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PROBABILISTIC COST MODEL FOR ANALYSIS OF OFFSHORE WIND ENERGY COSTS AND POTENTIAL

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Abstract

A computer program named OWECOP (Offshore Wind Energy Cost and Potential) has been developed by ECN in order to quantify the energy production costs of offshore wind energy. This program couples a Geographic Information System (GIS database) with an Excel™ workbook.

This report describes a probabilistic analysis implemented into the OWECOP cost model. Therefore the @RISK software package for probabilistic analyses is implemented into the Excel workbook of OWECOP. The cost model obtained bears the name OWECOP-Prob.

Some typical results of the OWECOP-Prob model are: probabilistic distribution functions (PDF) for the energy yield, PDF's for overall offshore wind energy implementation costs and tornado diagrams showing the relative influence of the uncertain parameters. These results are obtained by Monte Carlo simulations.

After an introduction, chapter 2 of this report presents the deterministic and the probabilistic input parameters of the OWECOP-Prob model. In chapter 3 the different probabilistic distributions used are described. In chapter 4, the integration of the probabilistic cost model into OWECOP is presented.
An evaluation of the results is given in chapter 5 and some graphs obtained with the model are shown.
The conclusions and recommendations are given in chapter 5.4.

Keywords

Offshore, wind energy, cost model, probabilistic model, @RISK, OWECOP.

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CONTENTS

LIST OF ABBREVIATIONS

Abbreviation	Full Text
AHT	Anchor Handling Tug
EEZ	Exclusive Economical Zone
GIS	Geographic Information System
LPC	Levelized Production Costs
MSL	Mean Sea Level
MT	Metric Tonnes
OWECOP	Offshore Wind Energy Cost and Potential
PDF	Probability Distribution Function
PV-curve	Power-Velocity (wind speed) curve

SUMMARY

ECN has developed a computer program named OWECOP (Offshore Wind Energy Costs and Potential) in order to quantify the energy production costs for offshore wind energy. This program couples a Geographic Information System (GIS database) with an Excel™ workbook.

An @RISK add-in is implemented in the Excel workbook to enable probabilistic analyses of the costs of offshore wind energy. This so-called OWECOP-Prob version of the cost model has been used to analyse the case of a 480 MW wind farm consisting of 80x 6 MW wind turbines on the NEEZ as an example.

The OWECOP-Prob model includes, like the deterministic OWECOP model, an input section, a calculation section, a database section and a result section. The latter includes analytical and graphical results. The model analyses all wind farm implementation costs, at a specified location on the Dutch Exclusive Economical Zone (NEEZ).

In expectation of results of the variability of Operation en Maintenance costs, a probabilistic analysis of O&M has not yet been performed with OWECOP-Prob.

1. INTRODUCTION

1.1 Objectives

ECN has developed a computer program named OWECOP (Offshore Wind Energy Costs and Potential) in order to quantify the investment costs of offshore wind energy [Refs. 1 and 2]. This program couples a Geographic Information System (GIS database) with an Excel™ workbook.

This report describes the implementation of a probabilistic cost model into OWECOP. The probabilistic analysis is realised with @RISK add-in software for Microsoft® Excel [Ref. 3]. The probabilistic model implemented into OWECOP bears the name OWECOP-Prob.

To implement the probabilistic cost model, the following approach was followed:
- Identification of relevant parameters;
- Choice of the probability distribution type for the identified parameters;
- Implementation of the relative probability distribution parameters of each distribution.

Based on this approach, a cost model has been built into an Excel workbook. Where applicable all considered aspects and simplifications are mentioned.

1.2 Objectives of a Probabilistic Analysis

The OWECOP model is an EXCEL workbook program that enables an integrated analysis of the potential energy yield and the costs of wind energy exploitation in large water areas from a technical and market perspective. To this purpose, engineering cost models and information stored in a database are used.

