be the same as the occurring swell waves.

Calculating wave height by super-positioning the wind waves and swell can thus lead to an overestimate of the actual wave heights in cases where waves and wind come from the same direction for a considerable time. The overestimate of wave heights leads to an underestimate of workability and energy yield, and increases O&M cost. The influence of this will be small for small fetch lengths and can be determined by comparing results to a simulation with a zero fetch length and increased swell.

When sufficient data on wind speed and wave heights at a certain location is available, a correlation matrix can be determined. By counting all transfers from wind speed $V$ to wind speed $V + \Delta V$ and dividing this by the total number of transfers from wind speed $V$, the probability of transfer from $V$ to $V + \Delta V$ can be determined. Doing this for all wind speeds and following the same procedure for all wave heights leads to a four-dimensional matrix that assigns a probability to all transfers $V, H \to V + \Delta V, H + \Delta H$.

$$P(V_i, H_i \to V_j, H_j)$$

By assessing all $\Delta V$ and $\Delta H$’s a probability can be assigned to all transfers.

The four-dimensional matrix will thus have to be calibrated for a specific site. This process is too cumbersome for the simulation of the offshore energy farm and its O&M. For now the correlation between wind and waves will come from the calculated wind – waves and the correlation increases for increasing fetch length. Calibrating the four-dimensional matrix and implementing it into the simulation might be subject for further study.
4 Economic Analysis

4.1 Costs versus Revenues

Energy production was long considered as a government task and minimising the cost of this production was the generally accepted design rule when examining new energy resources. With the privatisation of many government enterprises, the factor profit plays an increasingly important rule. Recently (February 2001) the state of California (US) was forced by court rule to provide affordable energy. The discussion on whether energy should be produced for maximum profit or for minimum cost is yet undecided. The outcome however could lead to a different design optimum or O&M strategy. The influence of this will be examined in this section.

In general profit is defined as total revenues minus total economic cost. The total economic cost herein must be calculated as the sum of the opportunity cost of all the inputs. Both revenues and part of the expenditures are spread over a large time span. This time effect will be accounted for by taking discounted values for all amounts.

The revenues per produced kWh equal a certain market price, plus a possible added value accounted to the cleaner way of production. The amount of produced energy depends on the installed capacity and the available production time. Performing O&M tasks reduces the available production time. Yearly energy yield can be roughly calculated with:

$$E_t = P(V) \times (T - T_{O&M})$$

with

- $E_t$ = Energy Yield in Year t
- $P(V)$ = Yearly Average Energy Production as function of V
- $V$ = Year Average Wind Speed
- $T$ = Total Time
- $T_{O&M}$ = Downtime due to O&M

Revenues, the product of price and produced energy, thus equal:

$$Revenues = \sum_{t=1}^{n} \frac{P(V) \times (T - T_{O&M}) \times price_t}{(1 + r)^t} = \sum_{t=1}^{n} \frac{E_t \times price_t}{(1 + r)^t}$$

with

- $E_t$ = Energy Yield in Year t
- $price_t$ = Average Price in Year t
- $n$ = Economic Lifetime of System
- $t$ = Timestep of 1 year
- $r$ = Interest Rate

The costs made to produce this energy are:

$$Cost = ICE + \sum_{t=1}^{n} O & M_t \times \frac{Dismantling \cdot Cost - Salvage \cdot Value}{(1 + r)^t} \cdot \frac{1}{(1 + r)^n}$$

with

- $ICE$ = Initial Capital Expenditure
- $O&M_t$ = Cost of O&M in Year t
The profit from the OWECS can thus be calculated as:

\[
\text{Profit} = \sum_{t} \frac{P(V) \times (T - T_{O&M}) \times Price_{t}}{(1 + r)^t} - \sum_{t} \frac{O & M_{t}}{(1 + r)^t} \left(\text{Dismantling} \cdot \text{Cost} - \text{Salvage} \cdot \text{Value}\right)
\]

This shows that both direct cost of O&M and O&M time reduce the systems profit. The latter should be valued against the market price. Maximising profit will thus become difficult because the optimum time spent on O&M tasks depends on the market price. The higher this market price the more urgent it becomes to have a short duration of O&M. This is true as long as the extra costs to shorten the O&M duration, do not rise above the gained revenues from extra production.

Rearranging the formula for the system's profit after differentiating to \( t \), shows that the price received for produced energy equals:

\[
\text{Price}_{t} = \frac{\left\{ \text{ICE} + \frac{\text{Dismantling} \cdot \text{Cost} - \text{Salvage} \cdot \text{Value}}{(1 + r)^t} \right\}}{P(V) \times (T - T_{O&M})} + \frac{\text{O & M}_{t} + \text{Profit}}{P(V) \times (T - T_{O&M})}
\]

The received price for produced energy is thus partly compensation for the costs that are made and partly profit. Wind energy producers can be seen as price takers on the energy market, since their output level does not affect the price level of the market; their market share is too small and energy prices mainly depend on prices of traditional energy sources. This market price level can however not be predicted. In the current situation the market price is just around the cost to produce energy via an OWECS and profit margins are small. In this particular case, profit maximisation will mean minimising the cost of produced energy.

The costs of produced energy are commonly expressed as the Levelised Production Cost (LPC). These are the average production cost over one year. The ICE, dismantling cost and salvage value are spread over the economic lifetime by an annuity factor. The sum of ICE and discounted values of dismantling cost and salvage value is also known as the Initial Capital Cost (ICC). By dividing this ICC by the annuity factor the total investment is thus spread over the system's lifetime.

\[
\text{ICC} = \text{ICE} - \frac{\left(\text{Dismantling} \cdot \text{Cost} - \text{Salvage} \cdot \text{Value}\right)}{(1 + r)^n}
\]

The LPC then become:

\[
\text{LPC} = \frac{\text{ICC}}{a \times E_{t}} + \frac{\text{O & M}_{t}}{E_{t}}
\]

thus the first and second terms on the right hand side of the price formula.

with \( \text{LPC} = \text{Levelised Production Cost} \)

\( \text{ICC} = \text{Initial Capital Cost} \)

\( \text{O&M}_{t} = \text{Total Operation and Maintenance Cost in Year} \ t \)

\( E_{t} = \text{Energy Yield in Year} \ t \)

\( a = \text{Annuity Factor} = \frac{1}{r} \left[ \frac{1}{1 + r} \right]^{n} \]

with \( r = \text{Interest Rate} \)

\( n = \text{Economic Lifetime} \)
Minimising the LPC can thus be seen as a way to economically optimise the system, as internationally agreed in the evaluation procedure of the IEA [33], although the true goal remains maximising profit. Therefore relative importance and build-up of cost drivers, both in initial investment and during O&M, will have to be taken under consideration since the LPC can only give an indication of the systems efficiency, but not of its profitability. When profit margins rise, more effort should be made to use the installed capacity to its maximum potential. With a low or no profit margin, costs will have to be minimised or production may even have to be halted when operational costs exceed the revenues.

### 4.2 Build-up of Energy Costs

The lifetime of the OWECs can be divided into three phases: installation, operation and dismantling. Each phase has distinctive costs and or revenues. O&M or exploitation cost, together with the initial investment and energy yield will determine the outcome of the LPC formula. The costs and revenues from this formula can be divided into several categories. An overview and breakdown of these categories is given in Fig. 4.1.

![Fig. 4.1 Breakdown of LPC Formula](image)

The ICC consist of purchase and installation cost of the OWECs subsystems and components. The dismantling cost should not be underestimated since offshore regulations for removal of the OWECs are strict. Operation cost include business rates, insurance and administration cost and land rent for the operation base. Examples of insurance can be against public liability, technical risk and perhaps against inability to produce energy [11]. Maintenance cost can be broken down into all requirements to keep the OWECs in, or bring it back to, an available state. It includes costs of spare parts, personnel to install these, and cost of transportation of both. The energy yield from the turbines, and thus the revenues, depend on the joint probability of wind speed and availability of the OWECs. The availability will be determined by the chosen O&M strategy in combination with occurrence of wind, waves and failures of the system.
An indication of contributions to the levelised energy cost is for a number of categories given in [4] as:

![Pie chart showing contributions to LPC](image)

*Fig. 4.2 Contributions to LPC*

The design of the OWECS and the choice for a particular O&M strategy are the outcome of their combined effect on the LPC. The process through which these choices affect the LPC is given below.

![Flowchart showing from Design and O&M Strategy to LPC](image)

*Fig. 4.3 From Design and O&M Strategy to LPC*

The choice for a particular design and strategy can be derived from relationship 1 to 7

1. The main cost drivers within the ICC, as they result from the design of the OWECS, can be derived from previous feasibility studies.
2. The same goes for the O&M strategy and costs. However, these costs are influenced by the sea state, e.g. wind and waves. These will effect the duration and therefore cost of the maintenance, given the chosen strategy.
3. The design choices of the OWECS do not only affect the ICC but the availability during its lifetime as well. Main drivers of unavailability should be identified as well as the ways in which they can be improved by design changes.
4. Corrective maintenance is aimed at returning the system to its original, available state. The duration of this, again under influence of the sea states, determines the systems availability. Preventive maintenance is less influenced by prevailing sea states because it can be planned, in contrast to corrective maintenance. Its effects on the system’s reliability will determine the influence of preventive maintenance on the system’s availability.
5. From the availability, the revenues e.g. energy yield, can be derived as a function of the wind distribution during this availability, via the Production-Wind speed curve.
6. As can be seen from the previous relations, the wind, waves and their distribution in time, play an important role in the O&M cost and revenues that form the input of the LPC formula. Both can be modelled as stochastic processes. Creating this model and determining the way wind and waves coincide with O&M on the system is one of the main goals of this thesis.
7. This last relationship can be expressed as shown in the LPC formula in section 4.1
4.3 Farm Design and Initial Capital Expenditure

In order to determine the relationship between design and ICE, data is available from several feasibility studies [2,4,16 and 281]. Abstracts of these studies with respect to cost of subsystems and components are made in Appendix 4.

conclusions

The average Total Initial Capital Expenditure per installed kW wind farm, according to the different studies, is 1340 Euro / kW. There are about 3300 hours of production time at rated power per year, see Appendix 8. Availability, array – and transmission efficiency average res. 94, 94 and 97 %, although the availability is highly dependent on the O&M strategy and cost. With an interest rate of 5 % and an economic lifetime of 15 years the ICC contributes 0.05 Euro to the price of energy.

Because of the differences in calculation e.g. no division between turbine and foundation cost or grouping of purchase and installation cost, a breakdown of the ICE into cost of purchase and installation of subsystems is a matter of interpretation.

An approximation of cost parameters with respect to design is given below:

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Parameters</th>
<th>Effect on ICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbines</td>
<td>Farm Size (in kW)</td>
<td>600 Euro / kW</td>
</tr>
<tr>
<td>Foundation</td>
<td>Turbines Size</td>
<td>450 Euro / kW</td>
</tr>
<tr>
<td>MV - network</td>
<td>Number of Turbines, Farm spacing</td>
<td>300 Euro / m</td>
</tr>
<tr>
<td>HV - network</td>
<td>Distance to Shore</td>
<td>700 Euro / m</td>
</tr>
<tr>
<td>Transformer</td>
<td>Transformation Capacity</td>
<td>23 Euro / kW</td>
</tr>
</tbody>
</table>

Table 4.1 Cost Parameters of ICE

These figures give an indication of the ICE for the current (March 2001) state of the art farm design, they vary with technological progress and are limited to AC current networks.

Because these prices vary too much with time and per contract, they will be variables in the input of the simulation, in order to calculate and optimise the system's LPC with respect to O&M cost. The figures above can be used for a first approximate when farm size and location are known.

relation to profit

As was shown the previous chapter, the ICE and the energy yield that can be achieved with this investment determine in part the profit and the cost of produced energy. The size of this part and the sensitivity of the profit to this part have to be known to come to a well-based overall design.

From the data in the abstracts, it can be concluded that the main cost drivers of ICE are the cost of the turbines, their support structure and the electrical net. All subsystems thus form a considerable contribution to the overall cost.

The costs per aspect of installing or purchasing the OWECs are for a great deal site or contract specific. Since turbine installation is not yet standardised, the used tools will depend on how contractors find ways to use existing equipment to install the turbines. This can be done with either jack-ups, floating work platforms etc. The choice will also depend on the type of support structure that will be used. Costs will vary accordingly. The exact split-up between purchase and installation cost cannot always be made because both manufacturers and contractors often only give prices of components including installation.

For optimising the system however, only the total ICE and its relation to installed power and achieved reliability of the system, is of importance. Investing in a higher reliability, aimed at improving availability, will be economic when the extra revenues during the lifetime of the system at least equal the investments made.
increasing reliability

A higher availability will show in the number of productive hours per year. A productive hour at rated power will bring in revenue, equal to the installed power multiplied by the market price. In the base case situation this would mean about 100 MW * 0.12 Euro/kW = 12.000 Euro can be spent to improve availability for the total system against rated power with one hour.

The data in the reports however, does not show a relationship between the systems reliability and the investment made. Used reliability data are still estimates, of the reliability that may be achieved in the future. Investing in more reliable turbines can therefore not be explored.

increasing installed power

Another way to improve the availability of the system can be found in installing extra production capacity. Adding turbines to a farm design can be seen as increasing the availability of the initially installed capacity.

Before exploring this option, an overview of figures and conclusions from the reports is given below, as an indication of the ICC and their variation with different farm designs.

![Graph showing trends in ICE](image)

This shows that about 70 % of the ICC is formed by cost directly related to the turbine and its support structure and 30 % of the cost comes from the electrical net. The ICC for the base case are:

40 Turbines of 2.5 MW * 600 Euro / Installed kW = 60 000 000
40 Turbines of 2.5 MW * 450 Euro / Installed kW = 45 000 000
10 km Shore Connection * 700 Euro / m = 7 000 000
35 km Grid Connection * 300 Euro / m = 10 500 000 10 strings of (3*650 + 1500) m
100 MW farm * 23 Euro /kW transformer power = 2 300 000
Other Cost = 10 000 000
Decommissioning Cost = 15 000 000 +

ICC Cost = 149 800 000

The grid connection cost will hardly increase when a few extra turbines are connected. Installing two extra turbines would add about 1300 m to the MV network, increasing the ICC by 1300 * 300 = 390 000 Euro. Expanding the transformer capacity would cost about 23 Euro / kW * 5 MW = 115 000 Euro. Together with the additional costs of the turbines and their support structure, the ICC of a 42 turbines farm will be 155 555 000 Euro, instead of the base case 149 800 000 Euro for 40 turbines, thus a total increase by a factor 1.03842.

In Fig. 4.2 can be seen that the ICC make up about 75 % of the LPC and 25 % is accounted for by O&M cost.
Adding two extra turbines to the base case with 40 turbines will have consequences for the LPC as given below.

\[
LPC_{\text{new}} = 0.75 \times \left( \frac{1.03842 \times ICC}{a \times E_x \times 42/40} \right) + 0.25 \times \left( \frac{O \& M \times 42/40}{E_x \times 42/40} \right) = 0.992 \times LPC
\]

* see section 4.1 for parameters

The LPC will thus decrease with little less than 1% when two extra turbines can be connected to the existing grid. The number of turbines that can be connected to a MV – string however depends on the capacity of the used cables. From this can thus only be concluded that the installed electrical capacity must be used to its maximum when economically optimising the system. Were the effects on the reliability of the network also taken into account, installing extra turbines does not prove to decrease the LPC or raise profits.
4.4 Operations, Maintenance and Cost

The same reports [2, 4, 16 and 28] as used to determine the relationship between design and ICC were used to investigate the relationship between O&M tasks and cost.

In [2] and [16] a deterministic approach of O&M cost is chosen in order to give a first estimate of these costs and of their contribution to the LPC. These approaches each assume a standard average duration for O&M tasks as well as equipment cost e.g. day rates. These approaches do not suffice in a more detailed description as intended here.

The approach in [4] uses hourly wages, crew data and cost of equipment to simulate O&M operations. In each period, the number of failing turbines is determined and a decision on whether or not to repair them based on two-state weather model is made. This gives more accurate results, but availability is determined at the end of the simulation and energy yield is then calculated against the yearly average wind speed.

overview

The average O&M cost on the farms is about 35 Euro per installed kW, based on farm sizes of 100 MW, with some cost advantages when the size increases. The Opti-OWECS report shows the most detailed approach to O&M, resulting in 30 Euro O&M cost per installed kW for their 300 MW farm. This contributes 0.014 res. 0.012 to the LPC, when the energy yield is calculated as in section 4.3.

The relative importance of the different O&M tasks, eventually depends on their frequency. This will be studied in the next chapter. Here an overview of the costs per O&M operation will be made. The duration of the different O&M tasks, excluding transport and waiting on weather, is more or less given. These are the workable hours needed to replace or repair components. Workable hours are limited, depending on equipment choice. Not yet accounting weather delays during repairs, the downtime about equals the repair time.

The lost revenues in Table 6.7 are based on market price of 0.12 Euro/kWh. A failure in the MV net is considered to leave all turbines connected to the string unavailable, thus 4 in the base case. A failure in the transformer or the HV net reduces to production capacity to nil. A Nordex turbine would produced 2.5 MW per hour, assuming rated speed to compensate for possible weather delays, representing about 300 Euro per hour downtime.

<table>
<thead>
<tr>
<th>Corrective Maintenance Event</th>
<th>Repair or Replacement Time (hrs / days)</th>
<th>Crane Needed</th>
<th>O&amp;M Cost (Out of Pocket + Downtime cost)</th>
<th>Total O&amp;M Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Failure</td>
<td>48 / 2</td>
<td>yes</td>
<td>73,000 + 14,400</td>
<td>87,400</td>
</tr>
<tr>
<td>Minor Failure</td>
<td>24 / 1</td>
<td>no</td>
<td>4,300 + 7,200</td>
<td>11,500</td>
</tr>
<tr>
<td>Resetable Failure</td>
<td>6 / 0.25</td>
<td>no</td>
<td>0 + 1,800</td>
<td>1,800</td>
</tr>
<tr>
<td>Broken Cable MV</td>
<td>336 / 14</td>
<td>no</td>
<td>210,000 + 403,200</td>
<td>613,200</td>
</tr>
<tr>
<td>Broken Cable HV</td>
<td>336 / 14</td>
<td>no</td>
<td>210,000 + 4,032,000</td>
<td>4,242,000</td>
</tr>
<tr>
<td>Transformer Failure</td>
<td>408 / 17</td>
<td>no</td>
<td>39,000 + 4,896,000</td>
<td>4,935,000</td>
</tr>
<tr>
<td>Failure of MV field</td>
<td>96 / 4</td>
<td>no</td>
<td>20,000 + 115,200</td>
<td>135,200</td>
</tr>
<tr>
<td>Failure of HV field</td>
<td>96 / 4</td>
<td>no</td>
<td>20,000 + 1,152,000</td>
<td>1,172,000</td>
</tr>
</tbody>
</table>

Table 4.2 Duration and Costs of Corrective Maintenance
<table>
<thead>
<tr>
<th>Preventive Maintenance Event</th>
<th>Duration (hrs)</th>
<th>O&amp;M Cost (Out of Pocket + Downtime Cost)</th>
<th>Total O&amp;M Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Five Yearly Maintenance</td>
<td>28</td>
<td>81,500 + 8,400</td>
<td>89,900</td>
</tr>
<tr>
<td>Major Overhaul Turbine</td>
<td>40</td>
<td>22,000 + 12,000</td>
<td>34,000</td>
</tr>
<tr>
<td>Overhaul Turbine</td>
<td>8</td>
<td>4,300 + 2,400</td>
<td>6,700</td>
</tr>
<tr>
<td>Minor Overhaul Turbine</td>
<td>4</td>
<td>2,200 + 1,200</td>
<td>3,400</td>
</tr>
</tbody>
</table>

*Table 4.3 Duration and Cost of Preventive Maintenance*

**Conclusions**

From the tables above can be seen that failures in the HV network and transformer are expensive because of the loss in production capacity. On the one hand the calculated cost are a maximum since production against rated power during the entire downtime is assumed. On the other hand extra weather delays could add to downtime cost. Installing an extra transformer would cost about 2.5 Mln Euro, which would be earned back when the other transformer fails only one time during the systems lifetime. A second HV connection would cost approx. 7 Mln. Euro, which will be earned back when this connection fails two times during the systems life. Failure rates of both transformer (≈ 0.02) and the HV net (≈ 0.035 for 10 km cable) do not justify double installation of either one.

Looking ahead at the next chapter, it can be concluded that PM and CM both contribute considerably to yearly O&M cost for the OWECS. Preventive maintenance is more or less fixed to about 62,000 Euro per turbine per year. With one major failure in three years and one minor failure per year, the CM costs for only the turbine are 40,000 Euro per year.

Whether equipment for executing O&M tasks should be bought or rented, will not only depend on the number of visits and relative cost, but also on deals with manufacturers, owners or fellow users of the equipment. The repair times can also vary with turbine design and will thus as well be subject to input in the simulation.

A simulation should thus provide the possibilities to use different O&M strategies with respect to equipment choice and financing. Obviously, tools that are not limited by weather with low costs are most economic. For economic optimisation of the farm’s O&M the cost of used equipment and their workability limits will be important parameters. How much energy yield can be gained with using tools that are less weather dependent, can only be determined in a simulation that determines O&M cost and energy yield simultaneously, this to account for coinciding periods of high production and low accessibility.