The engineering models are deterministic. They give a result for a specified wind farm under specific conditions. Analysis of the influence of the input parameters on the results is achieved by variations of the input parameters.
However, some of the input parameters are uncertain or may change over the time. That's why some parameters should be better defined in a range. Examples are the rent prices of offshore equipment (which are the result of a balance between offer and demand) and annual wind speed.

A probabilistic analysis intends to account for these uncertainties and to quantify their influence on the results. To achieve this goal, the uncertain parameters of the engineering model must be provided with a probability distribution function (PDF) that shows the likelihood of occurrence for each possible outcome. Furthermore, each parameter must be associated with a well-defined range whereto the PDF is associated. In this report, the uncertain parameters are also referred to as 'unknowns'.

Examples of questions that the probabilistic analysis intends to answer are:
- What parameters have the largest influence on the uncertainty of the expected costs of wind energy?
- What is the probability that the estimated cost of wind energy is less than a certain value?
- What is the probability that the estimated investment cost of offshore wind energy is less than the expected nominal calculated value?

2. INPUT PARAMETERS FOR PROBABILISTIC ANALYSIS

2.1 General

The list of input parameters of the OWECOP cost model is extensive:
- GIS parameters, i.e. parameters that depend on the chosen wind farm location;
- Turbine parameters;
- Turbine foundation parameters;
- Wind farm parameters;
- Parameters for transport and installation analysis;
- Parameters for scour protection and cable installation analysis;
- Sea condition parameters;
- Electric infrastructure parameters;
- Offshore equipment prices;
- Soil research parameters;
- Economic parameters.

Evidently, not all parameters are relevant for a probabilistic analysis. In fact, three main groups of parameters are identified:
- Wind farm design parameters;
- Wind farm unknowns;
- Cost model regulation parameters.

Wind farm design parameters are user input. These parameters determine the type and location of the wind farm to analyse. The parameters may be chosen arbitrarily between minimum and maximum values. Wind farm design parameters have no probabilistic distribution in OWECOP-Prob.

Wind farm unknowns represent the technical aspects of the design of the wind farm. In the OWECOP deterministic version of the cost model, the user chooses these parameters. In the probabilistic cost model, these parameters have a probabilistic distribution and therefore they are not user's input anymore.

The user may input cost model regulation parameters. These are fixed for proper functioning of the program. An example of this is the "wind speed bin" parameter, which regulates the plot settings of a PV-curve of the wind turbine. Cost model regulation parameters have no distribution.

In expectation of results of studies about the variability of Operation en Maintenance costs, a probabilistic analysis of O&M has not yet been performed with OWECOP-Prob.

The following sections clarify the choice of the parameters used for the probabilistic model. Parameters that have a PDF are described in section [3.3].

2.2 Wind Farm Design Parameters

From the overall list of input parameters of the OWECOP cost model, the following parameters are identified to be of the design type. Design parameters do not include a probabilistic distribution function.

GIS Parameters	Depends on
Distance of grid cell to electrical grid on shore	Farm location
Distance of grid cell to harbour	Farm location
Water depth, distance below MSL	Farm location

Turbine Parameters	Depends on
Robustness	Specific user's choice
Cut in wind speed	Turbine type
Cut out wind speed	Turbine type
Maximum aerodynamic power coefficient	Turbine design
Nominal turbine power	Specific user's choice
Rotor speed operation	Turbine design
Specific power	Turbine type

Turbine Foundation Parameters	Depends on
Minimum wall thickness monopile	Turbine design
Maximum wall thickness monopile	Turbine design
Maximum pile diameter	Turbine design
Corrosion excess	Turbine design
Annual average design wind speed	Farm location
Axial aerodynamic coefficient for 50 yr. extreme wind speed	Turbine design
Load factor	Turbine design
Yield stress (sigma 0.2)	Turbine design
Material density (rho steel)	Turbine design
Miscellaneous components weight factor	Turbine design
Rig slenderness (length / diameter) for jacket	Turbine design