Costs of spare parts, wages and stock keeping will vary per location, turbine or O&M strategy. These will thus also be part of the input for a simulation. They can be added to the input as either day- and stand-by rate or as yearly fixed cost.
4.5 Sensitivity Analyses of Production Cost from Model Schöntag

The sensitivity of the energy cost to changes in the economic conditions, cost of subsystems and the overall energy production has been investigated [4]. Results are shown in Appendix 6: an impression of the relative importance of several parameters, and to determine which parameters should or should not be taken into account in further research or simulation.

discount rate and life time

The sensitivity of a number of parameters is investigated in a simple fashion by changing one parameter and observing the effect on the overall energy cost. This showed only a small effect of discount rates on the LPC, about 0.35 Euro cents per changes in rates of 1 %. Because of the small effect, and the fact that the discount rate is a given variable, an estimate will have to be chosen in a simulation to correctly represent profit and costs of produced energy.

The economic lifetime of the system plays a role since the ICC will be written off over this period, and the yearly write off cost form a large part (about 75 %) of the LPC. The systems lifetime is usually set to 15 up to 20 years. This however is quite arbitrary; the technical lifetime of most turbine components is much shorter, about 5 years and that of support structure and electrical grid is much longer, over 50 years. Perhaps there can be cost advantages in linking up the lifetimes of the latter with the economic life of the system.

ICC, O&M cost and energy yield

Energy yield is the parameter that has the largest effect on energy production cost. The analysis shows that the LPC will decrease with about 20 % when energy yield increases of 25 %. This is explained by the fact that the energy yield is part of the denominator in each part of the LPC formula. This first analysis however does not take into account that to achieve the higher energy yield, extra investment or O&M cost will have to be made. It thus overestimates the effect of energy yield. Despite this, the choice of a site with a high energy potential remains important. This is shown in a sensitivity analysis to the mean annual wind speed. Higher wind speeds lower the price of energy as long as O&M operations are not disturbed and availability drops.

Sensitivity to the cost of subsystems and O&M corresponds to their contribution in the LPC. An increase of 30 % in cost of the turbines, support structure, grid connection or O&M leads to an increase of res. 10, 7, 5 and 7 % in the LPC. For ways to increase profits, a reduction of turbine cost thus seems the most promising, but decreasing any of the other cost is also attractive.

other parameters

Other parameters that play a role are distance to shore, size of the wind farm and its spacing ratio. With increasing distance to shore the transmission efficiency decreases and cost of the HV net and O&M time increase, all unfavourable for the LPC. As long as the mono-pile foundations can be used, the total effect however is limited to about 5 % when moving 15 km more from the shore. This effect will have to be compensated by a higher energy potential of the site.

One of the reasons for going offshore was the space that is required for a wind farm. Advantages in number of turbines and distance between turbines expressed in their rotor diameter D, will thus have to be fully used. A spacing ratio of about 12 D seems to be the optimum between decreased wake effects and increased grid cost. This may vary for other types of grid connections as the star-based type that was used here.

With increasing farm size come advantages because the investment made for the shore connection and O&M infrastructure can be put to more use. Not much can be gained in this respect, with farms consisting of more than 100 units.
5 Energy Yield

5.1 Transmission Losses and Array Efficiency

The total energy yield from a wind farm will depend on availability, transmission losses and array efficiency. Transmission losses are inherent to energy transport. They cannot be avoided, however, currently used transportation methods are generally seen as most economical. Array efficiency will increase with increasing turbine spacing. This however will also increase transmission losses on investment cost in the MV network. The economic optimisation of this, just as for transmission losses, does not promise a large reduction of the LPC, since the effect on total energy yield is far smaller (factor five to ten) then the effect of availability. Therefore these two factors will be left out in the remainder of this thesis.

5.2 Reliability

A reliability analysis of the system has been made in Appendix 2. This shows that all specified component or subsystem failures, are critical for energy production or transport. The delivery of produced energy to shore can thus be seen as a chain system that will fail as soon as any link is broken. The location of the broken link will determine the production capacity that will be unavailable e.g. a single turbine, a string of turbines or the entire system.

The relative importance of the different failure mechanisms within the system should be identified. This can be done by calculating the unavailability caused by the different components within the system.

5.3 Availability

In order to determine the systems' availability, an independent calculation of failures of all subsystems, and their effect on reduction of production capacity is made. This, together with the repair times of the components or subsystems, leads to an indication of the main causes of unavailability. Data used in the calculation can be found in Appendix 3.

Downtime due to noticeable failures of single components equals failure rate times repair time. Time for testing will be accounted for by seeing it as a part of the repair itself. The total repair time can be seen as the time to repair the component plus weather delays before or during the actual repair. Weather delays depend on the equipment that is used and occurring sea state at the time of failure.

Preventive maintenance is not included in the calculation since there are no penalties given when execution of PM is delayed. When this is the case PM will be planned during periods when the wind speed is below cut-in wind speed of the turbines and thus no revenues will be lost and PM cost are more or less fixed.
For a first calculation, independency of failures in different strings of the MV network seems to be a justified assumption, since these are mostly the result of collision with fishing gear or anchors. Failures on the turbines are positively correlated, since both design, manufacturing and carried loads will show large similarities. The calculated unavailability caused by failures of the turbines and their support structure will therefore be an underestimate of the actual situation. An upper limit of the total unavailability of the system is formed by the sum of the unavailability of its components. The lower boundary is formed by the maximum of the unavailability of its components. Results for the base case are given in Table 5.1.

| Length of One String in MV net | 4060 m | Number of Turbines total | 40 |
| Distance Transformer to Shore | 8000 m | Number of Turbines in one serie | 4 |
| Average Distance String-Transformer | 1500 m |

<table>
<thead>
<tr>
<th></th>
<th>Failure Rates (per year)</th>
<th>Repair Time (days)</th>
<th>Unavailability Components</th>
<th>Unavailability Subsystems</th>
<th>Failure Rate Subsys</th>
<th>Av. Rep. time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV field</td>
<td>0.002</td>
<td>4</td>
<td>2.19E-05</td>
<td>0.110 %</td>
<td>0.03</td>
<td>13.3</td>
</tr>
<tr>
<td>HV cable</td>
<td>0.028</td>
<td>14</td>
<td>1.07E-03</td>
<td>0.180 %</td>
<td>0.05</td>
<td>12.7</td>
</tr>
<tr>
<td>MV field</td>
<td>0.0036</td>
<td>4</td>
<td>3.93E-05</td>
<td>0.091 %</td>
<td>0.02</td>
<td>16.7</td>
</tr>
<tr>
<td>MV cable</td>
<td>0.0483</td>
<td>14</td>
<td>1.77E-03</td>
<td>0.609 %</td>
<td>1.79</td>
<td>1.2</td>
</tr>
<tr>
<td>Transformer</td>
<td>0.02</td>
<td>17</td>
<td>9.13E-04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OWEC minor</td>
<td>1.35</td>
<td>1</td>
<td>3.70E-03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OWEC major</td>
<td>0.44</td>
<td>2</td>
<td>2.41E-03</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1 Causes of Unavailability without Weather Delays

The table above shows that failures of the turbines are the main cause of unavailability, when there are no weather delays. The tools used for O&M however will have a certain workability; a percentage of the total time in which the tool can operate under prevailing wave and wind conditions.

Each O&M task requires its own tools. The effect of worsening weather on workability during the different O&M operations is determined by the workability limits of the used equipment and the probability distributions of waves and wind.

Probability of a workable situation can be seen as the joint probability that both wind and waves are below the limits of the equipment used. In [28] workability limits for several tools used for O&M on Danish wind farms are collected. They can be found in Appendix 5.4. The probability of exceeding these limits is given in Table 5.2

The probability of exceedance is for the wind speed given by the cumulative Weibull distribution as was discussed in Section 3.6.1. At the base case location, 15 km of the Dutch coast near IJmuiden, parameter $\alpha = 9.4$ and $\beta = 2.2$. Probability of exceeding a certain wave height can be represented by a Gauss distribution, as discussed in Section 3.6.2, for a first indication a year average significant wave height of 1.5 m is used. Because the wind and waves will be highly correlated, the workability limit that forms the largest restriction for a certain tool, will be used as the joint probability.
<table>
<thead>
<tr>
<th>Limit Formed By</th>
<th>Access with Vessels</th>
<th>Tasks on Turbine</th>
<th>Diver Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>4.6</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>DWT (t)</td>
<td>12</td>
<td>10</td>
<td>1.5</td>
</tr>
<tr>
<td>Pull (kN)</td>
<td>20</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>20</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>Wave Height (m)</td>
<td>0.5</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>P(V&lt; V_{\text{max}}) Probability of Non-Exceedance Wind Speed</td>
<td>0.99</td>
<td>0.97</td>
<td>0.99</td>
</tr>
<tr>
<td>P(H&lt; H_{\text{max}}) Probability of Non-Exceedance Wave Height</td>
<td>0.20</td>
<td>0.60</td>
<td>0.86</td>
</tr>
<tr>
<td>Joint Probability with full correlation</td>
<td>0.20</td>
<td>0.60</td>
<td>0.86</td>
</tr>
<tr>
<td>Estimated Workability</td>
<td>0.20</td>
<td>0.60</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 5.2 Workability of Equipment

The probability of not exceeding the workability limits of the tools however is only the probability at a certain time, while for the workability however, the probability that a tool can be used over a certain period should be known. This depends on the autocorrelation of the wind and wave distribution functions.

Overall workability for a certain task is thus determined by workability of all used equipment, wind and waves and the period over which the equipment is needed. The actual O&M time for a certain task can thus not simply be calculated by:

\[ T_{O&M_i} = T_{O&M_{\text{ew,}i}} \times \frac{1}{\text{workability}_i} \]

with

- \( T_{O&M_i} \) = Total time for completing O&M on component i
- \( T_{O&M_{\text{ew,}i}} \) = Time needed for O&M exc. weather delays on component i
- workability = Workability of tools used for O&M on component i

With a 50% workability, a component with a failure rate of once a year, needing a repair time excluding delays of 2 days, would be unavailable for 4 days. The workability however is not randomly distributed in time. It could well be that a tool can be used the entire summer, but not during a 6 months winter period, thus having the same overall workability of 50%. Assuming a random failure halfway the winter, unavailability would however be:

\[ \sqrt{\frac{1}{2} \times 2 \cdot \text{days} + \sqrt{\frac{1}{2} \times (3 \cdot \text{months} + 2 \cdot \text{days})}} \approx 46 \cdot \text{days} \]
For a first estimate of the influence of weather on O&M, its costs and effect on energy yield, estimated workability’s during operations are taken from [4] and [16]. This leads to unavailability’s as given in Table 5.3

<table>
<thead>
<tr>
<th>Length of One String in MV net</th>
<th>4060 m</th>
<th>Number of Turbines total</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance Transformer to Shore</td>
<td>8000 m</td>
<td>Number of Turbines in one serie</td>
<td>4</td>
</tr>
<tr>
<td>Average Distance String-Transformer</td>
<td>1500 m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure Rate (per year)</th>
<th>Repair Time (days)</th>
<th>Unavailability Components</th>
<th>Unavailability Subsystems</th>
<th>Failure Rate Subsys</th>
<th>Av. Rep. time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV field</td>
<td>0.002</td>
<td>6</td>
<td>3.29E-05</td>
<td>0.371%</td>
<td>0.03</td>
<td>45.2</td>
</tr>
<tr>
<td>HV cable</td>
<td>0.028</td>
<td>48</td>
<td>3.68E-03</td>
<td>0.611%</td>
<td>0.05</td>
<td>43.0</td>
</tr>
<tr>
<td>MV field</td>
<td>0.0036</td>
<td>6</td>
<td>5.90E-05</td>
<td>6.231%</td>
<td>1.79</td>
<td>12.7</td>
</tr>
<tr>
<td>MV cable</td>
<td>0.048314</td>
<td>48</td>
<td>6.05E-03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transformer</td>
<td>0.02</td>
<td>17</td>
<td>9.13E-04</td>
<td>0.091%</td>
<td>0.02</td>
<td>16.7</td>
</tr>
<tr>
<td>OWEC minor</td>
<td>1.35</td>
<td>4</td>
<td>1.48E-02</td>
<td>6.231%</td>
<td>1.79</td>
<td>12.7</td>
</tr>
<tr>
<td>OWEC major</td>
<td>0.44</td>
<td>48</td>
<td>5.79E-02</td>
<td>6.231%</td>
<td>1.79</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Table 5.3 Causes of Unavailability including Weather Delays

The relative importance of the different O&M operations can be determined by multiplying their overall cost as were discussed in Section 4.4 by their frequency of occurrence.

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure Rate</th>
<th>Cost per Operation</th>
<th>Expected Yearly Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV field</td>
<td>0.002</td>
<td>1.172.000</td>
<td>2.344</td>
</tr>
<tr>
<td>HV cable</td>
<td>0.028</td>
<td>4.242.000</td>
<td>118.776</td>
</tr>
<tr>
<td>MV field</td>
<td>0.0036</td>
<td>135.200</td>
<td>486</td>
</tr>
<tr>
<td>MV cable</td>
<td>0.048314</td>
<td>613.200</td>
<td>29.626</td>
</tr>
<tr>
<td>Transformer</td>
<td>0.02</td>
<td>4.935.000</td>
<td>98.700</td>
</tr>
<tr>
<td>OWEC minor</td>
<td>1.35</td>
<td>11.500</td>
<td>15.525</td>
</tr>
<tr>
<td>OWEC major</td>
<td>0.44</td>
<td>87.400</td>
<td>38.456</td>
</tr>
</tbody>
</table>

Table 5.4 Expected Yearly Cost of CM on Subsystems

The table above shows that the main drivers of O&M cost are failures in the transformer or broken HV - cables. As was already stated in Section 4.4 however, doubling their capacity does not seem to be profitable. Focus, when optimising the O&M of an offshore farm will thus be on reducing O&M cost on turbines and finding an optimum grid connection, this in combination with the initial capital cost.

Downtime due to failures of turbines is affected the most by decreasing weather. Given the relative failure rates and costs, choosing the right O&M strategy on the turbines is the most promising option when optimising the farm’s O&M, because it has the largest effect on the cost of O&M and unavailability. For these reasons, the availability of the turbines and probability of their output level at a certain O&M cost level, will be an important relationship within the LPC and the profitability of an OWECs. This will be investigated in the next paragraph.
5.4 Output Level Probability

The wind speed - production curve of a turbine is not equal to the curve wind speed - available energy e.g. proportional to the third power of the wind speed. There is a maximum, rated power, because of generator capacity and rotor speed. Somewhat before the rated speed the pitch system will slow the rotor down leading the gradual transition towards the rated power, see Appendix 8.

Although there is no physical basis, the part of the production curve between \( V_{\text{cut-in}} \) and \( V_{\text{rated}} \) can be expressed with the exponential function as shown in Fig. 5.1, in which \( \gamma \) and \( \delta \) are parameters depending on the turbine. For the Nordex N80 \( \gamma = 4.1 \) and \( \delta = 10.6 \) given the best fit.

In order to determine the probability of a certain output level of the system, first the probability of production of a single turbine should be known. In case of a 100% availability of the turbine, the yearly probability distribution of output can be found by filling in the yearly wind speed distribution in the production curve of the turbine thus:

![Fig. 5.1 Probability Distribution of Production Level](image)

In formulas the production can be written as:

\[
P(V) = \begin{cases} 
0 & \text{for } V = 0 \\
1 - \exp \left[ -\left( \frac{V}{\gamma} \right)^{\delta} \right] & \text{for } \frac{V_{\text{cut-in}}}{\gamma} \leq V < \frac{V_{\text{rated}}}{\gamma} = 13.5 \text{ m/s} \\
\frac{V_{\text{rated}}}{\gamma} & \text{for } \frac{V_{\text{rated}}}{\gamma} \leq V < \frac{V_{\text{cut-out}}}{\gamma} \\
0 & \text{for } V \geq \frac{V_{\text{cut-out}}}{\gamma} = 25 \text{ m/s}
\end{cases}
\]

with

\[
V = \text{Actual wind speed in m/s} \\
P = \text{Power in kWh} \\
\gamma = \text{Logarithmic base shape parameter [ - ]} \\
\delta = \text{Characteristic production wind speed in m/s}
\]

The probability density of the wind speed can also be expressed in a Weibull function as:

\[
f(V) = \frac{\beta}{\alpha} \cdot \left( \frac{V}{\alpha} \right)^{\beta-1} \cdot \exp \left( -\frac{V}{\alpha} \right)^{\beta}
\]

with

\[
f(V) = \text{Probability of occurrence of wind speed } V [ - ] \\
V = \text{Wind speed in m/s} \\
\alpha = \text{Characteristic (average) wind speed, Weibull scale parameter } = 9.4 \text{ m/s at the base case location} \\
\beta = \text{Logarithmic base, Weibull shape parameter } = 2.2 [ - ] \text{ at the base case location}
\]
Giving for the probability of production:

\[
f(P(V)) = 1 - \exp \left( -\left\{ \frac{\beta}{\alpha} \right\}^{\frac{\lambda}{\alpha}} \cdot \exp \left( -\frac{V}{\alpha} \right)^{\beta} \right) \]

For \( P < 0 \leq P < P_{\text{rated}} \)

\[
\begin{align*}
\left( \frac{V}{\alpha} \right)^{\beta-1} \cdot \exp \left( -\frac{V}{\alpha} \right)^{\beta} \\
\frac{1}{\alpha^\beta} \cdot \left( \frac{\alpha}{\beta} \right)^{\beta} \\
\delta
\end{align*}
\]

The probability of yearly production however is not only a function of wind speed probability but also of availability. The availability of a turbine is determined by the time needed for waiting on and execution of preventive and corrective maintenance tasks. This duration of O&M in turn depends on the prevailing weather conditions and sea states.

Assuming that a) corrective maintenance is the major cause of unavailability, since this cannot be planned in contrast to preventive maintenance, and b) the time of failure is independent of weather conditions and sea states, the probability density of O&M duration will have a similar shape as the wind distribution, since access criteria can be derived from this wind distribution:

\( f(O&M \text{ time}) \)

\( f(\text{Production Time}) \)

\( f(\text{Production Time}) \)

\( f(\text{Production Time}) \)

Fig. 5.2 Probability Distribution of O&M Duration

Since the available time equals total time minus O&M time, the probability of available production time can be derived from this.

Fig. 5.3 Probability Distribution of Available Production Time
This distribution can be seen as triangular. Data shows an average availability of 94% thus about 49 weeks, a minimum of 44 (85%) and as a maximum availability of 98% based on turbines onshore. In formulas:

\[
f_{Tp}(T_p) = \begin{cases} 
0 & \text{if } T < T_{T_{\min}} \\
\frac{2(T - T_{\min})}{(T_{\min} - T_{gem}) \times (T_{\min} - T_{\max})} & \text{when } T_{\min} \leq T < T_{gem} \\
-\frac{2(T - T_{\max})}{(T_{\min} - T_{\max}) \times (T_{gem} - T_{\max})} & \text{if } T_{gem} \leq T < T_{\max}
\end{cases}
\]

Combining the previous equations leads to a lengthy integral, but since the assumption that was made before, independent occurrence of availability and wind speed, does not hold for this system, it would not lead to a correct prediction of the energy yield. In fact the relationship between availability and occurring wind speeds is the key to determine the optimum O&M strategy. During periods of strong wind, accessibility will be low, leading to longer repair times. Because failures in the system occur randomly in time, the energy yield of a single turbine over one year is the sum of all energy yields per time step. When the probability of both yearly wind speed and available production time are discarded, the yearly energy yield can be seen as:

![Graph showing yearly energy yield](image)

*Fig. 5.4 Yearly Energy Yield*
The probability of reaching a certain production level of Fig. 5.4 is given by the joint probability of available production time and wind speed during these hours. This, for now, under the assumption that the two are independent. This joint probability is given in Fig. 5.5

**Fig. 5.5 Joint probability of Produced Power and Yearly Production Time**

* The cone shapes at hourly productions of 0 and 2500 are in fact flat areas (projection against the back "wall" leads to picture as in right side of Fig. 5.1) this due to the step size and drawing program limitations

Taking the effect of the probability distributions, of both wind speed and available production time, on the energy yield into account, can be done by multiplying the joint probabilities with the yearly energy yield levels in Fig. 5.4. The volume under the surface of Fig. 5.6 is the expectation of yearly energy yield. This can be visualised as:

**Fig. 5.6 Contributions to Expected Yearly Energy Yield**
The probability of a yearly energy yield level can be determined by integrating the joint probability surface of Fig. 5.5 over an iso-production line of Fig. 5.4. This is shown in Fig. 5.7.

![Joint Probability Diagram]

**Fig. 5.7 Probability of A Production Level**

In formulas this probability of a reaching a particular production level can be calculated with

\[ f(E_y) = \int_{E_y=0}^{E_{\text{max}}} \int_{T=0}^{T_{\text{max}}} f(E_i) \times f(T) \times dT \cdot dE_i \]

The expected yearly energy yield can be calculated with

\[ E(E_y) = \int_{E_y=0}^{E_{\text{max}}} \int_{T=0}^{T_{\text{max}}} f(E_i) \times E_i \times f(T) \times T \cdot dT \cdot dE_i \]

With the parameters for the wind distribution, production function and available production time, the expected yearly energy yield, determined numerically as the volume under the surface in Fig. 5.6, is 7 750 000 kW per year, with an overall availability of 93 % and a standard deviation of 75 000 kW.

The assumption that was made before, independent occurrence of availability and wind speed, does however not hold for this system, in fact the relationship between the two is the key for determining the optimum O&M strategy. During periods of strong wind, accessibility will be low, thus leading to longer repair times. Because failures in the system occur random in time, the applied O&M strategy will determine this joint probability of availability and wind speed. This relationship, its effect on both energy yield and O&M cost and thus the LPC cannot be quantified without a simulation of the system.
5.5 Conclusions on Availability

From previous paragraphs it can be concluded that failures of the turbines are responsible for most losses in production capacity. This even when the optimistic estimates as described before are used. Furthermore, the failure rates used in this calculation where design goals of turbine manufacturers that have yet to be met. Per turbine the average energy yield is 7 750 000 kWh per year and the average availability is 93 %. This represents 3000 production hours at rated speed. In the light of this thesis, the unavailability should be combined with prevailing wind speed and effort or cost that have to be made in order to bring the system back to its original state.

With a Monte Carlo simulation of wind, waves and failures in the system, the energy yield and O&M cost can be calculated. In order to correctly simulate the system, a correct simulation of the weather is important because of the before mentioned relation between O&M time and possible high energy production.

By bookkeeping of failures e.g. indexing turbines and the strings of the MV network they are connected to, availability per turbine and per time step can be kept. With the available turbines the production per time step can be calculated, with wind speeds from the Monte Carlo simulation. With the given accessibility limits, the duration of O&M over the successive time steps can be determined, together with consequential cost.
6 Simulation of OWECS

A simulation of the OWECS and its O&M will be required in order to determine the influence of wind and waves on the cost of O&M and energy yield (relationship 6 in Section 4.2). The increased loss of revenues and higher O&M cost during strong winds will be taken into account simultaneously.

The simulation consists of a model of the systems' functioning and input into this model. First the desired output and the model required to provide this output will be discussed. Finally the input into the model will be discussed and the ways to acquire this input.

6.1 Output

The goal of the simulation is to predict the effects of the used O&M strategy on O&M cost and energy yield. and several O&M strategies are investigated to determine an optimum between initial investment and O&M expenditures. The optimum results in the highest system profitability. A minimum in the cost of produced energy expressed as LPC gives an indication that the system is optimised.

To evaluate the O&M strategies, the simulation will have to provide information on build up of total O&M costs using different tools and the effect of the strategy on energy yield. The overview of extra O&M costs and the ICC of the different components, shows which components require extra investment to increase reliability or whether extra O&M tools are profitable e.g. bring in more revenues than the made expenditures.

6.2 Model

A simulation in time steps is required to correctly represent that the system is inaccessible for maintenance during periods of strong winds, resulting in possible large losses in energy production. Per time step, the wind and the waves determine the accessibility, which together with the occurrence of failures leads to the system's availability. The same wind speed also determines the production during the time step. Failures, wind and waves can be determined with a Monte Carlo simulation.

The tools used to perform O&M tasks can be used when occurring wind and waves are within the tools workability limits. The use of a specific tools will lead to a certain cost for each time step depending on whether the equipment actually performing O&M or standing by, waiting on weather.

The production that is possible in a time step depends on the state of the system's components. Each component of the OWECS (See chapter 3) can be temporarily unavailable leading to a reduction in production capacity.
**state - space model**

The state of the system is thus built up of states of its components. Each component can be unavailable because it has failed, is being repaired or when it is undergoing preventive maintenance. The best way to represent the states of a component is a state-space diagram. The diagram shows the possible states and transitions between these states.

![State Space Diagram](image)

*Fig. 6.1 State Space Diagram*

Initially all components will be available and in an "available" state. When failures occur in the system, this will lead to an abnormal stop and the component transitions to the "failed" state. When accessibility limits of the tool used to repair the component are met, the CM transfer takes place and the components enter the state of "corrective maintenance". When sufficient workable time has passed to repair the failed component, it will become available again. Details on the transitions between states can be found in the flowcharts of Appendix 10.

When preventive maintenance intervals are due the system will make a normal stop and the component will transfer (PM) into the "preventive maintenance" state. Again when sufficient workable time for the used tools has passed it transfers back into "available" state (maintained).

These four states of a component are the basis for the calculation of both the O&M cost and the energy yield per time step.

**state "available"**

The state space diagram of an entire turbine is completely similar to that of its components, except for the fact that the turbine is only available when all of its components are in the state "available". Furthermore, the MV network it is connected to, the central transformer and the HV network have to be available, for the turbine to supply energy to shore.

By indexing each state for the components in the turbine, and giving them a value true or false, each component finds itself in a particular state at a certain time when the value is true. Since a component can be in only one state at the time, only one of the states of the component can be true. To safe time in calculation the state "available" will be considered true when all others states are false.

**state "failed"**

Because the turbines are numbered, they can be assigned to a string in the MV network. Simultaneous failures of turbines and strings in the MV network are thus accounted for. The same goes for failures of multiple components in one turbine. Failure of components is
determined by calculating the probability of failure during a time step. When a random drawn number (Monte Carlo) is smaller than or equal to the calculated value, the component is considered to fail.

Components can only fail when they are in "available" state. The probability of failure of a component can be calculated with its failure rate. Another important parameter is the decline rate of the reliability of components per year. This rate will determine the benefits that can be gained by executing PM. Because there is little know about the way the reliability of the different components deteriorate, a choice can be made between a linear or progressive decline. These types of decline are defined as below.

![Graph showing Failure Rate vs Age with equations for Progressive and Linear Decline]

**Fig. 6.2 Decline Types**

The probability of failure of a specific component in a certain time step equals:

\[ f(\text{Failure}) = \lambda \cdot t \cdot \exp^{-\lambda t} \]

with

- \( f(\text{Failure}) \): Probability of Failure
- \( \lambda \): Occurring Failures in a Time Step
- \( t \): Time Step

**state "corrective maintenance"**

By assigning a tool for each component, the workability limits under which the component can be repaired are set. The prevailing weather conditions and the time it costs to repair the component using a certain tool determine the downtime per event.

The transitions "CM" and "repaired" in Fig. 6.1 take time e.g. the time to travel to or from a site, which is sometimes of the same order as repair time of components. The costs resulting from this downtime are determined by valuing sailing time at dayrate. Time for testing after a repair will be included in the net repair time.

The cost of CM can than easily be calculated by adding the cost of using the tools for all operational hours. When a tool is used to execute O&M, dayrate cost will be accounted. Stand-by cost will be accounted for from the moment of failure until the start of the repair, since the required equipment will have to be mobilised. During weather delays the stand-by rate will also apply. Possible fixed or yearly cost of vessels, maintenance base etc. will be added at the end of the year.

**state "preventive maintenance"**

Since failure rates in the simulation are constant in time, the effect of preventive maintenance cannot be determined. In fact it only decreases availability and adds to O&M cost. However, preventive maintenance appears to be necessary by manufacturers based on classified data.

The interval since the last performance of PM or CM determines whether or not to perform PM. Because PM is not urgent and no penalty can be given due to unavailability of data, it can be scheduled during periods when wind speeds are below cut-in speed.
The cost of and downtime due to PM are calculated almost similar to those of CM. The difference is however that PM will be scheduled. Therefore, stand-by rate will only be calculated during weather delays.

**the simulation**

The simulation consist of procedures representing three of the four states in which each component find itself in, as described above a turbine will be “available” when the other states were “false” during the time step. The state is kept for each component \( i \) of turbine \( n \).

The components, of which the state will be kept as described before are grouped in subsystems. All of the components within a subsystem will have to be in the state “available”, in order for the particular subsystem to be available, as shown in Appendix 2. In the simulation the layout of the farm is as in Fig. 6.3.

![Fig. 6.3 Components, Subsystems and Farm Layout](image)

The subsystems above contain the following components:

![Fig. 6.4 Components within Subsystems](image)

A failure of any component in the turbine will thus cause the loss of production capacity of the turbine, a failure in the MV net to the loss of \( n/m \) turbines and a failure in the HV net to the loss of all production capacity. The same holds for the execution of PM and CM tasks.

During each time step, the wind speed and wave heights are determined first, in a weather simulation. Based on the prevailing wind speed and wave height a decision is made on execution of PM when the time interval of PM has passed for the particular component.
When a component is not in PM, the simulation determines if the components fails during the time step as was described under the state "failed". Based on whether or not a component has failed CM will be executed, when the wind speed and wave height are below the workability limits of the tool used for O&M, as taken from the input sheet.

With the prevailing wind speed, the energy yield is then calculated, using the P(V) function. The P(V) function has to be configured on another input form. By changing two parameters, the function to can be fit to a data series obtained from the turbine manufacturer.

Revenues are then calculated by multiplying the energy yield of a time step by the market price. Cost of O&M is determined by adding the direct cost per time step based on the given day and-, stand-by rates and adding the yearly fixed cost at the end of each year. With the ICC, the O&M cost and the Energy Yield the LPC will be calculated. A flowchart of the simulation can be found in Appendix 10.

wind and waves

As stated in section 3.6 a correct representation of wind and waves is important for both the calculation of the energy yield and the execution of O&M. Not only the distributions of wind speeds and wave height over the year, but also their course during the year are important. For the yearly energy yield the distribution of the wind speed over the year is important. The courses of wave height and wind speed will determine how often O&M tasks will have to be interrupted due to bad weather, determining both direct cost and missed revenues of O&M.

The course of wind speed and wave height is determined by their autocorrelation function. Determining the true autocorrelation functions is however cumbersome and requires a large set of measured values. The variance of the two parameters, normally determined by their autocorrelation functions, should be large enough to give a correct representation of the weather over the year and at the same time small enough to correctly represent the course of wind and waves.

A single parameter for the time variance of wind res. waves showed not to suffice; they had to be too large to give a correct course of wind and waves, in order to give a correct yearly distribution. A solution was found by allowing for a larger weekly variation of wind speed and wave height and a small variation of the parameters during the week.

The acting drawn probabilities of wind speed res. wave height will be kept in the variables prob_windspeed res. prob_waveheightswell. Every week these parameters change by the following procedure:

\[
\text{Prob}_{-}\text{WindSpeed}_{\text{week} \cdot i+1} = \left( \text{Prob}_{-}\text{WindSpeed}_{\text{week} \cdot i} + 4 \times \text{Random} \cdot \text{Number} \right) / 5
\]

\[
\text{Prob}_{-}\text{WaveHeight}_{\text{week} \cdot i+1} = \left( \text{Prob}_{-}\text{WaveHeight}_{\text{week} \cdot i} + 3 \times \text{Random} \cdot \text{Number} \right) / 4
\]

The random number used here, is equal or greater than zero and smaller than one, and is a standard function in Visual Basic. The waves thus have a slightly higher correlation with values from a previous week than the wind (averaged after adding 3 in stead of 4 times the random number).

The period of a week was chosen because the actual weather can be predicted with reasonable accuracy for this period. The decision to execute O&M can thus be based on this, the time variance could however still cause an interruption of the O&M task, depending on how far the wave and wind limits are away from the current weather.
During the week the probabilities than changes with their time variance, determined by:

\[
\text{Time Variance Wind} = (\text{Random} \cdot \text{Number} - 0.5) \times \text{Max Time Variance Wind}
\]

\[
\text{Time Variance SwellWave} = (\text{Random} \cdot \text{Number} - 0.5) \times \text{Max Time Variance SwellWave}
\]

The acting probabilities in the Monte Carlo method during the week thus become:

\[
\text{Prob WindSpeed}_{t+1} = \text{Prob WindSpeed}_{t} + \text{Time Variance Wind}
\]

\[
\text{Prob WaveHeight}_{t+1} = \text{Prob WaveHeight}_{t} + \text{Time Variance SwellWave}
\]

Good results were found for maximum time variances of the wind and waves of 0.25 res. 0.2. The above described probabilities act on the cumulative probability distributions as determined by the parameters for the summer and winter as given in the input.

### 6.3 Input

The basic input into the model consists of a number of values that can be assigned to text boxes in forms. These forms can be accessed from the main menu. Optional, a wave - and or a wind data files can be used, so a simulation can be run with either known or measured wave and wind data or with a Monte Carlo simulation of wave heights and wind speeds.

The menus that can be entered for input of parameters used during the simulation are:

#### Design Cost

The costs of creating and breaking down an offshore wind energy farm both determine the input of the simulation. With higher ICC a higher reliability of components can be bought, again a standard relation is lacking, but with the simulation the combined effect on profit can be determined, given the costs, failure- and decline rates. Except for decommissioning cost all amounts are assumed to be discounted values. The split up between purchase and installation cost is mostly quite arbitrary and does not affect the outcome of profit or LPC calculation. It is made for extra information and installation cost will most likely not increase as much as purchase cost when "buying" more reliable components. The ICC consist of costs of purchase and installation of:

- Turbines
- Support structure
- Grid connection
- Shore connection
- Others
- Decommissioning
Simulation Parameters

simulation time: The simulation does not need to be run for the entire economic life of the farm to optimise its design. For a first analysis few years will be sufficient. The duration of a simulation is about proportional with the simulation time. Input should be whole years, although any part of a year divided by the time step in the simulation resulting in an integer, can be used.

number of turbines: The number of turbines in the OWECs. The simulation time will increase more than the square of increase in the number of turbines.

number of turbines per MV string: The number of turbines in a string determines how much of the production capacity will be lost when a string fails. Failure rates of MV cables are mostly given per km length, more turbines will increase the length and thus the failure frequency of a string.

average distance string - transformer: The strings of turbines are placed around a central transformer in most OWECs configurations. The length of a string used for calculation of its failure rate equals:

\[(\text{number of turbines in one string}-1) \times \text{distance between the turbines} + \text{the average distance string - transformer}\]

distance between turbines: The distance between turbines of one string is used in calculating the failure rate of a string. In fact, this distance also determines the array efficiency of the system. Because determining this relation requires extensive calculation and is outside the scope of this thesis, the array efficiency will also be part of the simulation’s input.

distance to shore: As with the length of a string in the MV network, the distance to shore determines the failure rate of the shore connection. Furthermore it determines the travel time for O&M operations and thus affects the O&M cost and availability of the system.

array efficiency: The array efficiency is required to give a correct representation of the achieved energy yield and revenues. See also "distance between turbines" and Appendix 1.

transmission efficiency: The transmission efficiency is also required for calculation of energy yield and revenues. The efficiency depends on the length and type of grid and shore connection. As with the array efficiency, this relation is outside the scope of the thesis and not directly related to optimising the system’s O&M.

economic lifetime of system: The economic lifetime of the system is the time in which the investment made must be earned back, together with the desired profit. Usual a period of 20 years is taken for similar projects. This period determines the part of the ICC that are accounted for each year when calculating the LPC. Although taken arbitrary, the economic lifetime has a large influence on the profitability of the OWECs.

real interest rate: Together with the economic lifetime, the real interest rate determines the annuity factor, see section 4.1. The real interest rate will vary over the economic lifetime of the system. With an estimated average over the system’s lifetime, a good indication of the profit and cost of produced energy can be obtained.

market price of energy: Even more unpredictable than the real interest rate, but with a larger effect on profit than any other parameter. The current price of energy is about 0,12 Euro per kWh but could vary considerably in the near future.
Wave and Wind Parameters

wind and or wind data file: When wind and or wave data for a specific site are known these can be used as input to the simulation. The data has to be stored in text format. Care should be taken, in using the same interval in the data file, as the time step in the simulation, currently set to 3 hours. When the end of the data files are reached before the end of simulation time, the data files will loop back to their first item. When a data file is not specified the parameters below will be used to determine wind speed and or wave height during the simulation.

start of summer and winter: Sea states for most sites suitable for offshore wind energy production, can be described with distributions of wind speeds and wave heights for two seasons. In the simulation, January first is always considered winter. The start of the summer is the end of winter and vice versa.

Weibull parameters for wind distributions in summer and winter: The wind speed at hub height of the turbines can be described with a Weibull probability distribution in both summer and winter as described in section 3.6.1. Parameter $\alpha$ increases with increasing average wind speed of a season and an increase of parameter $\beta$ increases the variation of the wind speed during each season.

fetch length: A fetch length is required to calculate local wave heights generated by the wind. It is the length over which the waves propagate under the sustained influence of the wind, thus making the calculation dependent on the direction of the wind speed. The actual wave height however also depends on the duration of the sustained influence. To simplify the calculation an average fetch length will have to be chosen. See section 3.6.2.

Weibull parameters for swell waves in summer and winter: The simulation will superposition the calculated wind-waves over the swell waves that are propagated over long distances towards the site. The height of the swell waves is determined by a Monte Carlo simulation using a Weibull probability distribution.

Preventive Maintenance

mean time between maintenance of all components: Although for a single component, several preventive maintenance tasks can be required with different intervals, a good indication of out of pocket cost of PM and downtime can be acquired using a single PM operation per component. The simulation will look for sea states in which the PM can be executed after the mean time between PM has been expired. The time since the last PM task is kept in the simulation and reset after either PM or CM has been executed.

repair times excluding weather delays: This repair time plus the travel time to and from the site are required to execute PM has expired. PM will start after mean time between PM, when limits to wave height and wind speed are met. When after arriving at the site, enough workable hours have passed to complete PM, the components become available again. PM and accounting its cost will end when the used tolls arrive back at the O&M base.

wind and wave limits for use of PM tool per component: The execution of PM tasks to different components will require different tools. The wind speed and wave height under which the tool can still operate determine its workable hours and thus its variable cost and downtime of the component. Optimising O&M will consist of using the tools that results in maximum overall profit.
dayrate, stand-by rate and yearly fixed cost of used tools: The use of each tool will result in cost. These costs can be split up into those directly related to using the tool (variable) and those that are not (fixed). The variable cost can be expressed in a dayrate at times the tools actually perform O&M tasks. While waiting on weather stand-by rate will be accounted for. These costs can be either cost of renting a tool from a third party for a day or the direct cost of using a self-owned tool. Yearly fixed cost can be either contract cost, rent of the O&M base etc. The total yearly cost of PM will be calculated as the number of workable hours times the hourly rate of the used tool plus the fixed cost.

summer only: When desired, PM will only be executed during the summer when calmer weather can be expected. Once PM is started however, the task will be completed even when winter season starts during the operation.

Corrective Maintenance

For corrective maintenance the same data as for PM are required, in which the mean time between maintenance is however replaced mean time between failures of the components. After failure, a component will remain failed or in corrective maintenance until enough workable hours have passed to complete repairs to the component.

A decline rate of the components reliability can be given as a percentage of the initial failure rate. The reliability will than deteriorate, according to the formulas described in the previous section.

When desired, CM will only be executed during the summer when calmer weather can be expected, by checking the boxes under the label “summer only”. Once CM is started however, the task will be completed even when winter season starts during the operation.

An example of all input forms can be found in Appendix 11
7 Simulation Results and Maintenance Strategies

With the model described in the previous section a number of strategies will be assessed. First the results from the base case simulation will be discussed. Then parameters that play a role in maintenance decisions will be investigated.

7.1 Base Case Results

The base case as described in the design assumptions (section 2.5) is simulated for 25 years. The results of this simulation can be found in Appendix 12. It shows that the turbine and its support structure the components that have mayor influence on the overall cost and thus the LPC. This influence is according to the predictions in section 5.3. The turbine and support structure represent 54 % res. 33 % of the total cost.

![Results of Simulation](image)

Fig. 7.1 Results of Simulation

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>PM Cost</th>
<th>CM Cost</th>
<th>Total Cost</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support Structure</td>
<td>745044</td>
<td>224762</td>
<td>969825</td>
<td>3</td>
</tr>
<tr>
<td>Hydraulic System</td>
<td>781944</td>
<td>2245218</td>
<td>3027162</td>
<td>9</td>
</tr>
<tr>
<td>Control System</td>
<td>752964</td>
<td>3790807</td>
<td>4543771</td>
<td>13</td>
</tr>
<tr>
<td>Gearbox and Generator</td>
<td>791790</td>
<td>2231107</td>
<td>3022987</td>
<td>9</td>
</tr>
<tr>
<td>Rotors</td>
<td>3148622</td>
<td>4327366</td>
<td>7475988</td>
<td>22</td>
</tr>
<tr>
<td>Electrical System</td>
<td>1286395</td>
<td>4292152</td>
<td>5578547</td>
<td>16</td>
</tr>
<tr>
<td>Others</td>
<td>1308541</td>
<td>4939121</td>
<td>6247662</td>
<td>10</td>
</tr>
<tr>
<td>MV - Field</td>
<td>42113</td>
<td>161417</td>
<td>203530</td>
<td>1</td>
</tr>
<tr>
<td>MV - Cable</td>
<td>290757</td>
<td>1963385</td>
<td>2254142</td>
<td>7</td>
</tr>
<tr>
<td>HV - Field</td>
<td>5434</td>
<td>5434</td>
<td>5434</td>
<td>1</td>
</tr>
<tr>
<td>HV - Cable</td>
<td>24011</td>
<td>840628</td>
<td>864840</td>
<td>3</td>
</tr>
<tr>
<td>Transformer</td>
<td>33864</td>
<td></td>
<td>33864</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>9211524</td>
<td>98200600</td>
<td>10741218</td>
<td></td>
</tr>
</tbody>
</table>

Investment Cost: 186526922

Total Revenue: 443577440
Profile: 149638394
Availability: 90.8
LPC: 0.080
Fig. 7.2 Graphical Display of Simulation Results

In the build-up of PM as well as CM cost, the rotors play an important role (34 % and 17 % of PM res. CM cost). This can be explained by the fact that these operations require an offshore crane and the duration of the repair or preventive maintenance is longer than that of most other components.