Wind Farm Parameters	Depends on
Number of turbines in the farm	Specific user's choice
Number of turbines in a group	Specific user's choice
Number of cable platforms present in the farm	Farm location
Spacing (x); distance in a line of turbines	Specific user's choice
Spacing (y); distance between turbine lines	Specific user's choice
Farm orientation (direction of line turbines)	Farm location
Air density	Farm location and height

Parameters for Transport and Installation Analysis	Depends on
Number of vessels used for transport	Specific user's choice
Number of vessels used for installation	Specific user's choice
Transport "fixed" time between turbines	Turbine design
Installation "fixed" time between turbines	Turbine design

Parameters for Scour Protection and Cable Installation Costs	Depends on
Number of mobilisation days	Farm location
Travelling speed of stone vessel	Specific user's choice
Maximum cargo of stones of stone vessel	Specific user's choice
Density of rocks used	Wind farm design
Layer thickness of applied scour protection	Turbine design
Number of days in one operational season	Fixed
Number of cable crossings (cable to shore)	Farm location
Quantity of rocks at each cable crossing	Wind farm design
Distance of horizontal drilling	Farm location

Wave Parameters	
Water density	Farm location

Moment coefficient	Turbine design
Drag coefficient	Turbine design

<u>Electric Infrastructure Parameters</u>	<u>Depends on</u>
Factor direct distance/effective cable length	Wind farm design
Voltage of cable to shore	Wind farm design
Maximum current of HVAC cable	Wind farm design
Approximated value of cosine of electric phase	Wind farm design

<u>Soil Research Parameters</u>	
Number of points to be investigated	Wind farm design

<u>Economic Parameters</u>	<u>Depends on</u>
Preparation period	Specific user's choice
Construction period, following end of preparations	Specific user's choice
Economic life time of the farm	Specific user's choice
Percentage of equity capital	Specific user's choice
Percentage of private capital	Specific user's choice
Percentage of capital loan	Specific user's choice
Interest rate on equity capital	Specific user's choice
Interest rate on private investment	Specific user's choice
Annual interest rate on debts	Specific user's choice

2.3 Wind Farm Unknowns

Similar to the wind farm design parameters, the following wind farm unknowns are identified. All unknowns include a probabilistic distribution in the cost model.

<u>GIS Parameters</u>
Average annual wind speed at reference height
Vertical wind shear exponent
Weibull shape factor at hub height, wind
50 year return significant wave height

<u>Turbine Foundation Parameters</u>
Material cost factor for monopile and tower
Material cost factor for tripod

<u>Wind Farm Parameters</u>
Farm availability
Farm array efficiency
Farm electric efficiency

<u>Parameters for Transport and Installation Analysis</u>
Probability of good weather for transport
Probability of good weather for installation
Percentage of waves below 1.0 m

<u>Parameters for Scour Protection</u>
Unit costs of scour protection rocks

<u>Wave Parameters</u>
Wave number
Weibull shape factor for wave height

Weibull scale factor for wave height

Electric Infrastructure parameters
AC power loss per km
DC power loss per km

Prices of Offshore Equipment
2 tugs
1 cargo + 1 tug
Jack-up
Construction vessel
Sheer leg
Crane barge
Directional drill
Pontoon 80x25 + crane
Pontoon 60x20
2x trenching equipment
60 MT AHT
35 MT AHT
Tow tug
Divers
Cargo barge (large working area)
Cargo barge (normal working area)
Submarine cutting equipment
Supply vessel
Stone vessel

Soil Research Parameters
Mobilisation costs
Day-rate of equipment

Economic Parameters
Annual inflation rate

2.4 Cost Model Regulation Parameters

These parameters do not include a probabilistic distribution in the cost model. They are mentioned here for the sake of completeness:

GIS Parameters

Reference height for average wind speed	This parameter must be in accordance with the value of the annual average wind speed, defined as an unknown parameter.
Grid size (square)	User's choice

Turbine Parameters

Wind speed bin	This parameter regulates the output of the PV-curve of the chosen wind turbine.

3. IMPLEMENTATION OF THE PROBABILITY DISTRIBUTIONS

3.1 General

In this section, the type of the probability distribution functions and the choice of the distribution parameters are presented for each of the wind farm unknowns defined in section 2.3.

3.2 Used Probability Distributions Types

Three probabilistic distribution types are used:
1. Uniform distribution. See Appendix C for definition.
2. Normal distribution. See Appendix C for definition.
3. PERT distribution. See Appendix C for definition.

ad 1) For all parameters that have an equal probability to get a value between a given range, a Uniform probability distribution is chosen. For the Uniform distribution, it is necessary to specify the minimum and maximum values. These minimum and maximum are "educated guesses".

ad 2) For all parameters that have a big chance of getting a certain value, but (small) fluctuations around that value are expected, a Normal probability distribution is chosen. For the specification of a Normal distribution, it is necessary to estimate the mean value and its standard deviation.

ad 3) For all parameters with more uncertain distributions, a PERT probability distribution is chosen. A PERT distribution is used as an approximation for sampled data. For the definition of a PERT distribution, a minimum, a maximum and a most likely value are needed. In the cost model, these values are derived from expert opinions and therefore no references are included in this report.

In some cases, the cost model requires an integer as input. Example of this is the construction time in years. When the required parameter is provided with a probability distribution, the outcome of the distribution function is rounded to the closest integer.

The above-presented guidelines for choosing a probability distribution have some exceptions. These exceptions are highlighted when necessary in the following paragraphs.

3.3 Probability Distribution Functions, Variables Used

All unknowns include a probabilistic distribution function. When not referred, the choice of the minimum, maximum, most likely and standard deviation values are derived from expert opinions.

<u>GIS Parameters</u>

a) Average wind speed at reference height. This parameter is assumed to distribute according to a Normal probability function. Its value is related to the parameter "Reference height for average wind speed", which is set at 85 [m]. Distribution: Normal; Mean value 9.35 [m/s] [ref. 11] and standard deviation set to $\sigma = 0.6$. Analysis of known data have shown that the average wind speed fluctuates from year to year between 9.35 m/s ± 15% (9.35*0.85 = 7.95 [m/s] and 9.35*1.15=10.75 [m/s]). With the value of the standard deviation chosen, 98% of the probability of occurrence lies between the observed minimum and maximum values.

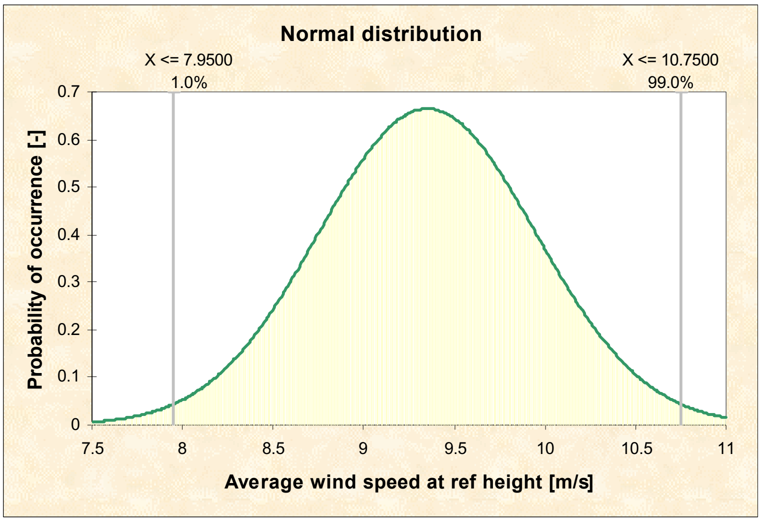

Figure 1. Normal probability distribution for the average wind speed at reference height.

b) Vertical wind shear exponent. This parameter is considered to distribute according to a truncated Normal function with a mean value of 0.08 [-] and standard deviation σ = 0.01; minimum value is set at 0.06 [-]; maximum value is set at 0.10 [-]. The mean, minimum and maximum values are taken from expert opinions. The standard deviation is taken to be equal to the half of the difference between the mean value and the lowest/upper limit (71.5% probability that the value lies between the mean ± 1σ).