The results match those of calculations in [1, 4 and 16], both in overall cost as in build-up of these cost.

7.2 Corrective Maintenance

Maintenance can be executed when a certain loss of capacity occurs due to failures of components or subsystems. This can be either directly, when one turbine fails or when e.g. the availability of the entire farm drops under a certain level. Another option is to execute all CM during a scheduled period, and accept all failures that occur in periods in between.

Parameters that play a role in the decision on strategy are the duration of the repair, failure rate of the component, stand-by rate of CM tools and their workability limits. The parameters determine the expenditure on the CM task and its duration and lead to lost potential revenues.

Assuming that the failed components have to be repaired sooner or later, the decrease in expenditure due to the delay will have to compensate the lost revenues during the delay of CM. The decrease in expenditure comes from the increased probability of completing the task uninterrupted by bad weather. The lost revenues during the delayed CM of one Nordex N80 turbine can be estimated as:

\[ 2500 \text{ kW} \times 24 \text{ hrs} \times 33 \% \text{ of rated power per day} \times 0.12 \text{ Euro per kWh} = 2400 \text{ Euro per day}. \]
The 33 % in the previous calculation, is based on the 3300 hours production time at rated power per year, see Appendix 8.

The decrease in expenditures can be estimated by:

\[
\frac{((1 / 0.25) - 1) / ((1 / 0.75) - 1) - 1)}{2500 \text{ Euro / day Stand-by Rate (Waiting on Weather)}} \approx 13500 \text{ Euro}
\]

The lost revenues due to waiting more than about one workable week, with executing CM on most turbine components, will thus be hard to earn back by decreased CM expenditures. For CM operations needing an offshore crane the decrease in expected expenditures will increase to about 80000 Euro, thus about a 6 weeks delay can be afforded, when this results in the expected increase in workability. This means that it will be profitable to wait with the execution of CM needing a crane during most storms.

When CM would be scheduled e.g. only executed during the summer, the choice will depend on the probability of failures and the interval between the scheduled CM. Assuming random failures during the year, a failure can be expected to leave a turbine unavailable for production for 3 months when CM is only executed during the summer. This is clearly not an option.

In general, it will thus be most profitable to execute CM as soon as a workable situation occurs, when the farm consists of turbines in the megawatt range.

### 7.3 Preventive Maintenance

The preventive maintenance schedule can be based on either the system’s or component’s age only, or the expected condition. This condition can be based on this age, number of productive hours or for instance number of rotations. Age is here defined as the time since the last execution of PM or CM. The condition of a component can be expressed in its reliability. The reliability at which PM should be executed depends on the effects of the component’s failure. When the decision is based on the age of the components only, a schedule can be made up of Mean Times Between PM.

The decision whether to execute PM or not is based on its benefit for the system; the reduction in CM cost, compared to the expenditures and lost revenues due to PM.

The reduction of CM costs from PM depends on the decline rate of the component’s reliability and the way this reliability declines. In the simulation the time since the last execution of PM or CM is taken as the age of a component and at the components reliability will decline during this age either linear or progressively; Linear decline will add a part of the initial failure rate to this failure rate, progressive decline will add a part of the current failure rate to the failure rate.

The decline in reliability is thus the factor that creates the relation between PM and CM. Unfortunately however, this is also the parameter that is most classified to the turbine manufacturers. Since there is no data available, assumptions will be made, based upon decline rates of similar systems or components. With these assumptions an estimate can be made of the need for PM for the different components.

The decline rate is however not the only parameter in the decision on the ratio between PM and CM efforts. The frequency, duration and expenditures on both CM and PM operations will also play a role.

The sensitivity to the decline rate and all other parameters will be investigated by assessing the effects on availability, total O&M cost and the LPC, of a change of one of the parameters.
Parameters that are expected to increase the need for PM when they increase are:
- Duration of corrective maintenance
- Workability limits of PM tool
- Day- and stand-by rate of CM tool
- Failure rate of component
- Decline rate and type of Component

Parameters that decrease this need are:
- Duration of preventive maintenance
- Workability limits of CM tool
- Day- and stand-by rate of PM tool

In short: factors that increase the (probability of) cost of CM, increase the need for more frequent PM. When assumed that the tools used for transport are the same for PM and CM, the effect of the workability limits can be neglected when both execution of PM and CM occur randomly during the year. Often however PM will only be executed during the summer and although the tools may have the same limits, when used in the summer this can lead to a higher workability.

### 7.4 Seasonal Preventive Maintenance

As was seen in section 7.2, it will not be likely that executing CM in the summer only, will be profitable. Not executing PM however does not lead to direct production losses more so, the potential of the stronger winter winds should fully used and executing PM in the summer may lead to no losses in production at all. Again the decline of the systems reliability plays an important role.

The same relation as discussed in the previous section is applicable, only here PM will only be profitable in the winter at a higher decline rate, depending on the differences in workability between the seasons.

### 7.5 Task Specific Tool Decision

For each specific PM and CM task the decision on what tool to use, depends on what costs of more expensive equipment can be earned back by their higher workability. The increase in day- and stand-by rate should be compensated by the increase in workability. For an operation that requires two days work, a tool can be chosen as shown below.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Day Rate</th>
<th>Stand-by Rate</th>
<th>Overall Workability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel A</td>
<td>5500</td>
<td>2250</td>
<td>50 %</td>
</tr>
<tr>
<td>Vessel B</td>
<td>7500</td>
<td>3750</td>
<td>70 %</td>
</tr>
</tbody>
</table>

*Table 7.1 Tool Decision Data*

When the expected revenues are calculated as in 7.2, the total costs of operation using a tool are:

\[
\text{Day Rate} \times \text{Net Duration} + \text{Stand-by Rate} \times \left(\frac{1}{\text{Workability}}\right) - 1 \times \text{Net Duration} + \left(\frac{1}{\text{Workability}}\right) \times \text{Net Duration} \times \text{Expected Revenues} = 24\,500 \text{ Euro for vessel A}
\]

\[
23\,900 \text{ for vessel B}
\]

Vessel B will be thus be preferred.
7.6 Relation Availability – Energy Potential

One of the goals of this thesis was to study the correlation between periods of low availability and potential high energy yield. During a number of simulations this correlation was checked by grouping the availability in wind speed categories and then averaged over the times a certain wind speed occurred. This gave the following results:

![Correlation of Wind Speed and Availability](image)

**Fig. 7.3 Correlation of Wind Speed and Availability**

This shows that there is a decline in availability for high wind speeds, however at rated wind speed the turbine the decline does not yet show. Logical, since the wind speed limitations of O&M are around 15 to 20 m/s. The decline does not give a significant loss of revenue because these percentage of time that these high wind speeds occur is only about 10% of the total time. With a 5% decrease the lost revenue due to the decline are about

\[ 10 \% \times 5 \% \times 8766 \text{ hours} \times 2500 \text{ kW} / \text{hour} \times 0.1 \text{ Euro} = 11,000 \text{ Euro per turbine per year} \]

This is not significant (≈ 2%) compared to the 450,000 Euro of revenue per turbine per year.
Fig. 7.4 Availability, Wind Speed and Cash Flow

A comparison of the course of revenues and profits with that of the availability shows a clear positive correlation between drops in availability and drop in revenue and profit. It also shows that a wind farm as given by the input can be earned back in about a quarter of its lifetime with current energy prices.

Fig. 7.4 also shows that producing energy with an OWECS can result in profit. Largest uncertainty herein is the used failure rate of a turbine. The overall failure rate of a turbine e.g. the sum of the failure rates of its components is about 1.8 times per year in the base case. As said before this is estimate of the reliability that can be achieved. When the overall failure rate increases by a factor 2, which gives a better representation of the current reliability, the system breaks even.
8 Conclusions and Recommendations

During this graduation project a number of previous studies have been analysed to design the probabilistic model as described in this report. The analyses and simulations made with the model show large similarities. From this, together with other tests, it can be concluded that the written program correctly simulates the system.

8.1 Conclusions

The main cost drivers of ICC are turbines and their support structure. As expected the main O&M costs are caused by the turbine and in particular the rotors. The turbines are also the main cause of unavailability: 7% compared to around 2% for the shore- and grid connection. It can be concluded that the turbines are the subsystem that is most important for the optimisation of the farm and its O&M strategy.

There is a relationship between unavailability of the system and the occurrence of high wind speeds. It shows a decline in availability of about 5% for wind speeds higher than the wind limit of used O&M tools. This results in a loss of revenues of about 2% per year, which can be neglected in the calculation of profit.

The model of the sea states is not implemented in the model of Schönäug. Implementing the sea state model however should show a decrease in revenues of about 2% as predicted by the relationship above. Implementation thus does not seem necessary.

The program predicts the effects of changes in O&M strategy and can be used to optimise these strategies. Not all parameter effects have been investigated, simply because there are too many. The following relationships have however been investigated:

- The relationship between PM interval, failure- and decline rate shows a trend towards a decreased need for PM than the intervals used in the base case. The influence of the decline in reliability can be neglected for decline rates up to 25%. Higher decline rates are not very likely for mechanical or electrical systems. For a final conclusion on the relationship between PM intervals, failure- and decline rates more simulations will have to be made.

- The relationship between O&M tools and their workability limits indicates that the equipment used for O&M will have to be able to operate at $H_s > 1\, \text{m}$. Equipment that cannot operate at these wave conditions will cause a low availability of the farm and high O&M costs.

- The availability of the system is one of the most important aspects in the profitability of the farm. Calculations show that about a week can be waited with the execution of O&M if this results in a significant (≈ 50%) increase in workability. The delay that can be afforded depends on the used tools and the size of the turbines, it can increase to about 6 weeks when offshore cranes are used. Only executing CM in the summer will thus not be profitable.
8.2 Recommendations

A good understanding of the model and the way it simulates the system is necessary when working with the program. The model can be further improved by accounting for:

- The availability of crew and spare parts. In the simulation all spare parts are assumed to be directly available when a failure occurs. Ordering a new rotor blade at the moment of failure could lead to a waiting period. It is assumed that for the farm sizes the program was intended for, a stock of spare parts will be available. This stock keeping can be optimised separately.

- Another expansion of the model could be to enable execution of PM based on the estimated reliability of the components or to execute CM when a certain level of unavailability is reached. This would provide more options for possible O&M strategies.

- The wind-wave correlation could be further improved by implementing a wind-wave correlation matrix or relating the fetch length to a direction of the wind. Current weather simulation shows however good results, both in the course and values of wind and waves as well as their correlation.

- Finally, the influence of the simplification in the accessibility limits could be further investigated. Current criteria are wind speed and wave height. In reality, the wavelength and frequency also play a role in the workability of the vessels.
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- Mr. Ir. M. Van der Meulen,
  Simtech Engineering

- Dr. Ir. P.H.A.J.M. van Gelder,
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APPENDIXES

by

Graduation Project

Probabilistic Design
of Operations & Maintenance on

Offshore Wind Energy Conversion Systems

MARCH 2001

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CT 9599256
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i.c.w Hydronamic bv
Faculty of Civil Engineering and Geo Sciences
Delft University of Technology
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1 Theoretical Background

1.1 Wind Energy

Wind is kinetic energy and can be harvested directly. The power available in the wind is the flux of kinetic energy crossing the cross-sectional area $A$ of the wind turbines. With wind velocity $V$ and air density $\rho$, the theoretical power is given by the equation:

$$P_0 = \frac{1}{2} \cdot V_1 \cdot A \cdot \rho \cdot V^2 = \frac{1}{2} \cdot \rho \cdot A \cdot V_1^3$$

Given the fact that the energy content of the wind increases with the cube of the wind speed, the energy yield offshore may be some 73 per cent higher than on land, given the 20 percent higher wind speeds offshore. Economically optimised turbines, however, will probably yield some 50 per cent more energy at sea than at nearby land locations. [17]

The cubic average speed indicates the amount of energy that can be extracted, per year, for each square meter of disc. It can be given by:

$$V^3 = \int_{V_{\text{in}}}^{V_{\text{out}}} V^3 P(V) \, dV$$

with $V_{\text{in}} = \text{Min} \cdot \text{Production} \cdot \text{Speed}$ and $V_{\text{out}} = \text{Max} \cdot \text{Production} \cdot \text{Speed}$

**Fig. 1.1 Energy Extraction**

In theoretical sites where the wind speed would be constant through the year, the year average cubic speed $V^3$ and the year average speed $V$ to the third power are equal, but this is virtually never the case; their ratio expresses the regularity of wind intensity $I_w$.

The turbine can not extract all the power from the wind; the air behind the turbine would stand still and thus stop the flow entirely. The ratio of the energy that can be extracted is determined by the ratio of wind speed before and after the turbine. [21]

**Fig. 1.2 Ideal Wind Speed and Power Ratio**
With conservation of mass and energy, it can be shown that the power is maximal when, in the end, wind speed is reduced to 1/3 of its original value. Then the amount of air that is decelerated equals 2/3 of the wind flowing through the wind turbine when not in operation. From this amount of air 8/9th of the kinetic energy is extracted (wind speed reduces to 1/3), which results in a maximum achievable power coefficient of $2/3 \times 8/9 = 16/27$.

In formulas the same can be proven, leading to a ratio:

$$c_p = \frac{\Delta P}{P_0} = \frac{1}{2} \left[ 1 - \left( \frac{v_2}{v_1} \right)^2 \right] \left[ 1 + \frac{v_2}{v_1} \right]$$

Wherein $v_1$ and $v_2$ are wind speeds respectively before and after the wind turbine.

The optimum is found when $\frac{v_2}{v_1} = \frac{1}{\sqrt{3}}$, which gives $c_p = \frac{16}{27} \approx 0.5933$.

This shows that about 60% of the theoretical power can be extracted. The actual extracted energy will vary with pitch angle and tip speed ratio $\lambda$ (the ratio of the blade tip speed and the free flow velocity of the wind).

The total wind power present in the atmosphere is estimated at $2600 \times 10^{12}$ GWh/yr [6], but guesses as to how much of this energy can be converted vary widely. Because the available energy flow increases with the cube of the wind speed, the selection of the site is a major factor. The lower $I_w$ and the higher $V^3$ the better the site. The cube relation between wind speed and power also means that most energy will be obtained during periods of high winds. This needs for a continuous recording of the wind speed distribution, rather than the average wind speed.

All the above on energy extraction is under the assumption of a 100% availability of a single turbine. In reality however the turbine will be placed in a farm of multiple units. This will cause energy losses due to wake effects, because the airflow behind a turbine will not completely return to an undisturbed situation, before it reaches the next turbine. These losses are expressed in the so called "array efficiency" which will increase with increasing distances between the turbines.

Furthermore the transport of energy is always attended with energy losses due to resistance of the cables. The lost energy is transferred into heat and absorbed by the cable surroundings e.g. the seabed.

Another loss of energy, which forms a large part of this thesis' subject, is caused by failures within the system. Turbines, transformers, MV- and HV-networks can break down, each causing a certain loss of production capacity. The availability is determined not only by the number of occurring failures but also by the repair times of the different components.

The total energy yield can thus be written as:

$$\text{Energy \cdot Yield} = \text{Theoretic \cdot Energy \cdot Yield} \times \eta_{\text{availability}} \times \eta_{\text{array}} \times \eta_{\text{transport}}$$

with

- $\eta_{\text{availability}}$ = Percentage of available production time due to system failures
- $\eta_{\text{array}}$ = Percentage of remaining production after accounting for wake effects
- $\eta_{\text{transport}}$ = Percentage of remaining production after transport

Many factors are involved in selecting the type of wind turbine to use at a specific site. Among these are cost of the system per produced MWh, the match between the operating characteristics of the turbine and the site's wind characteristics, wind turbine size and installation requirements and accessibility of the site. Ultimately the expected profit form the installed system is the main criterion.
### 1.2 Wind Turbines and Grid Connection

The main function of the system is to convert wind into electrical energy. The path of conversion starts at the rotor blades, where wind energy is converted to mechanical energy. The blades are placed in optimum direction with regard to the wind by a yaw system, rotating the nacelle over the tower axes.

The rotor blades also rotate around their own axes (pitch) in order to create a constant torque on, or rotation speed of the hub and main shaft. The pitch system is also used as aerodynamic break by pitching the blades perpendicular to the sense of rotation.

The main shaft drives the rotor in the generator, this often after intervention of a gearbox. The gearbox enables a constant torque and rotation speed on the generator. Depending on the use of a gearbox the generator can produce either an asynchronous or a synchronous current. This influences the possibilities for the grid connection of the turbines and therefore their reliability as a system.

Wind turbines come in many shapes and sizes. Choices have to be made about generator capacity, foundation and grid connection. Furthermore, a great number of design choices in the interior of the nacelle can be made.

![Fig. 1.3 Power Distribution on Rotor Blades](image)

Economies of scale in the offshore wind energy area are twofold: In terms of machine size, and in terms of number of units per farm [17]. Even though weight and costs increase of the turbines, it is far more economic to use larger wind turbines, since the size and costs of foundations do not increase in proportion to the size of the wind turbine. Another important cost factor is grid connection. Here, it is obviously far cheaper to attach fewer turbines to the grid for a given wind farm capacity.

The economic optimum capacity of an offshore wind farm will be significantly higher than on land. The cost of installing an undersea 150 MW cable is not very different from the cost of at 10 MW cable. Mass production of turbines and steel foundations in the future will also tend to decrease costs.

The offshore location means a number of substantial changes in the design specification of the turbine, because of the change in accessibility and environment:
- Increased demand on protection of components and systems
- Longer maintenance intervals
- Higher reliability
- Remote stand-by capacity
- Noise reduction of minor importance
- Not structural weight but length e.g. height is critical during transport

A more thorough description of the turbine and its components as manufactured by Nordex is made in the thesis, because not all design choices have a significant impact on the availability of the entire system. After determination of significant failure modes with respect to cost and availability, alternative design choices within the failure mode will be considered.
1.3 Operations and Maintenance

Every operating system will experience malfunctioning at some point during its lifetime. The objective of maintenance is to keep the system in, or bring it back to, a state of failure free operation. A number of maintenance policies exist. Each attempts to balance initial capital cost and O&M cost during the lifetime of the system. Possible strategies are [14,4]:

- **Preventive maintenance**, this aims at prevention of failures, either periodically or condition based. With periodic preventive maintenance, components are renewed at regular time intervals. This is usually done with components with low replacement costs. Condition based preventive maintenance is based on periodic inspections to determine state of degradation and need for replacement.

  - Inspection
  - Inspection and repair

![Graph of preventive maintenance](image)

*Fig. 1.4 Condition Based Maintenance*

- **Corrective maintenance** is performed to restore failed or malfunctioning components. The occurrence of the breakdown is stochastic, therefore the corrective maintenance cannot be scheduled.

- **Opportunity Maintenance**’s main intention is to execute corrective maintenance on demand. However, this opportunity will also be used to carry out preventive maintenance, which will thus be carried out on an irregular basis and only after failure. Idea behind this is to reduce the number of visits.

![Graph of corrective maintenance](image)

*Fig. 1.5 Course of Strength*

- With the **No Maintenance** strategy, neither preventive nor corrective maintenance is executed. The failure and thus shutdown is incorporated in the design by redundancy. This redundancy will have to be sufficient to meet or exceed the design power output.

- **Periodic maintenance** schedules visits at regular intervals. These visits are used to inspect the turbines and execute preventive and corrective maintenance tasks where necessary. Aside this scheduled visits no maintenance is performed and failed turbines are left inoperable.
A first comparison of the usefulness of strategies can be made with the schedule below [14].

![Flowchart](dummy)

The optimal choice of strategy is often a combination of the above and depends on the maintenance characteristics of the offshore turbines and the maintenance structure and available hardware at or near the site.

Before choosing a policy the intentions of the maintenance have to be defined. Two basic approaches are cost- or reliability based maintenance. Since structural or functional failure of the turbines does not impose any threats to its surroundings and energy supply does not fully depend on the wind farm, the cost based approach will apply here e.g. the design of a farm will be based on economics rather than a desired reliability.
The effect of maintenance will be an increase in the expected value of the reliability and a decrease of the variance in this strength. The reduction in reliability is not always equal in each interval because ageing can depend on e.g. previously executed maintenance or productive hours within the interval. With the aid of inspections and condition parameters, the systems' strength can be determined at a given time. It should however be possible to measure the condition parameters with a reasonable accuracy. Without this, the inspection cannot give a better view on the systems' condition [B]. Line A shows the probability density with increased knowledge of the systems' strength [14].

Fig. 1.7 Effects of inspection
Reducing the maintenance interval will reduce the risk e.g. increase reliability, but increase the maintenance cost. Therefore an optimum will be sought in maximum profit or a minimum of net discounted cost of produced energy.

The main cost drivers of maintenance appear to be expenses for transportation to and from the site and possible lifting operations. The access to the offshore wind farm is limited so a reliable turbine and careful O&M strategy is required in order to achieve an acceptable availability. This O&M strategy can be established considering [23]:

- OWECs objectives
- Turbine design
- Maintenance approach
- O&M hardware

The maintenance required is for a great deal depending on the reliability of the system. Since the occurrence of failures can not be determined in deterministic ways, a probabilistic approach will be taken here. Furthermore, the availability of the system together with its production will depend on the wind and wave conditions in the field, which for simulation purposes rely on stochastic processes. Therefore an overview will be made of probabilistic design and its applications, which can be used in the rest of this thesis.
1.4 Probabilistic Design

Probability or chance of an event is generally defined as a function that appoints a number to each part of the collection of events of the total collection of all possible events. The probability of an event is equal or greater nil and the chance on the total collection of all events equals one.