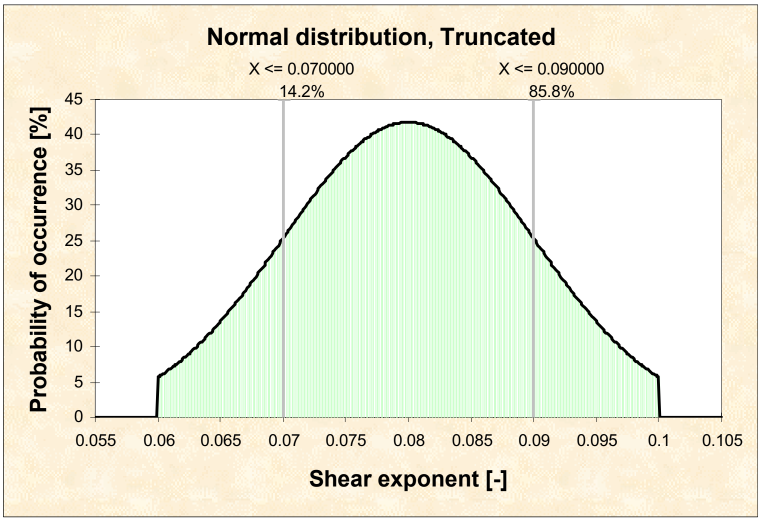

Figure 2. Truncated Normal distribution for wind shear exponent.

c) Weibull shape factor at hub height, for wind. The lower limit of 1.88 [-] and the upper limit of 2.25 [-] are observed for the North Sea [ref. 12]. This parameter is assumed to distribute uniformly between these limits and it is applicable for a height of 85 m above MSL.

d) 50-year return significant wave height. The distribution of this variable is not known. Therefore, a PERT distribution function is chosen with a minimum value of 8.0 [m], a maximum of 12.0 [m] and a most likely value of 9.0 [m]. These values have been derived from reference [10].

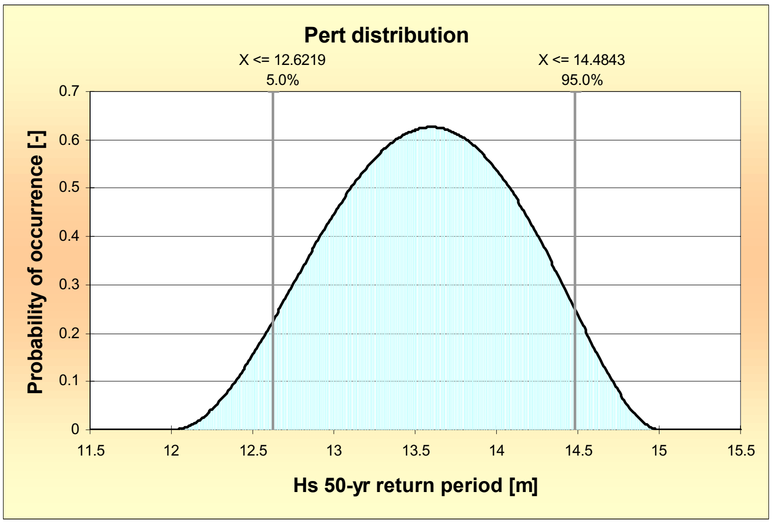

Figure 3. PERT distribution for Hs, 50-year return.

Turbine Foundation Parameters

a) Material cost factor for monopile and tower. For this parameter, a PERT probability distribution function is assumed. The lower limit is set to 1.8 [€/kg], the upper limit is set to 5.0 [€/kg], and the most likely value is set to 2.0 [€/kg]. These values have been derived from personal communication of the author of this report with experts in offshore engineering projects.
b) Material cost factor for tripod. Similar to above. Distribution PERT; minimum value set to 3.0 [€/kg], a maximum of 5.0 [€/kg] and a most likely value of 3.5 [€/kg]. These values have been derived from personal communication of the author of this report with experts in offshore engineering projects.

Wind Farm Parameters

a) Farm availability. The value of this parameter is derived from expert opinions taken out of reference [13]. The distribution used is a PERT, with lower limit set to 0.95 [-], upper limit set to 0.99 [-], and the most likely value at 0.985 [-].

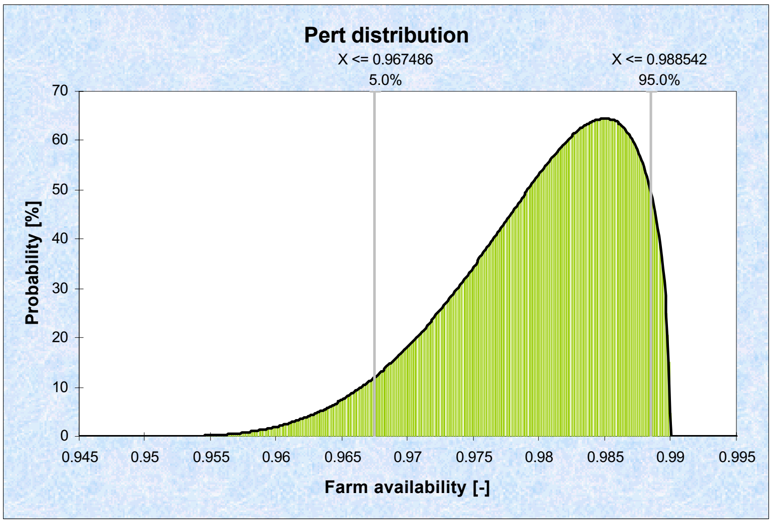

Figure 4. Probability distribution of wind farm availability.

b) Farm array efficiency. The array efficiency of the farm is derived analytically based on an empirical model. This efficiency is tuned to the results obtained with verified software [7]. For the parameter “Wind Deficit”, defined as the unity minus the array efficiency, a PERT distribution is used. For a given wind farm layout and size, the lower limit is set to 0.05 [-]

and the upper limit is set to 0.30 [-]. The most likely value is calculated according to a verified algorithm.
Figure 5 shows the distribution of the wind deficit.

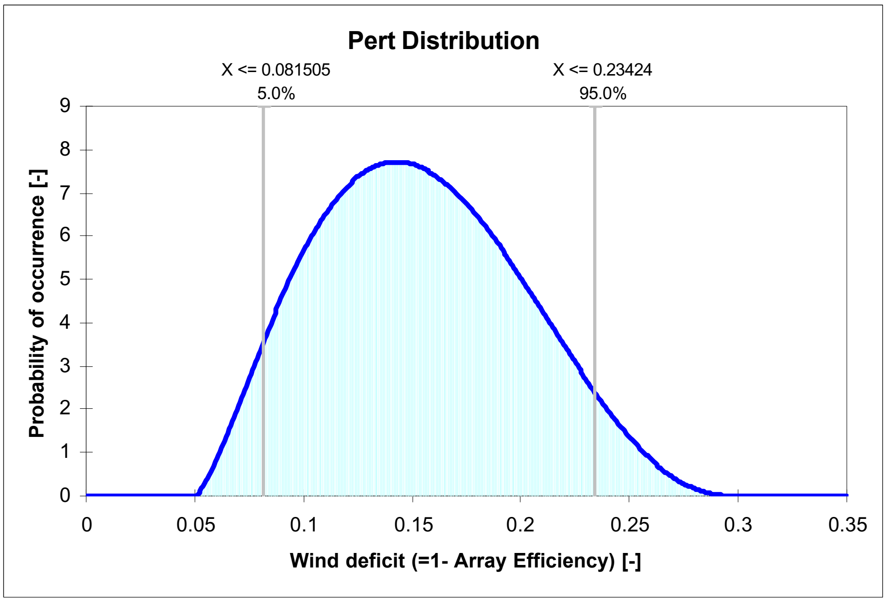

Figure 5. Pert distribution for the wind deficit (1-array efficiency) of the wind farm.