1.4.1 Risk analysis

Risk can be defined as a function of probability and its consequences. Both probability and consequences are evaluated in this definition, which allows for weighing certain unwanted events in order of seriousness.

General purpose of a risk analysis is to provide a basis for making rational decisions. This can be done qualitatively as well as quantitatively. The latter is not always possible or wanted. In this case, a qualitative analysis can be done to improve certain processes, or to come to a global judgement of the involved risk.

Risk analysis uses basic system schematics to describe the process or object as input - output element. The system is broken down in to subsystems and components to a level where probability of failure can be determined. Failure occurs when a system, or part of the system, can no longer fulfil one or more of its desired functions. This state of failure can be reached through several paths. Each path is called a failure mechanism. The situation between functioning and failure is known as a limit state. These limit states can be divided in serviceability limit state and ultimate limit states. The first is a temporal state during which functions or no longer fulfilled, the second is permanent as long as the system is not repaired.

Probability of unwanted events can be approached in two ways:

- Inductive (empirical): probability is determined by statistics (database). This method will not leave out any important failure mechanism in case of identical processes and systems but does not provide much insight and is therefore not useful to prevent failure mechanisms from happening.
- Deductive: This method investigates all failure mechanisms and does give insight to the process or system.

Probability of consequences and effects can be determined in similar ways. These probabilities are conditional. The total risk is:

\[
\text{(Probability of Cause)} \times \text{(Probability of Effect given the Cause)} \times \text{(Probability of Consequences given the Cause And the Effect)} \times \text{Consequences.}
\]

The consequences above are mostly events that are perceived as negative. Once the risk is calculated it can be evaluated and compared to the norm. Often the steps in the risk analysis will be taken several times with improved system specifications, to come to an optimum design.

1.4.2 Reliability analysis

Reliability analysis identifies the causes of failures, quantifies the probability of such a failure, and assesses the way, in which the failure probability of a component influences the failure probability of the system as a whole. The scope of a reliability analysis also includes the assessment of the availability and maintainability. Objectives of the analysis can be:

- Identification of weak points in a design
- Assessment of relative importance of identified failures
- Optimisation of the design by quantifying margins
- Maintenance planning and optimisation of expenditures
- Quantification to show compliance with safety or design regulations.
The question, which information is relevant and which detail is needed, depends on the objective of the reliability analysis. Qualitative analysis can be sufficient to gain understanding of the systems’ operation, or to identify failure mechanisms or maintenance procedures. If a numerical estimate is needed of the system’s reliability and availability, a quantitative analysis will be necessary.

Reliability analysis also includes aspects such as testing and inspection in the broadest sense. These are tools for obtaining failure data of components and systems. Incident and accident reporting, cost-optimisation, maintenance and quality assurance are also part of reliability engineering.

For a qualitative analysis, failure data are essential. Sources of data can be reliability testing, operating experience, logbooks, generic industry-averaged data, data books or engineering judgement. One of the most characteristic type of data is the failure rate \( \lambda \), which is defined as the expected number of failures in a given time interval. In case of a constant \( \lambda \), the mean time between failures equals \( 1/\lambda \). The failure rate is often a function of time and follows a "bathtub" curve.

![Bathtub Curve](image)

The better the quality assurance of design and construction the shorter the first period and the lower its start. The reliability of the wind turbine can not be quantitatively assessed during this period due to teething problems, but with a qualitative analysis and a quality assurance program, the reliability and safety can be improved. The second period is normally considered in a quantitative analysis. The failure rate is usually small and constant and represents random failures.

Fig. 1.8 "Bathtub Curve"

In the last period, the failure will increase due to ageing and deterioration of the component. Actions to delay the starting point of this part of the curve include preventive maintenance and regular monitoring.

The aspects reliability, availability and maintainability are closely related. Reliability is the probability that a system will perform its intended functions satisfactory (e.g. within specified performance limits) at a certain time, for a specified length of time, when operating under the specified environmental and usage conditions.

Availability is the probability that a system is able to perform its functions, for the OWECS this will be the production of energy and transport to shore, at any point in time, where the total time considered includes operating time, active repair time and logistic time.

Maintainability is the probability, that a product or a system will conform to specified conditions within a given period of time when maintenance action is performed with prescribed procedures and resources.

Most commonly used reliability techniques are probabilistic in nature and in various industries, experience is gained with different types of systems. These can be divided in two groups; system reliability and structural reliability. The first is related to the safety and reliability of systems, which contain components, of which the failure probability is known from operating experience or manufacturers. The latter quantifies the failure probabilities of the load carrying parts.
A survey of the existing methods [23] for system analysis and reliability gives results as summarised in table 3.1

<table>
<thead>
<tr>
<th>Method</th>
<th>Characteristics</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Identification of Failure Modes and Initiating Events</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure Mode, Effect and Criticality Analysis (FMECA)</td>
<td>All failure modes of every component, their relative criticality and effects are tabulated. Hardware orientated (qualitative)</td>
<td>Useful for identifying all possible failure modes. Standardised approach</td>
<td>Combinations of failures and human factors not considered; only single components</td>
</tr>
<tr>
<td>Hazard and Operability Analysis (HAZOP)</td>
<td>An extended FMECA which includes cause and effect of changes in major system variables. Relies on experience (qualitative)</td>
<td>Suitable for large chemical plants</td>
<td>Technique is not standardised. Only used in chemical industry</td>
</tr>
<tr>
<td>Preliminary Hazard Analysis (PHA)</td>
<td>Identifies the system hazards (qualitative)</td>
<td>Additional to FMECA; goes beyond hardware; identifies also environmental impact, crew errors etc.</td>
<td>Not a detailed analysis of the process or facility</td>
</tr>
<tr>
<td><strong>Event Sequence and Consequence Modelling</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cause Consequence Diagrams (CCD)</td>
<td>Follows the causal order of events. Complex branching; more than yes/no logic (qualitative)</td>
<td>Compact models by grouping of parallel branches, by logical gates</td>
<td>Inconvenient arrangement for sequence by sequence assessment</td>
</tr>
<tr>
<td>Event Sequence Diagrams (ESD)</td>
<td>As CCD. It depicts how successive safety functions can be accomplished, showing all sequence options considered (qualitative)</td>
<td>Can identify alternative consequences of failure; lends itself for quantification</td>
<td>Diagram can be too detailed (much design and operational information included)</td>
</tr>
<tr>
<td>Event Tree Analysis (ETA)</td>
<td>Starts with initiating event and examines all alternative sequences (both quantitative and qualitative)</td>
<td>Lends itself for quantification. Other faults than hardware failure can be included easily. Dependencies between components can be modelled</td>
<td>Not suitable for detailed analysis</td>
</tr>
<tr>
<td><strong>System Modelling and Quantification</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault Tree Analysis (FTA)</td>
<td>Start with most undesired event and finds the combinations of failures that causes it</td>
<td>Easy to use</td>
<td>Large fault trees are not easily understood. No resemblance to system flow diagram</td>
</tr>
<tr>
<td>Reliability Block Diagrams (RBD)</td>
<td>Similarly laid out to a flow diagram; components as series of interconnecting blocks</td>
<td>Compact model which follows the normal process flow</td>
<td>Causes of failure are not schematically identified</td>
</tr>
<tr>
<td>Go Chart</td>
<td>A number of operators are used, modelling the process in parallel with the flow diagram</td>
<td>Analytical solution of the process but only for simple events</td>
<td>Failure modes are not explicitly modelled. Only failures documented in the system schematic</td>
</tr>
<tr>
<td>State Space Diagrams (SSD) and Markov Analysis</td>
<td>Analytical description and solution of the process, where systems change from one to another</td>
<td></td>
<td>Inconvenient for a qualitative understanding of failure importance of components. Transitions only depend on preceding state</td>
</tr>
</tbody>
</table>

Table 1.1 Methods of System Reliability Analysis
To perform a reliability analysis, the following data are essential [23]:
- Design specifications
- Frequencies of initiating events or accident initiators
- Component failure frequencies and its associated repair, test and maintenance parameters
- Human error probabilities and
- Common cause failure probabilities

Reliability calculations can be done with several approximation methods depending on what level of practicability or accuracy is required. They can be divided into:

Level 0: This level is a deterministic analysis based on fixed data; a deterministic "high" load and "low" strength and an overall safety factor.

Level 1: This level is used for routine design use. For each of the stochastic variables a certain unfavourable value is chosen, usually based on a 5% confidence limit (characteristic value). In addition, a set of partial safety factors is applied that should ensure the margin between load and strength for the various cases considered.

Level 2: Here an approximate analysis based on the so-called first order / second moment principal is made. In short, only the mean value and the standard deviation of each stochastic variable are taken into account, linearisation is used where necessary. Level 2 studies are used to underpin the safety factors used in a Level 1 analysis and where above-normal standard level of reliability is needed.

Level 3: This level comprises complete and exact analysis performed with the aid of numerical integration procedures or Monte Carlo simulations. These analyses generally demand too much computational effort to be practicable for dealing with major problems, due to the large number of stochastic variables. Mostly applied to verify and complement Level 2 approximations.

One of the objectives of this study is the economic optimisation of wind energy from an offshore wind turbine farm. Furthermore, the methodology to be developed should enable Hydronamic and Nordex to make a well-balanced design. In order to do so, the model should facilitate an analysis that meets the following objectives:

- Assessment of the importance of identified failures, where emphasis will lay on the Serviceability Limit State, e.g. unavailability of parts of the system for energy production.
- Determining the relation between initial investment and O&M cost
- Optimisation of maintenance planning and expenditures
1.4.3 Selected methods

To select the methods to use, they have to be assessed on their applicability to meet the above stated objectives. Although the design of the Nordex N80 is optimised from previous models, the model itself is relatively new and no reliability analysis or data, are available. The applied methods will thus have to be fit for a first-of-a-kind wind turbine. This even more, to make the applied method fit for the analysis of future models. The following steps, as stated in [22], are recommended for the study:

1. System description:
   The system description should clearly outline the design and operation of the wind turbine and consist of:
   - Performance and operation of the offshore wind turbine farm and its subsystems and components. The operational modes of the system, manually and automatically, together with the functions of the subsystems should be described in detail.
   - Specification of the design limits of the components in accordance with their operational modes, for instance the maximum rotor speed.
   - Description of the system's environment as far as this influences the functioning of the system or operations that have to be carried out on the system.
   - Procedures to be carried out during the operational life of the system, e.g. tests, maintenance and inspection procedures as well as procedures for data collection.

2. Reliability modelling consisting of:
   - Identification of Failure modes, Hazards and Initiating Events. This can be done with a FMECA, which gives a good understanding of the systems' operation, and the effects of failure of one of its components. First, a structural breakdown into subsystems and components has to be made. The level of detail will depend on the relevance of the component and the objective of the analysis.
   - The initiating events that have to be considered are not only failure within the system but also external conditions and human failures. These can be obtained from design rules and interviews with the manufacturer.

3. In addition to the FMECA, the causal effects will be considered by an Event Sequence and Fault Tree Analysis. With these techniques the relationship between failures can be more easily determined. The response of the system to initiating events can be determined with an Event Tree Analysis, a Fault Tree Analysis will be used for analysing the compound events in the ETA.
   For the modelling of the system, and quantification of the top events, a FTA is recommended. A State Space Diagram will be used to model scenarios where system states change cyclically in time.

4. Where sufficient failure data is available, the probability of top events can be quantified. With a sensitivity analysis, the relative importance of events can be determined. Most importantly, these analyses can be used to determine and evaluate the influence of changes in the design or the maintenance procedures on the availability of the offshore wind energy.

5. The structural reliability can be seen as a method to determine failure data, different from the methods as mentioned in the previous sections. Therefore it will be dealt with separately. The selected method is a Level II approach based on first and second order moments, like is often used on offshore constructions.
1.5 Process Modelling

When analysing statistical data first the nature of the process should be studied. Processes can be [15]:

![Stationary Process](image)

![Seasonal Process](image)

![More than One Process](image)

*Fig. 1.9 Process Types*

If data originates from one stationary process than one consecutive period of observations of about a year can give enough information to make a statistical description of the process. A distribution of the process can then be determined from these observations. When for instance seasons influence the process, it is often possible to consider each season as a separate stationary process. Exceptions to this are extreme processes, for instance cyclones or hurricanes, which will have to be superimposed on the more stationary processes.

During each more or less stationary process, a distribution for the Serviceability Limit State can be determined. The Ultimate Limit State distribution will have to be determined superimposing all occurring processes.

![Limit States](image)

*Fig. 1.10 Limit States*

By definition the chance that a stochastic variable $X$ is smaller than or equal to a certain fixed value $x$ is equal to $F_x(x)$ thus

$$P(X \leq x) = F_x(x)$$

If we take $N$ draws than the probability that all $N$ draws

$$\leq x = F_x(x) \times F_x(x) \times F_x(x) \times \ldots = F_x^N(x)$$

This distribution of the highest of $N$ draws from a basic distribution is called the extreme value distribution $F^N_E(x)$ of maximums.

The probability density function (p.d.f.) follows from this by differentiating in respect to $x$:

$$f_E(x) = N \cdot f_x(x) \cdot F_x^{N-1}(x)$$

Distributions for probability mass and density functions for minimums can be determined analogue to the above-described maximums.
Binned data can be displayed in histograms and by applying a goodness of fit test, a suitable mathematical description can be determined, as an estimate of the probability density function. The fitting of the measured data to a certain distribution should not only be based on statistical techniques but also on the underlying physical relations. This leads to so-called censored distributions. These will show leaps where a boundary to the process will censor its possible outcome.

If a process is determined by more than one stochastic variable, its probability density function will be more dimensional. The variables each have their marginal probability density, and the process has a probability density of all variables combined.

![Joint Distributions](image)

*Fig. 1.11 Joint Distributions*

Many times however difficulties will arise in defining and using a predictive model because of [23]:

- Inadequate databases,
- Poorly defined physical basis,
- The definition of the return value is not always understood,
- Difficult evaluation of results.
2 Reliability Analysis

The reliability of the system will be determined by design choices, leading to ICC as described in Appendix 4. Together with the O&M strategy the reliability will determine the systems availability. In order to determine relations 3 & 4 from Section 4.2, an inventory of unwanted events e.g. failure mechanism will be made to calculate the systems reliability. To decide what is unwanted first a clear definition should be made of the "unwanted event". Unwanted events will be taken as events that cause downtime in production of energy by the turbine or downtime in transport of produced energy ashore, this either in itself or in combination with other events.

2.1 Failure Mode, Effect and Criticality Analysis

As stated in Appendix 1.4.3 there are several techniques to come to a complete as possible inventory. First of all the Failure Mode Effect and Criticality Analysis will be made to come to identify failure modes, hazards and initiating events. The lowest level of the components is normally determined by the availability of failure data. Because of a lack of data and to give more insight into the functioning of the system this is not the case here. Furthermore a more detailed analysis can give some indication on data that needs to be collected in the future.

The importance of the effect is accounted for by categorisation as follows:
- Negligible: The effect is temporary and will not affect the system when its cause is no longer present
- Marginal: This causes is temporary failure as well, but can lead to permanent failure in combination with other effects
- Critical: The failure will leave (part of) the system unavailable until repairs can be made.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Failure Mode</th>
<th>Effect</th>
<th>Criticality</th>
<th>Failure Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbines</td>
<td>1. No Energy Conversion</td>
<td>1: Turbine doesn't produce energy 2: Produced energy can not be used 3: All other functions halt 4: Setting can't be updated</td>
<td>1 &amp; 2: Critical res. Marginal when failures can not res. can be reset. 3: Critical, long repair times to be expected 4: Marginal as long as conditions do not change</td>
<td>Estimates for future = 1.1 failure / year per turbine for all failures combined. Currently = 3 failures / year for all failures combined, depending on manufacturer</td>
</tr>
<tr>
<td></td>
<td>2. No Energy Transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Failing Support Structure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. No Control System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MV - network</td>
<td>1. Broken Cable</td>
<td>Depending on type of grid connection, energy of (part of) connected turbines not transported to transformer.</td>
<td>1: Critical, long repair times to be expected 2,3,4: Marginal when power can be re-routed or failure can be reset. Critical in other cases.</td>
<td>Directly related to length of MV net. Estimate = 0.012 * cable length failures / year</td>
</tr>
<tr>
<td></td>
<td>2. Voltage to high / low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Current to Large for Cable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Phase Differences to large</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transformer &amp; HV - network</td>
<td>1. Broken Cable (HV net only)</td>
<td>1 to 4: None of the produced energy can be transported to shore</td>
<td>1 to 4: Critical. Power can not be re-routed (assuming a single shore connection). Transformer errors may be resetable, depending on severity</td>
<td>For HV net: Directly related to length of HV net. Estimate = 0.0035 * cable length failures / year Transformer: 0.02 times /year</td>
</tr>
<tr>
<td></td>
<td>2. Voltage to high / low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Current to Large for Cable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Phase Differences to large</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 FMECA of Subsystems OWECS
The failure mode "broken cable" of the MV- and HV network is primarily caused by colliding anchors or fishing gear. Besides restricting fishing areas, solutions can be found in changing fishing gear design. The other failure modes of the transformer, MV- and HV network are mostly caused by phase differences between produced power of the different turbines. They can be minimised but not completely prevented by improving the regulatory systems.

The causes of the different failure modes of the turbine can be found below.

<table>
<thead>
<tr>
<th>Component of Turbine</th>
<th>Failure Mode</th>
<th>Effect</th>
<th>Criticality</th>
<th>Failure Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor</td>
<td>1. Over speed</td>
<td>1: Aerodynamic and Mechanical brake to slow down or stop</td>
<td>1: Marginal</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>2. Structural failure</td>
<td>2: No energy conversion</td>
<td>2: Critical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Vibrations</td>
<td>3: Increase wear and fatigue of parts</td>
<td>3: Marginal</td>
<td></td>
</tr>
<tr>
<td>Pitch System</td>
<td>1. Defect drive</td>
<td>1 to 3: Aerodynamic brake unavailable, No pitch adjustment, updating setting not possible</td>
<td>1: Critical</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>2. Turntable</td>
<td></td>
<td>2: Critical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Electrical system</td>
<td></td>
<td>3: Critical</td>
<td>(marginal as far as redundancy can take over)</td>
</tr>
<tr>
<td>Main Shaft</td>
<td>1. Torque Overload</td>
<td>1: Not allowed loading of gearbox</td>
<td>Marginal</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>2. Heavy vibrations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gearbox</td>
<td>1. Lubrication</td>
<td>1,2: No energy conversion</td>
<td>1,2: Critical</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>2. Coupling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Control system</td>
<td>3: Unable to update settings</td>
<td>3: Marginal</td>
<td></td>
</tr>
<tr>
<td>Lightning Protection</td>
<td>1. Overload</td>
<td>1,2: Overload of electrical system, short circuits</td>
<td>Critical</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>2. Non-interception</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generator</td>
<td>1. Short circuit</td>
<td>1,2: No energy Conversion</td>
<td>Critical, Marginal if retestable</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>2. Field Error</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brake System</td>
<td>1. Failed aerodynamic brake</td>
<td>1: Unable to slow rotor down</td>
<td>1: Marginal</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>2. Failed emergency brake</td>
<td>2: Unable to stop / secure the rotor</td>
<td>3: Critical</td>
<td></td>
</tr>
<tr>
<td>IGBT Converter</td>
<td>1. Short Circuit</td>
<td>No energy conversion</td>
<td></td>
<td>?</td>
</tr>
<tr>
<td>Yaw System</td>
<td>1. Defect drive</td>
<td>No yaw adjustment, in case wind direction changes</td>
<td>1 to 3: Marginal</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>2. Turntable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Electrical system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower</td>
<td>1. Fatigue</td>
<td>Nacelle and rotor no longer supported</td>
<td>1,2: Critical</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>2. Ultimate Loading</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foundation</td>
<td>1. Fatigue</td>
<td>Nacelle and rotor no longer supported</td>
<td>1 to 3: Critical</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>2. Ultimate Loading</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Erosion</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2 FMECA of Components Turbine

The causes and frequency of the failure modes in Table 3.2 are for the greater part unknown. Failures for a large number of turbines are mapped in [32], this shows a large difference, in frequencies of the different failures between turbines, as well as in the relative importance of these failures. Furthermore, most of the mapped turbines are shore based and how failure modes will differ offshore is unclear yet. Lastly, the statistics that are available show much higher failure rates than those used in for instance [4] but these are taken from only a small number of turbines and their values can be seen as infant mortality.
2.1.1 Conclusions FMECA

From the FMECA's can be concluded that almost all failures or errors occurring in the system will result in loss of possible energy production. This either from one turbine when an OWEC fails, a number of turbines when failures in the MV network occur or all of the production capacity when errors occur in the HV network or the transformer.

2.1.2 Operational modes

The lifetime of the turbine shall be divided into modes of operation to perform design and reliability calculations. In this lifetime normal and abnormal operational modes can be distinguished. During the first the wind turbine functions without defects and is controlled by the normal control system. The abnormal modes are generally initiated by component failures.

<table>
<thead>
<tr>
<th>Normal Operation Modes</th>
<th>Abnormal Operational Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Failures</td>
</tr>
<tr>
<td>Energy Production</td>
<td>Generator short-circuit</td>
</tr>
<tr>
<td>Start-up Procedure</td>
<td>Other</td>
</tr>
<tr>
<td>Stop procedure</td>
<td></td>
</tr>
<tr>
<td>Braked farming</td>
<td></td>
</tr>
<tr>
<td>Idle</td>
<td></td>
</tr>
</tbody>
</table>

*Table 2.3 Operational Modes*

2.2 Event Sequence Analysis

Event trees order and depict events according to the safety requirements of each group of initiating events. These events, the headings of the event trees, can be basic events, safety functions, system’s status or human actions. These can be derived from the influences on the system as described in section 3.1

The event sequence analysis is limited by the fact that all system functions; energy conversion and transport, conversion support and control and support structure, can be seen as chain systems. Failing of one of the components will then mean that (part of) the production capacity will be lost since a link in the chain will be missing. In the ESA the initiating events or thus the same as the top events.

Since causes of most failure modes in the turbine are unclear, an Event Sequence will not be made. Causes are considered as random failures and all failure modes lead directly to the top event; reduction of production capacity. Therefore the sequence of the events is irrelevant.
Exception to this, are failures of the control system. When somewhere in the conversion or transport chain, a link is missing, the control or remote monitoring system will halt the turbine either by aerodynamic or mechanical brake. When the control system does however not identify or act upon the failure. This can lead to excessive loading of all other components. The cost of redundancy in the control system will be low compared to cost of other components or redundancy hereof, so in a design solution this case of event can be neglected.
2.3 Fault Trees Analysis

The top event of the Fault Tree Analysis is a reduction of power supply to the shore by the offshore wind farm. This reduction can be the result of any combination of unavailability of turbines and / or electrical transmission in the system. Therefore one single top event for the entire system cannot be defined. The fault tree will therefore reflect the unavailability of a single OWEC.

2.3.1 System fault tree

![Fault Tree Diagram]

Fig. 2.2 System Fault Tree

The support structure can fail when its Ultimate Limit State is reached due to fatigue or due to erosion. In the U.L.S. the exerted forces on the structure exceed its strength. Failure due to fatigue will occur when the number of tensile changes in the structure reaches its limit. Aerodynamic dampening can decrease the tensile changes in the structure; the blades vibrate less powerful when rotating. The soil surrounding the support structure can erode when its erosion protection fails and the current is strong enough to transport the material. All failure mechanisms are thus correlated since there are subject to the same loads.

Because the correlation between the U.L.S. fatigue and erosion is too complex to be discussed in detail, the failure of the support structure will be not be developed any further. Furthermore, the loads on the structure will be monitored and the five yearly inspections will ensure that the failure of the support structure can be neglected.
2.3.2 Fault tree of components

Uncontrolled or No Blade Rotation

Pitch System Unavailable

Lightning Strike

Failing Lightning Protection

Ground Terminal Disconnected

Air Terminal Fails to intercept

Conductor failure

Surge Arrests in system

Damaged Blade (structural)

Uncontrolled or failing Rotor Bearing

Pitch Drive or Pitch Fixation 1 fails

Pitch Drive or Pitch Fixation 3 fails

Pitch Drive or Pitch Fixation 4 fails

Pitch Drive or Pitch Fixation 2 fails

Uncontrolled or failing Elec. System

Fig. 2.3 Fault Tree Rotor
Fig. 2.4 Fault Tree within Nacelle
### 2.4 Load Cases

The failure mechanisms, related to the structural integrity of the turbine’s components, can be treated separately. Their occurrence is determined by the set of external conditions that is considered during the design of the turbines. These conditions have to be looked at in terms of frequency and characteristic values. Together with the operational modes as stated in section 4.4.1, these conditions determine the load cases that have to be considered in the design process. A summary of the relevant load cases is presented in Table 2.4.

<table>
<thead>
<tr>
<th>F = Failure</th>
<th>Wind</th>
<th>Ice</th>
<th>Grid failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>U = Ultimate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Operational modes</strong></td>
<td>Normal</td>
<td>Extreme</td>
<td>Extra Gusts</td>
</tr>
<tr>
<td>Normal</td>
<td>Energy production</td>
<td>F</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>Start-up procedures</td>
<td>F</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>Stop procedures</td>
<td>F</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>Braked farming</td>
<td>F</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>Idle</td>
<td>F</td>
<td>U</td>
</tr>
<tr>
<td>Abnormal</td>
<td>Failures</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>Generator</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>short-circuit</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>Emergency situations</td>
<td>Activation of emergency systems</td>
<td>F</td>
<td>F,U</td>
</tr>
<tr>
<td></td>
<td>Resulting situations</td>
<td>F</td>
<td>F,U</td>
</tr>
<tr>
<td>Failed operation</td>
<td>Failed farming</td>
<td>F</td>
<td>F,U</td>
</tr>
<tr>
<td></td>
<td>Failed yawing system</td>
<td>F</td>
<td>F,U</td>
</tr>
<tr>
<td></td>
<td>Failed pitch mechanism</td>
<td>F</td>
<td>F,U</td>
</tr>
<tr>
<td></td>
<td>Failed control system</td>
<td>F</td>
<td>F,U</td>
</tr>
<tr>
<td>Other</td>
<td>Blocked state</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>Assembly</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>Special tests</td>
<td>U</td>
<td>U</td>
</tr>
</tbody>
</table>

*Table 2.4 Load Cases*
3 Failure Statistics

3.1 Stork and Comprimo Protech

For the simulation of the O&M, failure characteristics of several turbines were selected. The following tables give figures concerning non-resetable failures of the turbines.

<table>
<thead>
<tr>
<th>Part</th>
<th>Failure statistics in cases per year on shore</th>
<th>Time needed for repairs (hrs)</th>
<th>Crane needed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1</td>
<td>Type 2</td>
<td>Type 3</td>
</tr>
<tr>
<td>Rotors</td>
<td>0.33</td>
<td>0</td>
<td>0.44</td>
</tr>
<tr>
<td>Transmission</td>
<td>0.086</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>Regulator System</td>
<td>0.32</td>
<td>0.28</td>
<td>0.29</td>
</tr>
<tr>
<td>Steering System</td>
<td>0.085</td>
<td>0.17</td>
<td>0.22</td>
</tr>
<tr>
<td>Electrical System</td>
<td>0.415</td>
<td>0.09</td>
<td>0.37</td>
</tr>
<tr>
<td>Others</td>
<td>1.614</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>Total</td>
<td>2.85</td>
<td>3.5 - 0.4</td>
<td>1.33</td>
</tr>
</tbody>
</table>

Table 3.1 Failure Statistics Onshore [16]

Statistics of type 1 and 2 are based on limited number of turbines. It is expected that the frequency of failure can be reduced by feedback (changes in design after failure). This can already be seen at type 2 where the number decreases to 0.4 cases per year. Manufacturers indicate that many of the failures can be reset by remote control (80 - 90 %). Furthermore some of the failure mechanisms can be excluded by design improvements.

<table>
<thead>
<tr>
<th>Part</th>
<th>Expected failure statistics in cases per year offshore</th>
<th>Crane needed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1</td>
<td>Type 2</td>
</tr>
<tr>
<td>Rotors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regulator System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steering System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 3.2 Failure Statistics Offshore [16]

Resetable failures of the turbines are estimated to occur 12 times per year. Per failure this will lead to a average downtime of 6 hours. This downtime is based on the non-continues remote monitoring and the need for enough time for decision making.
3.2 The Netherlands Energy Research Centre (ECN)

<table>
<thead>
<tr>
<th></th>
<th>Events per turbine per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Failure</td>
<td>0.3</td>
</tr>
<tr>
<td>Major Failure</td>
<td>0.02</td>
</tr>
<tr>
<td>Minor Service</td>
<td>0.5</td>
</tr>
<tr>
<td>Major Service</td>
<td>0.25</td>
</tr>
<tr>
<td>Major Maintenance</td>
<td>0.25</td>
</tr>
<tr>
<td>Spare Parts</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Table 3.3 Failure Statistics Offshore [16]*

3.3 Opti - OWECs

In [4] the following figures are given with respect to failure rates of components. Hereby, it should be noted that the "Design Solution" is based on estimates of future failure rates that yet have to be met by manufacturers.

<table>
<thead>
<tr>
<th>Failure Classes</th>
<th>Base Case (events per year)</th>
<th>Design Solution (events per year)</th>
<th>Crane Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blades / Heavy Components</td>
<td>0.44</td>
<td>0.32</td>
<td>yes</td>
</tr>
<tr>
<td>Gearbox / Generator</td>
<td>0.14</td>
<td>0.14</td>
<td>no</td>
</tr>
<tr>
<td>Electronics / Control</td>
<td>0.29</td>
<td>0.11</td>
<td>no</td>
</tr>
<tr>
<td>Hydraulics</td>
<td>0.22</td>
<td>0.15</td>
<td>no</td>
</tr>
<tr>
<td>Electrical Systems</td>
<td>0.37</td>
<td>0.20</td>
<td>no</td>
</tr>
<tr>
<td>Others</td>
<td>0.33</td>
<td>0.10</td>
<td>no</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1.79</td>
<td>1.02</td>
<td></td>
</tr>
</tbody>
</table>

*Table 3.4 Failure Rates from [4]*

3.4 Design Regulations for Offshore Wind Farms

In this report [28] experiences with existing near- and offshore farms on are collected. Although turbine- and farm size are smaller than used in the base case of this thesis, the information on executed O&M is useful, because of the distinct offshore data. Typical failure frequencies named in the report are one to three minor or major failures and one or two visits for services or inspection per year. Based on experiences the following maintenance intervals are given:

- General maintenance requires two days with a crew of three, excluding transport of spare parts or consumables (e.g. oil)
- Extra inspections for about one day per year requiring two workers.
- On top of this one to three visits for major failures or damage.
Failures per turbine in the report are divided in the categories as in Fig. 3.1 and Fig. 3.2

**Fig. 3.1 Breakdown of Failures in Germany in [28]**

**Fig. 3.2 Breakdown of Failures in Denmark in [28]**
4 Design - Initial Capital Expenditure

In order to determine the relation between design and ICE, data is available from several feasibility studies [2,4,16 and 281]. First, abstracts of these studies with respect to cost of subsystems and components will be made.

4.1 Stork & Comprimo Protech

In feasibility study [16], the Initial Capital Cost and O&M cost are described for a 100 MW wind farm, consisting one hundred 1 MW turbines (or 82 × 1.2 MW), located at "De Vlakte van Raan". The distance between turbines is 8D, the total farm size is 6.5×3 km.

Overall ICC

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Cost</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine excluding support structure</td>
<td>681</td>
<td>Euro / kW</td>
</tr>
<tr>
<td>Foundation</td>
<td>536</td>
<td></td>
</tr>
<tr>
<td>Transport and Installation at sea</td>
<td>143</td>
<td></td>
</tr>
<tr>
<td>Electrical Infrastructure</td>
<td>199</td>
<td></td>
</tr>
<tr>
<td>Cost of Cable Installation</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>Cost of Soil Research</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Spare Parts</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Design, Administration and Supervision</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1790</strong></td>
<td>Euro / kW</td>
</tr>
</tbody>
</table>

Additional data

- Cost of O&M: 3.83 Mln Euro/yr
- Energy Yield at 100% farm efficiency: 303 GWh/yr
- Farm Efficiency: 94%
- Electrical Losses: 2%
- Availability of OWECs: 90.5%
- Availability of Electrical Infrastructure: 98.5%
- Interest: 4%
- Internal Rate of Return: 15%
- Economic Lifetime: 15 years

From these data, the total energy yield will be 249 GWh/yr. In this calculation the dismantling cost and cost for expansion of the shore based electrical net are left out of consideration.

A number of design changes and their effect on the LPC, are investigated in this study, they are summarised below:

- When the distance between the turbines in the farm is increased from 8D to 10D, the length of the MV net increases with about 9 km. This adds 0.73 Mln Euro to cost of electrical infrastructure and 2.27 Mln Euro to installation cost of the cables. The farm efficiency increases with 3%. This change in layout will however increase the required space by 45%.

- Installing two cables in stead of one in the HV net increases the availability with 0.87%. The extra cost of this infrastructure and its installation are estimates at 17.8 Mln Euro

- Redundancy in the MV net can consist of connections between individual strings of this net. In [4] this estimated to require 2400 m of extra MV cable, leading to 0.74 Mln Euro extra cost, an increase in availability of 0.42%.
4.2 The Netherlands Energy Research Centre (ECN)

This study examines large scale, one and five GW, farms. Here, concrete caisson piles are used at a location 100 km offshore, in combination with 3 MW turbines and HVDC transport to shore. Since this farm design was not state of the art at the time the report was written, prices are (extrapolated) estimates. Furthermore, this design shows great differences with the base case in this thesis, so care should be taken when using figures from this report.

When costs of electrical infrastructure for the base case of this thesis are calculated with data from the report this leads to:

For material:
- Drilling operation = 2.31 Mln Euro
- Glass-fibre connection = 0.26 "
- Cable to shore = 410 Euro/m AC cable·8000 m = 3.27 "
- Cable between units = 81 Euro/m·600 m/unit·40 units = 1.95 "
- Transformer / Grid connection\(^1\) = 22.7 Mln Euro per GW·0.1 GW = 2.27 "
- MV system\(^1\) = 40000 Euro/MW·100 MW = 4.00 "
- Others = 0.86 "

\(^1\) Including installation

For installation:
- Cable to shore = 270 Euro/m·8000 m = 2.18 Mln Euro
- Cable between units = 195 Euro/m·600 m/unit·40 units = 4.68 "
- Others = 2.72 "

TOTAL = 24.5 Mln Euro

Breakdown of ICE:

<table>
<thead>
<tr>
<th>Component</th>
<th>1 GW farm</th>
<th>5 GW farm</th>
<th>Economies of Scale %</th>
<th>100 MW Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min Euro and Euro / kW</td>
<td>Min Euro and Euro / kW</td>
<td></td>
<td>Min Euro and Euro / kW</td>
</tr>
<tr>
<td>Turbine Purchase</td>
<td>355</td>
<td>1780 - 355</td>
<td>0</td>
<td>36(^1) - 360</td>
</tr>
<tr>
<td>Turbine Installation</td>
<td>20</td>
<td>101 - 20</td>
<td>0</td>
<td>2(^1) - 20</td>
</tr>
<tr>
<td>Foundation Purchase</td>
<td>182</td>
<td>907 - 181</td>
<td>1</td>
<td>18(^1) - 180</td>
</tr>
<tr>
<td>Foundation Installation</td>
<td>343</td>
<td>1702 - 340</td>
<td>1</td>
<td>34(^1) - 340</td>
</tr>
<tr>
<td>Electrical Infrastructure Purchase</td>
<td>417</td>
<td>1400 - 280</td>
<td>33</td>
<td>15(^2) - 149</td>
</tr>
<tr>
<td>Electrical Infrastructure Installation</td>
<td>24</td>
<td>82 - 16</td>
<td>33</td>
<td>10(^2) - 96</td>
</tr>
<tr>
<td>Total</td>
<td>1343</td>
<td>5974</td>
<td>11</td>
<td>115</td>
</tr>
</tbody>
</table>

Initial Capital Expenditure per Installed kW (Euro)

| | 1343 | 1194 | 1145 |

*Table 4.1 Breakdown of ICE in [2]*
The economies of scale used for the electrical infrastructure do not hold for the base case of this thesis. This due to the fact that the choice between either DC or AC networks depends on the distance to shore with a breakeven point at 60 km, above which DC current is preferred.

![AC versus DC networks](image)

*Fig. 4.1 AC versus DC networks*

As a certain cable diameter can only carry a certain amount of current, the voltage level chosen determines the maximum amount of power to be transported. In Table 5.2 an overview is given of the maximum power rating as a function of cable diameter and voltage level, for commonly used cables.

<table>
<thead>
<tr>
<th>Conductor Diameter (mm²)</th>
<th>Current Carrying Capacity (A)</th>
<th>Voltage Level values based on aluminium conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6 kV</td>
</tr>
<tr>
<td>185</td>
<td>415</td>
<td>5 MVA</td>
</tr>
<tr>
<td>400</td>
<td>710</td>
<td>7 MVA</td>
</tr>
<tr>
<td>800</td>
<td>1040</td>
<td>11 MVA</td>
</tr>
</tbody>
</table>

*Table 4.2 Rated power as function of cable diameter and voltage*

For the 2.5 MW turbines used in the base case, the number of turbines that can be connected to one cable given the diameter and voltage level, is given in Table 5.3.

<table>
<thead>
<tr>
<th>Cable Diameter (mm²)</th>
<th>Voltage Level Chosen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 kV</td>
</tr>
<tr>
<td>185</td>
<td>3</td>
</tr>
<tr>
<td>400</td>
<td>4</td>
</tr>
<tr>
<td>800</td>
<td>8</td>
</tr>
</tbody>
</table>

*Table 4.3 Number of turbines to be connected to one cable*

Especially at sea, the cost of the cables is mainly determined by the cost of laying them, so it is most economical to opt for the 800 mm cables. This way more turbines can be connected to one string, saving on investment cost per installed kW.
4.3 Opti - OWECS report

In the scope of the framework of the Non Nuclear Energy Programme JOULE III, the European Commission supported the project "Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters" (Opti-OWECS). The aim of the project was to extend the state of the art, to determine required methods and to demonstrate practical solutions, which significantly reduced the electricity cost. All design choices are therefore related to come to an overall optimum design.

A program was written in this study to simulate to O&M of the OWECS during its lifetime, following the state of each component of the wind farm over the consecutive time steps. This shows extensive information on O&M cost in relation to availability and the LPC.

Cost breakdown of design solution for an economic lifetime of 20 years an 5 % real interest rate:

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Cost Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Turbine Cost</td>
<td>170 Min Euro - 567 Euro / kW</td>
</tr>
<tr>
<td>Support Structure and Installation Cost</td>
<td>118 Min Euro - 393 Euro / kW</td>
</tr>
<tr>
<td>Offshore Grid Connection Cost</td>
<td>77 Min Euro - 257 Euro / kW</td>
</tr>
<tr>
<td>Project Management Cost</td>
<td>2 % of Total Capital Cost</td>
</tr>
<tr>
<td>Total Capital Cost</td>
<td>372 Min Euro - 1240 Euro / kW</td>
</tr>
<tr>
<td>Decommissioning Cost</td>
<td>10 % of Initial Capital Cost</td>
</tr>
</tbody>
</table>

*Table 4.4 Breakdown of ICE in [4]*
4.4 Conclusions on Design - ICE

From the data in the abstracts, on the relation between design and ICC can be concluded that the main cost drivers of ICE are:

**1 GW park**

- Turbine Purchase: 26%
- Foundation Installation: 26%
- Turbine Installation: 23%
- Foundation Purchase: 1%
- Electrical Infrastructure Purchase: 1%
- Electrical Infrastructure Installation: 14%

**5 GW park**

- Turbine Purchase: 28%
- Foundation Installation: 31%
- Turbine Installation: 23%
- Foundation Purchase: 1%
- Electrical Infrastructure Purchase: 15%
- Electrical Infrastructure Installation: 2%

**100 MW Base Case**

- Turbine Purchase: 30%
- Foundation Installation: 31%
- Turbine Installation: 13%
- Foundation Purchase: 6%
- Electrical Infrastructure Purchase: 2%
- Electrical Infrastructure Installation: 2%

*Fig. 4.2 Breakdown of ICE in [2]*

This shows that the contribution of electrical infrastructure cost to the ICE, decreases significantly with a decrease in the distance to shore. Given the location, the use of DC networks brings cost advantages with increasing farm size, which does not hold for AC networks. Main cost drivers appear to be the purchase of the turbines and support structure and installation of the latter.

*Fig. 4.3 Breakdown of ICC in [16]*

These data from Stork & Comprimo Tech support the conclusions of the ECN report. Again showing turbines and support structure as main cost drivers.
The Opti-OWECS design solution shows about the same; 21% of ICC cost from electrical grid vs. 22% by Stork - Comprimo Protech and ECN. The increased share of turbine cost in the Opti-OWECS solution is probably due to the higher emphasis on reliability e.g. availability which is considered as an important factor to keep the LPC low.

![Breakdown of ICC in [4]](image)

Putting all pies together, the following trends can be observed from Fig. 4.5. One should keep in mind that in the Stork & Comprimo Protech and the Opti OWECS report no explicit split up between cost of foundation purchase and installation was made. The different distribution this gives within the total cost of the foundations shall therefore be neglected.

<table>
<thead>
<tr>
<th></th>
<th>with ECN data 100 MW</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Stork &amp; Comprimo Protech 100 MW</td>
<td>80%</td>
</tr>
<tr>
<td>3</td>
<td>Opti-OWECS 300 MW</td>
<td>60%</td>
</tr>
<tr>
<td>4</td>
<td>ECN 1 GW</td>
<td>40%</td>
</tr>
<tr>
<td>5</td>
<td>ECN 5 GW</td>
<td>20%</td>
</tr>
</tbody>
</table>

![Trends in ICE](image)

The average Total Initial Capital Expenditure per installed kW wind farm according to the different studies is 1340 Euro / kW.

Because of the differences in calculation e.g. no division between turbine and foundation cost or grouping of purchase and installation cost, a breakdown of the ICE into cost of purchase and installation of subsystems is a matter of interpretation.

An approximation of cost parameters with respect to design is given below:

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Parameters</th>
<th>Effect on ICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbines</td>
<td>Farm Size (in kW)</td>
<td>600 Euro / kW</td>
</tr>
<tr>
<td>Foundation</td>
<td>Turbines Size</td>
<td>450 Euro / kW</td>
</tr>
<tr>
<td>MV - network</td>
<td>Number of Turbines, Farm spacing</td>
<td>300 Euro / m</td>
</tr>
<tr>
<td>HV - network</td>
<td>Distance to Shore</td>
<td>700 Euro / m</td>
</tr>
<tr>
<td>Transformer</td>
<td>Transformation Capacity</td>
<td>23 Euro / kW</td>
</tr>
</tbody>
</table>

*Table 4.5 Cost Parameters of ICE*

These figures give an indication of the ICE for the current (January 2000) state of the art farm design, they vary with technological progress and are limited to DC current networks.

Because these prices vary to much with time and per contract, they will be subject of the input in a simulation, in order to calculate and optimise the systems LPC with respect to O&M cost. The figures above can be used for a first approximate when farm size and location are know.
5 Operations, Maintenance and Cost

5.1 Stork and Comprimo Protech

Maintenance costs in this report are based on a strategy, in which one or more crew maintenance crews are standby and perform preventive maintenance. The cost of O&M and availability for different scenarios are estimated by [16] as:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Farm Maintenance (Mln Euro/yr)</th>
<th>Availability (%)</th>
<th>Number of Crews</th>
<th>Cranes Needed (days/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimistic(^1)</td>
<td>1.52</td>
<td>93</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Pessimistic(^2)</td>
<td>2.51</td>
<td>88</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Alternative (^3)</td>
<td>1.68</td>
<td>93</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Alternative (^4)</td>
<td>3.29</td>
<td>85</td>
<td>3</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 5.1 O&M scenarios from [16]

\(^1\) Optimistic estimate of manufacturers
\(^2\) Pessimistic estimate of manufacturers
\(^3\) High maintenance frequency (twice a year)
\(^4\) Conservative schedule based on literature

This leads to an average yearly maintenance cost on the turbine, estimated by the manufacturers of 2.02 Mln Euro and an availability of 90.5% for the 100 MW farm. Further obligatory maintenance on the support structure is estimated to cost 1.63 Mln Euro, based on a 5 yearly inspection, thus 20 OWECs per year, including all work on support structure plus equipment (e.g. shore base).

Availability and O&M costs on the electrical infrastructure are estimated to be respectively 98.5% and 0.17 Mln Euro. This is based on two repairs in the MV net per year and one in the HV net every 12 years. Total maintenance cost are thus estimated to be 3.83 Mln Euro/yr.

The average costs per failure or inspection in this report are:

<table>
<thead>
<tr>
<th>Event</th>
<th>Cost per Event (Euro)</th>
<th>Downtime per Event (in hrs exc. inaccessibility)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Failure</td>
<td>73 000</td>
<td>48</td>
</tr>
<tr>
<td>Minor Failure</td>
<td>4 300</td>
<td>24</td>
</tr>
<tr>
<td>Resetable Failure</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Major Overhaul</td>
<td>22 000</td>
<td>40</td>
</tr>
<tr>
<td>Overhaul</td>
<td>4 300</td>
<td>8</td>
</tr>
<tr>
<td>Minor Overhaul</td>
<td>2 200</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 5.2 Cost and Downtime of Maintenance
A survey among manufacturers shows the following figures for maintenance cost per turbine per year:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Maintenance Cost Onshore</th>
<th>Estimated Extra Cost Offshore Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nedwind</td>
<td>6353</td>
<td>4538</td>
</tr>
<tr>
<td>Lagerwey</td>
<td>15882</td>
<td>13613</td>
</tr>
<tr>
<td>Windmaster</td>
<td>5672</td>
<td>4538</td>
</tr>
<tr>
<td>Average</td>
<td>9302</td>
<td>7563</td>
</tr>
</tbody>
</table>

*Table 5.3 O&M Cost from Manufacturers [16]*

For repairs in the electrical infrastructure the data below are given in [16]:

<table>
<thead>
<tr>
<th>Event</th>
<th>Cost per Event (Euro)</th>
<th>Downtime per Event (in hrs exc. inaccessibility)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broken Cable</td>
<td>210 000</td>
<td>336 (14 days)</td>
</tr>
<tr>
<td>Transformer Failure</td>
<td>39 000</td>
<td>408 (17 days)</td>
</tr>
<tr>
<td>Failure of MV or HV Field</td>
<td>20 000</td>
<td>96 (4 days)</td>
</tr>
</tbody>
</table>

*Table 5.4 O&M Cost of Electrical Infrastructure*

Cost of transport is estimated at 6807 Euro per day, cost of diving teams and equipment at 11344 Euro per day.

### 5.2 The Netherlands Energy Research Centre (ECN)

Annual O&M cost are also calculated in this report. For the mono-pile foundations the annual inspection and maintenance cost are estimated at 3600 Euro, the same amount is needed for five yearly certification, 6800 Euro for the five yearly major overhaul and 900 Euro is reserved for vandalism. All amounts are per turbine. In their base case, the caisson pile foundations are chosen because it is assumed that they are free of major overhauls.

With respect to the turbine, the O&M cost are calculated as:

<table>
<thead>
<tr>
<th>Event</th>
<th>Cost per Event (Euro)</th>
<th>Cost per Turbine per year (Euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Failure</td>
<td>4300</td>
<td>1300</td>
</tr>
<tr>
<td>Major Failure</td>
<td>72600</td>
<td>1500</td>
</tr>
<tr>
<td>Minor Service</td>
<td>2200</td>
<td>1100</td>
</tr>
<tr>
<td>Major Service</td>
<td>4300</td>
<td>1100</td>
</tr>
<tr>
<td>Major Maintenance</td>
<td>21800</td>
<td>5400</td>
</tr>
<tr>
<td>Spare Parts</td>
<td></td>
<td>3800</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>14200</strong></td>
</tr>
</tbody>
</table>

*Table 5.5 O&M cost from [2]*

Failures in the electrical network are expected to occur 0.004 times per year per km HV cable and 0.012 times for MV cables, adding 210 000 respectively 20 000 Euro to the O&M cost per failure.
This leads to a breakdown of the total O&M cost as given in Table 6.6.

<table>
<thead>
<tr>
<th>Component</th>
<th>1 GW Farm</th>
<th>5 GW Farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundations</td>
<td>2800</td>
<td>13800</td>
</tr>
<tr>
<td>Turbines</td>
<td>4800</td>
<td>24800</td>
</tr>
<tr>
<td>Electrical Infrastructure</td>
<td>1200</td>
<td>6100</td>
</tr>
<tr>
<td>Others</td>
<td>2300</td>
<td>11300</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>11200</td>
<td>55000</td>
</tr>
<tr>
<td><strong>O&amp;M Cost per kW per year (Euro)</strong></td>
<td>11.2</td>
<td>11.0</td>
</tr>
</tbody>
</table>

*Table 5.6 Breakdown of O&M cost [16]*

### 5.3 Opti - OWECs

The cost of O&M are in this report calculated by running a simulation of the system. Input into the simulation consists of hourly wages, crew size and costs of lifting and transport etc. O&M tasks can only be executed when the system is accessible e.g. current sea state is "no storm"; a Monte Carlo simulation on a Weibull distributions of "storm" and "no storm" periods is used.

Data on failure rates and cost of O&M operations are derived from existing turbines, supplemented with engineers' expectations. Different categories of corrective maintenance are defined, ranging from 4 to 48 hours for the classes "others" and class "Gearbox / Generator / Yaw" respectively. The yearly O&M cost are estimated at 30 000 Euro per turbine per year.

Preventive maintenance hours used in the simulation are of a low maintenance strategy, which is concluded in [4] to minimise the LPC. These hours are:

- Blades 5.5 Man hours per year
- Pitch System 7.2
- Drive Train 5
- Electric System 1
- Yaw System 6.2
- Hydraulic System 2
- Fire Protection System 4
- Others 5

Preventive Maintenance assumptions are:
- PM is scheduled once a year and takes 16 hrs
- Large five yearly PM takes 28 hrs

### 5.4 Design Regulations for Offshore Wind Farms

In this report [28] experiences with existing near- and offshore farms on are collected. Although turbine- and farm size are smaller than used in the base case of this thesis, the information on executed O&M is useful, because of the distinct offshore data.
Typical failure frequencies named in the report, are one to three minor or major failures and one or two visits for services or inspection per year. Based on experiences the following maintenance intervals are given:

- General maintenance requires two days with a crew of three, excluding transport of spare parts or consumables (e.g. oil)
- Extra inspections for about one day per year requiring two workers.
- On top of this one to three visits for major failures or damage.

Further maintenance, mainly corrective, is mentioned in [28] for single turbines. Unless stated otherwise, these maintenance tasks are executed by a crew of two:

<table>
<thead>
<tr>
<th>Maintenance Task</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Inspection</td>
<td>2 days per year, crew of 3</td>
</tr>
<tr>
<td>Minor Inspection</td>
<td>1 day per year</td>
</tr>
<tr>
<td>Supervision</td>
<td>2 times per year</td>
</tr>
<tr>
<td>Divers' Inspection</td>
<td>2 days per year</td>
</tr>
<tr>
<td>Minor Repairs</td>
<td>4 hours per year</td>
</tr>
<tr>
<td>Gear replacement or exchange</td>
<td>3 days (crew of 3)</td>
</tr>
<tr>
<td>Generator</td>
<td>3</td>
</tr>
<tr>
<td>Blades</td>
<td>5</td>
</tr>
<tr>
<td>Transformer</td>
<td>3</td>
</tr>
<tr>
<td>Oil (from gear)</td>
<td>1</td>
</tr>
</tbody>
</table>

Workability limits are also stated in this report. An overview is given in table 6.7

<table>
<thead>
<tr>
<th>Limit Formed By</th>
<th>Access with</th>
<th>Tasks on Turbine</th>
<th>Diver Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vessels</td>
<td>Helicopter</td>
<td>Normal Transport</td>
</tr>
<tr>
<td>Length (m)</td>
<td>4-6</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.5</td>
<td>30</td>
</tr>
<tr>
<td>DWT (t)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.5</td>
<td>30</td>
</tr>
<tr>
<td>Pull (kN)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Wave Height (m)</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Wave Period (s)</td>
<td>2.5</td>
<td>3.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Min. Temperature (°C)</td>
<td>-15</td>
<td>-15</td>
<td>-15</td>
</tr>
<tr>
<td>Visibility (m)</td>
<td>1000</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Lightning (hits per km²)</td>
<td>&gt;0</td>
<td>&gt;0</td>
<td>&gt;0</td>
</tr>
<tr>
<td>Rain / Snow (mm/hr)</td>
<td>10/50</td>
<td>10/50</td>
<td>10/50</td>
</tr>
<tr>
<td>Current (m/s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water depth (m)</td>
<td>0.5</td>
<td>1.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 5.7 Workability Limits
5.5 Conclusions on Operations, Maintenance and Cost

In [2] and [16] a deterministic approach of O&M cost is chosen in order to give a first estimate of these cost and of their contribution to the LPC. These approaches each assume a standard average duration for O&M tasks as well as equipment cost e.g. day rates. These approaches do not suffice in a more detailed description as intended here.

The approach in [4] uses hourly wages, crew data and yearly fixed cost of equipment. This gives a minimum LPC as long as a large number of visits to the turbines are required. Whether equipment should be bought or rented, will however not only depend on the number of visits and relative cost, but also on constructed deals with manufacturers, owners or fellow users of the equipment.

A simulation should thus provide the possibilities to use different O&M strategies with respect to equipment choice and financing. Furthermore, cost of spare parts and stock keeping will vary per location and turbine. These will thus also be part of the input for a simulation. Since wages will also vary widely per strategy (permanent crew, hired crew on lump sum or day rate basis) they will be subject of input to the simulation as well.

The duration of the different O&M tasks, excluding transport and waiting on weather, is more or less given. These are the workable hours needed to replace or repair components. Workable hours are limited as given in table 5.7 and thus depend on equipment choice. Within these limits the hours needed for different O&M tasks are:

<table>
<thead>
<tr>
<th>Corrective Maintenance Events</th>
<th>Repair or Replacement Time (hrs / days)</th>
<th>Crane Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Failure</td>
<td>48 / 2</td>
<td>yes</td>
</tr>
<tr>
<td>Minor Failure</td>
<td>24 / 1</td>
<td>no</td>
</tr>
<tr>
<td>Resetable Failure</td>
<td>6 / 0.25</td>
<td>no</td>
</tr>
<tr>
<td>Broken Cable</td>
<td>336 / 14</td>
<td>no</td>
</tr>
<tr>
<td>Transformer Failure</td>
<td>408 / 17</td>
<td>no</td>
</tr>
<tr>
<td>Failure of MV or HV field</td>
<td>96 / 4</td>
<td>no</td>
</tr>
</tbody>
</table>

*Table 5.8 Duration of Corrective Maintenance*

<table>
<thead>
<tr>
<th>Preventive Maintenance Events</th>
<th>Duration (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly Maintenance</td>
<td>16</td>
</tr>
<tr>
<td>Five Yearly Maintenance</td>
<td>28</td>
</tr>
<tr>
<td>Major Overhaul Turbine</td>
<td>40</td>
</tr>
<tr>
<td>Overhaul Turbine</td>
<td>8</td>
</tr>
<tr>
<td>Minor Overhaul Turbine</td>
<td>4</td>
</tr>
</tbody>
</table>

*Table 5.9 Duration of Preventive Maintenance*

Of course these times can also vary with turbine design and will thus as well be subject of input into the simulation.
6 Sensitivity Analyses of LPC from Model Schöntag

The sensitivity of the energy cost to changes in the economic conditions, cost of subsystems and the overall energy production has been investigated [4]. Results are shown here to give a first impression of the relative importance of several parameters, and to determine which parameters should or should not be taken into account in further research or simulation. This study was performed in a simple fashion, by changing values of one parameter and observing the effect on the overall energy cost. Derivative effects are thus not taken into account.

6.1 Economic Parameters

These consist of the economic lifetime of the system or repayment period, and the real interest rate. The manner in which the LPC vary with both parameters is given in Fig. 6.1. The levelised production costs are based on an annual wind speed of 8.4 m/s at 60 m hub height.

Fig. 6.1 LPC versus Discount Rate

6.2 Parameters Energy Yield and Cost Drivers

These parameters are varied under the assumption of a 20 year economic lifetime and a 5 % real interest rate. Energy costs are normalised to a reference value of 5.1 Euro cent/kWh. Clearly, a change in energy production will have the most effect on the LPC, as it is part of the denominator in both parts of the LPC formula. Sensitivity to changes in cost of subsystems correspond to their contribution in the initial capital cost.

Fig. 6.2 LPC versus Energy Yield, ICC and O&M Cost
Two conclusions can be drawn from this.

- The sensitivity of the energy cost to the energy production means that great care must be taken in estimating its value for a proposed OWECS site. Relative small errors in energy yield predictions will be magnified into comparative large errors in predicted LPC. In order to improve these predictions, both a reliable wind model and O&M simulation a necessary.

- The economics of wind energy can be improved by increasing produced energy. Large investments in design cost can be tolerated in order to achieve this. For example a 10% increase in energy production would be economically worthwhile even with an increase in the turbine cost of approx. 30%. Striving for further reduction of subsystem cost appears less attractive too. Even though the turbine is the subsystem with the greatest influence on the LPC, a reduction of 10% would only bring a 5% reduction of the energy cost.

6.3 Parameter Study Based on the Opti-OWECS Cost Model

The cost model has been employed to perform integrated studies, on the influence that variations in the value of certain parameters have on the LPC of the design solution OWECS in [4]. Unlike in the previous section, these calculations do attempt to take derivative effects into account. Of course this only holds to the extent the cost model simulates the effects. Interactions that are of particular importance in this section are:

- Dependency of availability and O&M cost on both mean annual wind speed and distance from shore.
- Effect of distance from shore on power transmission costs, electrical energy losses, availability and O&M cost.
- Dependencies of energy yield and power collection cost on turbine spacing.

No parameters with main impact on the support structure design, e.g. water depth or hub height, have been investigated since the relation between such parameters and governing criteria i.e. fatigue loading is far too complex for the cost model. As a consequence, any analysis of other parameters related to extreme loading has not been performed, since no sensitivity can be expected in such a case.

The results are considered on a parameter-by-parameter basis.
6.3.1 Mean annual wind speed

The annual mean wind speed, one of the most important parameters for the economics of a wind farm, has been investigated under the assumption that rated wind speed, power rating and reliability of the turbines are not changed, which in reality would be the case.

In Fig. 6.3 the normalised energy cost is given as a function of the annual mean wind speed. At first sight it is surprising that the energy cost rise again for mean wind speeds above 10 m/s.

The yearly energy yield indeed rises with increasing speed, although it flattens for very high mean wind speeds, as the rated wind speed remained the same. The fact that energy cost rise for very high wind speeds is due to decreased accessibility. This again illustrates the importance of a good O&M strategy.

![Fig. 6.3 LPC versus mean annual Wind Speed](image)

6.3.2 Distance from shore

Another parameter with a strong effect on the LPC is the distance to shore. Both the transmission cable costs as the electrical losses increase with the distance to shore. Furthermore, the availability of the turbines will drop because the increased duration of O&M tasks. For large distances, 50 to 60 km to shore, it becomes interesting to consider DC transmission as shown in Fig. 4.1

![Fig. 6.4 LPC versus distance to shore](image)
6.3.3 Size of wind farm

In most studies on offshore wind energy it is stated that wind farms will be economically attractive for large farms only. Fig. 6.5 also leads to this conclusion. Although series effects are only partly considered, the costs increase strongly for small farms due to large expenses for the power transmission and O&M infrastructure. For the specific case in [4] can be seen that not much can be gained in this respect with farms consisting of more than 100 units.

![Diagram](image)

*Fig. 6.5 LPC versus number of OWEC's*

The shape of the curve can be explained by looking at the build up of the LPC. A part of the ICC remains constant when increasing the number of turbines in the farm. This part will become increasingly important for small numbers of turbines and for large numbers of turbines its effect will fade. The 100 turbines mentioned above, or the 300 MW installed power they represent, are thus by no means absolute but are determined by relative cost of subsystems and how they vary with park size. This will differ for each farm.
6.3.4 Spacing ratio

Increase in turbine spacing will have a positive effect on the farm efficiency due to decreased wake effects, but investment cost will increase because of the longer cables. Furthermore, increased cable length will increase failure probability and can thus lead to a lower availability. For the design solution used in [4] it turns out that the optimum, leading to the lowest LPC, is found with a spacing of 12 rotor diameters.

Fig. 6.6 Energy Yield en Grid Cost versus Wind Farm Spacing Ratio

Fig. 6.7 LPC versus Farm Spacing
7 Turbine Description

Each turbine consists in its turn of:

- **Rotors**, The Nordex N80/2500 kW wind turbine has a rotor diameter of 80 m and a swept area of 5026 m². The rotor consists of three blades, the hub, turntables, and drives to change the blade pitch, designed with a fourfold redundancy. The rotor blades are made of glass-fibre reinforced polyester. The turbine has two independent braking systems. The primary brake system is the aerodynamic brake formed by the pitch system, which functions fail-safe. The pitch adjustment is done independently on each blade. A backup system is available for the blade pitch, as in case of a voltage drop energy storage devices are activated to swivel the blades perpendicular to the direction of rotation. The blades are equipped with a lightning protection system including a lightning receptor deflecting the lightning to the rotor hub.

- **Nacelle**, which includes a.o.:
  - **Main shaft**: The drive train consists of the rotor, shaft, the gearbox connected by a shrink-fit coupling, an elastic cardanic coupling, and the generator. The main shaft is manufactured in alloy steel. It has a three point support, with a solid plunger block spherical roller bearing, supporting the shaft at the rotor in order to absorb the rotor thrust. In the gearbox, the shaft is supported by two cylindrical roller bearings and the gearbox unit again rests on two supports.

- **Gearbox**: The N80 uses a two-stage planetary gearbox. The gearbox is fitted in two rubber bushings in order to dampen the noise and load peaks. The gearbox is cooled through an air-oil heat exchanger. The bearings are constantly splash lubricated. Monitoring of the oil temperature ensures that the oil reaches its optimum temperature, and at the same time is kept constantly at the optimum temperature.

- **Generator**: The generator is a double fed asynchronous machine with a nominal power of 2500 kW. The generator is designed for insulation class F but is only operated to class B. The generator uses liquid cooling to control operating temperature, which prolongs the lifetime of the generator considerably.

- **Yaw system**: The active yaw system, which enables the wind turbine to be positioned correctly in the wind, is a ball-bearing type. Two geared motors do the yawing of the turbine. The yaw brake consists of a large disk brake, activated by hydraulic brake calibres. Furthermore, each yaw gear has a separate brake built into the fast stage. The nacelle is fixed when the yawing is inactive. In this way there is no load on the yaw gears and drives, when the turbine is not yawing. Two mutually independent wind vanes give signals to the master computer, which controls the yawing procedure of the turbine. The system ensures that the turbine is positioned correctly in the wind at all times, thereby resulting in the optimal power production and minimum stress on the turbine drive train.
- **Brake system**: The Nordex N80/2500kW turbine has two independent braking systems. The primary system is the pitch system and the secondary system is the mechanical disk brake system, which is located on the high-speed shaft of the gearbox. Both systems function fail-safe. The pitch adjustment is done independently and redundantly on each blade. A backup system is available for the blade pitch, as in case of a voltage drop energy storage devices are activated to swivel the blades perpendicular to the direction of rotation.

- The **mechanical brake system** exerts a torque equivalent to 1.2-times the nominal torque. The brake supports the braking by the rotor blades and brings the rotor to halt. The mechanical brake is also used to secure the rotor for engineering and maintenance. When the rotor is slowed down to a certain speed via the pitch mechanism, the mechanical disk brake system is activated and the turbine is brought to a standstill. The Nordex wind turbines use a soft braking system on the mechanical brake. This means that the braking torque is controlled according to a rampload-function, which reduces the strain on the drive train. In this way the risk of pitting of the gearbox is minimised, and at the same time the torque in blades and drive train is reduced. During emergency braking both the aerodynamic and mechanical braking systems are activated simultaneously.

- **Tower**: The Nordex N80/2500 kW wind turbine can be delivered with a conic-shaped steel tower with various hub heights. The tower is equipped with internal ladder, safety wire, working platforms and light fixtures. The climbing to the nacelle is from the inside of the tower. The painting and corrosion protection is in accordance with ISO 12944 Class 5. The tower is equipped with a lightning protection. With the gradual increase in wind turbine tower height, the risk that the turbine could be hit by a lightning also increases. The lightning protection system of the Nordex N80/2500 kW wind turbine is designed according to the IEC-1024-1 standard. If a lightning strikes the turbine blade or the nacelle, the protection system will safely lead the lightning current to the wind turbine earthing system, with minimal risk of damage to any part in the turbine. The electrical and electronic components in the turbine are protected by means of varistors, and the turbine internal communication is performed via optical fibre technique, which is immune to voltage peaks.

- **Foundation**: In previous feasibility studies (2,4,16) several options for the foundation of the tower structure have been taken under consideration. The choice will depend on the local circumstances such as water depth, ground parameters, waves and current. In general the tower structure and its belongings do not generate enough weight to make a caisson foundation effective. Some new foundation techniques are being proposed but under the offshore circumstances, a proven and reliable technique like a mono pile foundation is the preferred one. Given the experience with even far larger offshore foundations the probability that failure herein causes downtime can be neglected. The foundation will require maintenance however.
8 Production Curve

The fundamental relation between wind speed and available power showed that the available power is directly proportional to wind speed to the third power:

$$P_0 = \frac{1}{2} \rho A V^3$$

The minimum power needed to start the rotor in the generator limits the production of the turbine at low wind speeds. At high wind speeds the production is limited by the maximum rotor speed and maximum generator capacity. With these limits the basic shape of the production curve becomes:

In reality the pitch system will gradually start the system up at minimum wind speed and slow the rotor down when maximum production capacity is reached, by gradually catching more res. less wind.

For the Nordex N80 turbine this has led to the following production curve, which is derived from a data set of wind speeds and the turbine’s production.

Fig. 8.1 From Energy Potential to Production Curve

To prevent having to interpolate between given data points in a simulation, which is time consuming, a production function can be used.

Fig. 8.2 Nordex N80 Power Curve
The production function should of course match the actual production function to give a correct representation of the energy yield. This especially at wind speeds with a high energy potential. A function that fits well was found in:

\[
P(V) = \begin{cases} 
0 & \text{if } V < V_{\text{cut-in}} \\
\frac{P_{\text{rated}}}{1 - \exp \left( - \left( \frac{V}{\delta} \right)^\gamma \right)} & \text{if } V_{\text{cut-in}} \leq V < V_{\text{rated}} \\
\frac{P_{\text{rated}}}{V_{\text{rated}}} & \text{if } V_{\text{rated}} \leq V < V_{\text{cut-out}} \\
0 & \text{if } V \geq V_{\text{cut-out}}
\end{cases}
\]

with
- \( V \) = Wind speed in m/s
- \( P \) = Power in kWh
- \( \gamma \) = Logarithmic base shape parameter \( [\cdot] \)
- \( \delta \) = Characteristic production wind speed in m/s

In Fig. 8.2 the production function is fitted over the given production curve by changing parameters \( \gamma (= 4.1) \) and \( \delta (= 10.75) \). Further parameters are:

- \( V_{\text{cut-in}} = 3.5 \text{ m/s} \)
- \( V_{\text{rated}} = 13.5 \text{ m/s} \)
- \( V_{\text{cut-out}} = 25 \text{ m/s} \)
- \( P_{\text{rated}} = 2500 \text{ kWh} \)

The turbine uses its full capacity at wind speed higher than rated speed. Together with other parameters the rated speed is a design choice that will be adapted to a chosen location. This to fit the turbine’s performance characteristic to the local wind conditions, optimising the number of hours the turbine can produce at rated power.
The expected number of hours at which the turbine can operate at full capacity can be determined by dividing the expected energy yield per year at 100% availability by the rated power of the turbine thus:

\[
\text{Hours}_{\text{rated-power}} = \frac{\int_{V_{\text{cut-out}}}^{V_{\text{cut-in}}} f(V) \cdot p(V) \, dV}{\sum_{i=1}^{n} \left[ F(V_i) - F(V_{i-1}) \right] \cdot p(V)} = \frac{826233}{2500} \approx 3305
\]

For the Nordex N80 this results in 3305 production hours per year at rated power, see Table 8.1

<table>
<thead>
<tr>
<th>Wind speed V.</th>
<th>Produced Power</th>
<th>(F(V_i + 0.5) - F(V_i - 0.5))</th>
<th>Produced Power (\ast (F(V_i + 0.5) - F(V_i - 0.5)))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>0.07190</td>
<td>9454</td>
</tr>
<tr>
<td>5</td>
<td>105</td>
<td>0.08530</td>
<td>78515</td>
</tr>
<tr>
<td>6</td>
<td>253</td>
<td>0.09387</td>
<td>208196</td>
</tr>
<tr>
<td>7</td>
<td>438</td>
<td>0.09719</td>
<td>373193</td>
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<tr>
<td>8</td>
<td>676</td>
<td>0.09546</td>
<td>565702</td>
</tr>
<tr>
<td>9</td>
<td>984</td>
<td>0.08939</td>
<td>771072</td>
</tr>
<tr>
<td>10</td>
<td>1333</td>
<td>0.08006</td>
<td>935616</td>
</tr>
<tr>
<td>11</td>
<td>1692</td>
<td>0.06875</td>
<td>1019779</td>
</tr>
<tr>
<td>12</td>
<td>2024</td>
<td>0.05688</td>
<td>1005737</td>
</tr>
<tr>
<td>13</td>
<td>2315</td>
<td>0.04491</td>
<td>911553</td>
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<tr>
<td>14</td>
<td>2500</td>
<td>0.03423</td>
<td>750303</td>
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<tr>
<td>15</td>
<td>2500</td>
<td>0.02511</td>
<td>550340</td>
</tr>
<tr>
<td>16</td>
<td>2500</td>
<td>0.01773</td>
<td>388602</td>
</tr>
<tr>
<td>17</td>
<td>2500</td>
<td>0.01205</td>
<td>264214</td>
</tr>
<tr>
<td>18</td>
<td>2500</td>
<td>0.00789</td>
<td>172998</td>
</tr>
<tr>
<td>19</td>
<td>2500</td>
<td>0.00497</td>
<td>109091</td>
</tr>
<tr>
<td>20</td>
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<td>0.00302</td>
<td>66253</td>
</tr>
<tr>
<td>21</td>
<td>2500</td>
<td>0.00176</td>
<td>38750</td>
</tr>
<tr>
<td>22</td>
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<td>0.00099</td>
<td>21826</td>
</tr>
<tr>
<td>23</td>
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<td>0.00054</td>
<td>11838</td>
</tr>
<tr>
<td>24</td>
<td>2500</td>
<td>0.00028</td>
<td>6181</td>
</tr>
<tr>
<td>25</td>
<td>2500</td>
<td>0.00014</td>
<td>3107</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>826233</strong></td>
</tr>
</tbody>
</table>

*Table 8.1 Expected Hours of Production at Rated Power per Year*
<table>
<thead>
<tr>
<th></th>
<th>Length of One String in MV net</th>
<th>Number of Turbines total</th>
<th>Number of Turbines in one serie</th>
<th>Workability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4060 m</td>
<td>40</td>
<td>4</td>
<td>25</td>
</tr>
<tr>
<td>Distance Transformer to Shore</td>
<td>8000 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Distance String - Travo</td>
<td>1500 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance Between Turbines</td>
<td>640 m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Failure Rates (per year) | Repair Time | Repair Time incl. delays (days) | Unavailability Components |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HV field</td>
<td>frHVf</td>
<td>6</td>
<td>D7*100/Workability</td>
</tr>
<tr>
<td>HV cable</td>
<td>frHVc = 0.0035*thv/1000</td>
<td>48</td>
<td>D8*100/Workability</td>
</tr>
<tr>
<td>MV field</td>
<td>frMVf</td>
<td>6</td>
<td>D9*100/Workability</td>
</tr>
<tr>
<td>MV cable</td>
<td>frMVc = 0.0113*tmv/1000</td>
<td>48</td>
<td>D10*100/Workability</td>
</tr>
<tr>
<td>Transformer</td>
<td>frT</td>
<td>17</td>
<td>D11*100/Workability</td>
</tr>
<tr>
<td>OWECE minor</td>
<td>frOmi</td>
<td>0.666666667</td>
<td>D12*100/Workability</td>
</tr>
<tr>
<td>OWECE major</td>
<td>frOma</td>
<td>2</td>
<td>D13*100/Workability</td>
</tr>
</tbody>
</table>

### Unavailability Subsystems

<table>
<thead>
<tr>
<th></th>
<th>Labda Subsys</th>
<th>Av. Rep. time</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV field</td>
<td>frHVf+frHVc* (frHVf/365)^2+(frHVc/365)*2</td>
<td>(F6/G6)^365</td>
</tr>
<tr>
<td>HV cable</td>
<td>frHVf+frHVc</td>
<td></td>
</tr>
<tr>
<td>MV field</td>
<td>frMVf+frMVc* (frMVf/365)*2+(frMVc/365)*2</td>
<td>(F8/G8)^365</td>
</tr>
<tr>
<td>MV cable</td>
<td>frMVf+frMVc</td>
<td></td>
</tr>
<tr>
<td>Transformer</td>
<td>frT</td>
<td>(F10/G10)^365</td>
</tr>
<tr>
<td>OWECE minor</td>
<td>frOmi+frOma*</td>
<td>(F11/G11)^365</td>
</tr>
<tr>
<td>OWECE major</td>
<td>frOmi+frOma</td>
<td></td>
</tr>
</tbody>
</table>

### Unavailability due to OWECE failures

- 100*Uo %

### Unavailability due to MV failures

- 100*Um %

### Unavailability due to Other Failures

- 100*(Ut+frHVf*frT*(frHVf/365)^2+(frHVc/365)*2) %
10 Flowchart of Simulation

The meaning of the terms and indexes in the following flowcharts are:

\( t \) = Index of Time.
\( i \) = Index of Components within Subsystems (Turbines, MV-network or Rest).
\( \text{MV} \) = Index of Turbines.
\( m \) = Index of Strings in MV-network.

\( \text{OV} \) = single OWEC or Turbine.
\( \text{HV} \) = HV-network.
\( \text{Rest} \) = HV-network and Transformer.

\( \text{PrevMainO}(i,t,n) \) = Preventive Maintenance is being executed on component \( i \) of the turbine \( n \) when True.
\( \text{PrevMainMV}(i,t,m) \) = Preventive Maintenance is being executed on component \( I \) of MV network \( m \) when True.
\( \text{PrevMainRest}(i,t) \) = Preventive Maintenance is being executed on component \( I \) of the rest of the subsystems when True.

\( \text{PMCounterO}(i,n), \text{PMCounterMV}(i,m) \) and \( \text{PMCounterRest}(i) \) = Counters since last executed PM or CM task on components \( i \)

\( \text{TimeForPMO}(i,n), \text{TimeForPMMV}(i,m) \) and \( \text{TimeForPMRest}(i) \) = Time that is available for PM according to wave and wind speed limits of tools used on different components

\( \text{MTB PMO}(i), \text{MTB PMMV}(i), \text{MTB PMRest}(i) \) = Mean Time Between Preventive Maintenance of the different components and subsystems

\( \text{DurPMO}(i), \text{DurPMMV}(i) \) and \( \text{DurPMRest}(i) \) = Time that is required for execution of PM.

\( \text{FailureO}(i,t,n), \text{FailureMV}(i,t,m) \) and \( \text{FailureRest}(i,t) \) = A certain component Fails when True.

\( \text{Pf} \) = Probability of Failure of Component according to Poisson distribution.
\( \text{PMc} \) = Occurred Probability of Event according to random draw (Monte Carlo).

\( \text{CorrMainO}(i,t,n), \text{CorrMainMV}(i,t,m) \) and \( \text{CorrMainRest}(i,t) \) = Corrective Maintenance is being executed when True.

\( \text{TimeForCM} \) = Time that is available for CM according to wave limits. Similar to TimeForPM
\( \text{DurCM} \) = Time that is required for CM. Similar to DurPM

\( \text{WeatherPermission}(i) \) = Both the wind speed and wave height are below the wave and wind limits of tool \( i \)
AvailabilityO(t,n)  
AvailabilityMV(t,n)  
AvailabilityRest(t)  
= Turbine n or the MV-network of turbine n is available when true.  
When AvailabilityRest is False, all turbines are unavailable

Available(t,n)  
= Turbine n is available (AvailabilityO(n) & AvailabilityMV & 
AvailabilityRest are True)

Prod(wind(t))  
= Function that gives produced energy with calculated wind speed and 
given power curve

RateCMCost(i)  
= Cost of using tool for CM on component i per day
RatePMCost(i)  
= Cost of using tool for PM on component i per day
FixedCMCost(i)  
= Fixed cost of using tool i for CM for one year
FixedPMCost(i)  
= Fixed cost of using tool i for PM for one year

Ey(t)  
= Energy Yield during time step t
Revenue(t)  
= Revenues of produced energy in timestep t
Price  
= Market price of energy during timestep t
10.1 Flowchart Main Program

Fig. 10.1 Flowchart Main Program
10.2 Wind & Wave Simulation

Start

Initialise Local Variables

Determine wind speed
- According to 2 parameter Weibull distribution and autocorrelation function
- According to Wind - Wave relation of section 3.6.2

Determine swell
- From 2 parameter Raleigh distribution and autocorrelation function
- Super imposing waves from wind over swell.

Fig. 10.2 Flowchart Wind and Wave Simulation
10.3 Preventive Maintenance

Start

Initialise local variables

Get global variables time, wind, waves, counters and PrevMain from main program

Loop for i, j, and n

PrevMain

(i,(t-1),n) = true

PrevMain(component, estimate, time, turbine) = true : PM is being executed

Weather Permission

(i)

PMCounter > MTB PM

(i)

no

no

no

yes

yes

yes

yes

no

no

add 1 hr to PMTime

(i,n/m)

PMTime = DurPM

(i,n/m)

PrevMain

(i,n/m) = False

Reset PMCounter

(i,n/m)

next

i,n/m

End

Fig. 10.3 Flowchart Preventive Maintenance
10.4 Failures

[Flowchart diagram]

Get time, PrevMain, Failure from main program

Initialise local variables

Loop for i, n

Failure(t-1) & Prevmain (t) = False

no

yes

Pr(i) = 1 - e^(-t)

PMC = Random

no

PMC <= Pr(i)

yes

Failure (i,n,t) = True

next i,n

Fig. 10.4 Flowchart Failures
10.5 Corrective Maintenance

Fig. 10.5 Flowchart Corrective Maintenance
10.6 Availability, Energy Yield and Revenues

Fig. 10.6 Flowchart Availability, Energy Yield and Revenues
10.7 O&M Cost

Fig. 10.7 Flowchart O&M Cost
10.8 Levelised Production Cost

Fig. 10.8 Flowchart LPC
10.9 Output

Fig. 10.9 Flowchart Output
11 Example of Input

SimOWECS was written as part of a graduation project at the faculty for Civil Engineering and Geosciences, Delft University for Technology. Subject of the thesis was the "Probabilistic Design of Operations and Maintenance on Offshore Wind Energy Conversion Systems", and SimOWECS is intended as an evaluation tool for operation and maintenance strategies and general design. Program information and limitations can be found in the graduation report. Users of SimOWECS are hereby kindly requested to report any bugs in or changes to the program. Report and program by K. Neutrink, march 2001 in cooperation with Hydronic bv.

Repeat with same Weather and Failures
SimOWECS Simulation Time 20 year(s)

Fig. 11.1 Main Form Input

<table>
<thead>
<tr>
<th>Purchase Cost</th>
<th>Installation Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbines</td>
<td>60000000</td>
<td>6000000</td>
</tr>
<tr>
<td>Support Structure</td>
<td>45000000</td>
<td>4500000</td>
</tr>
<tr>
<td>Grid Connection</td>
<td>10500000</td>
<td>1050000</td>
</tr>
<tr>
<td>Shore Connection</td>
<td>9300000</td>
<td>9300000</td>
</tr>
<tr>
<td>Other</td>
<td>500000</td>
<td>500000</td>
</tr>
<tr>
<td>Future Decommissioning</td>
<td>1000000</td>
<td></td>
</tr>
</tbody>
</table>

Economic Lifetime of OWECS 20 years

Fig. 11.2 Input of Design Cost and Lifetime
### Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Turbines in Farm</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Number of Turbines in a MV-String</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Average Distance Between Turbines</td>
<td>640 m</td>
<td></td>
</tr>
<tr>
<td>Average Distance Turbine to Transformer</td>
<td>1500 m</td>
<td></td>
</tr>
<tr>
<td>Length of Shore Connection</td>
<td>10000 m</td>
<td></td>
</tr>
<tr>
<td>Average Water Depth in Farm</td>
<td>12 m</td>
<td></td>
</tr>
<tr>
<td>Array Efficiency</td>
<td>94%</td>
<td></td>
</tr>
<tr>
<td>Transmission Efficiency</td>
<td>97%</td>
<td></td>
</tr>
<tr>
<td>Average Market Price of Energy over Lifetime</td>
<td>0.12 Euro</td>
<td></td>
</tr>
<tr>
<td>Average Real Interest Rate over Lifetime</td>
<td>5%</td>
<td></td>
</tr>
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</table>

**Fig. 11.3 Input of Simulation Parameters**
<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Production (kWh)</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
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<td>5</td>
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<td>676</td>
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<td>9</td>
<td>984</td>
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<td>1333</td>
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<td>11</td>
<td>1892</td>
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<td>2024</td>
</tr>
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<td>2315</td>
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<tr>
<td>14</td>
<td>2500</td>
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<tr>
<td>15</td>
<td>2500</td>
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<td>25</td>
<td>2500</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
</tr>
</tbody>
</table>

Cut-In Wind Speed: 3.5 m/s
Rated Wind Speed: 14 m/s
Cut-Out Wind Speed: 25 m/s
Rated Power: 2500 kWh

Parameter A for Production Curve: 4.1
Parameter B for Production Curve: 10.75

Fig. 11.4 Turbine Data and Power Curve
Fig. 11.5 Wind and Wave Simulation Parameters

Fig. 11.6 Preventive Maintenance
## Corrective Maintenance

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>Failure Rate</th>
<th>Decline in Reliability</th>
<th>Duration of CM</th>
<th>Speed</th>
<th>Wind Limit</th>
<th>Wave Limit</th>
<th>Tool Data</th>
<th>Dayrate Cost</th>
<th>Stand-By Rate</th>
<th>Fixed Cost</th>
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<tbody>
<tr>
<td>Support Structure</td>
<td>0.02</td>
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<td>20</td>
<td>2</td>
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<td>2250</td>
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<td>2</td>
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<td>2250</td>
<td></td>
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<td>5500</td>
<td>2250</td>
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<td></td>
<td></td>
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<tr>
<td>Gearbox and Generator</td>
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<td>12</td>
<td>10</td>
<td>20</td>
<td>2</td>
<td>5500</td>
<td>2250</td>
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<td>2</td>
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<td>2250</td>
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<td>Others</td>
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<td>HV - Field</td>
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<td>2</td>
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<td>HV - Cable</td>
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<td>336</td>
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<td>5500</td>
<td>2250</td>
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</table>

### Save Cost per Year per Component

- /Year
- %/Year
- hrs
- km/hr
- m/s
- m
- Euro/Day
- Euro/Day
- Euro/Year

* = Execute in Summer Only

**Reliability Declines**

- Linear

---

*Fig. 11.7 Corrective Maintenance*
12 Example of Output

Fig. 12.1 Main Output Form

Fig. 12.2 Results of Simulation Time
Fig. 12.3 Graphical Display of Results of Simulation Time
### Correlation of Wind Speed and Availability

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Occurrence</th>
<th>Average Availability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>93</td>
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<td>1</td>
<td>88</td>
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<tr>
<td>26</td>
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**Fig. 12.4 Correlation between Wind Speed and Availability**
## Results per Year

<table>
<thead>
<tr>
<th>Year</th>
<th>PM Cost</th>
<th>CM Cost</th>
<th>Total Cost</th>
<th>Revenue</th>
<th>Profit</th>
<th>Availability</th>
<th>LPC</th>
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<td>1</td>
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<td>12000038</td>
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</tbody>
</table>

*Fig. 12.5 Results of Simulation per Year*
Fig. 12.6 Graphical Display of Yearly Results

Fig. 12.7 Graphical Display of Results per Year (8)
Fig. 12.8 Graphical Display of Result per Year (18)