c) Farm electric efficiency. Similar to above. Distribution: PERT; lower limit set to 0.95 [-], upper limit set to 0.99 [-], and the most likely value is set to 0.98 [-]. Values are derived from expert opinions.

Parameters for Transport and Installation Analysis

a) Probability of benign weather for transport. This parameter describes the probability of occurrence of a minimum weather-window length for a specified wave height. The weather-window length for the specified wave height determines if a transport vessel may operate. The distribution function used for this parameter is a symmetric PERT, with lower limit equal to 0.7 [-], upper limit equal to 0.9 [-] and most likely value equal to 0.8 [-]. These values have been derived by the author of this report, based on raw data from [16].
b) Probability of benign weather for installation. Similar to the above parameter but for installation vessels. Distribution PERT, with lower limit equal to 0.7 [-], upper limit equal to 0.9 [-] and most likely value equal to 0.8 [-]. These values have been derived by the author of this report, based on raw data taken from [16].
c) Percentage of waves below 1.0 m. For specific offshore rock transport vessels, a maximum wave height of 1.0 [m] limits their workability. The percentage of waves under this height is estimated to be about 66.5% [15]. For analysis purposes, a Normal probability distribution function, with a mean value of 66.5% and a standard deviation $\sigma = 2.5\%$ is assumed.

Parameters for Scour Protection and Cable Installation Costs

Scour protection costs of wind turbine foundations (approximately 2% of total investment costs) and cable installation costs (approximately 1% of total investment) are very small compared to other costs. Nevertheless, for the sake of completeness, the first parameter being part of the input of the cost model has a probability distribution function.

a) Unit costs of scour protection rock. Distribution: symmetric PERT. Lower limit equal to 20 [€/MT]; upper limit equal to 30 [€/MT]; most likely value equal to 25 [€/MT]. Data taken from [15].

Wave Parameters

a) Weibull shape factor for wave height. For this parameter, a PERT distribution is assumed. The values of the upper and lower limits are derived from wave data found on Internet

[Ref. 6]. The lower limit is set to 1.423 [-]; the upper limit is set to 1.605 [-]; most likely value equal to 1.4885 [-].

b) Weibull scale factor for wave height. Similar to above. For this parameter, a PERT distribution is assumed. The lower limit is set to 0.492 [-]; the upper limit is set to 1.01 [-]; most likely value equal to 1.840 [-].

Electric Infrastructure Parameters

In this section, only the estimated electric losses of the AC and DC cables (per km) include a probability distribution function. Both distributions are of the PERT type because these losses have been estimated based on expert opinions. By adding a relative probability distribution function to these parameters, their influence is determined.

In the following lines the used variables of the PERT distributions are given:

Parameter	**Minimum value**	**Most likely value**	**Maximum value**
AC power loss per km	0.01950 %	0.02175 %	0.024 %
DC power loss per km	0.00833 %	0.00917 %	0.010 %

Prices of Offshore Equipment

All these distributions are of the PERT type, because only a range of prices is known. By adding a probability distribution function to these cost parameters, their influence is determined. The following estimation applies:

- The upper and lower limits of the mobilisation costs are estimated as the mean value ±€5,000.
- The upper and lower limits of the day-rates are estimated as the mean value ±€5,000. For all prices under €20,000, the upper and lower limits of the day-rates are estimated as the mean value ±€2,000.
- The upper and lower limits of the significant wave height at which the offshore equipment can perform its activities are estimated as the mean value ±20%.

In the following lines the used most likely mean values of the symmetric PERT distributions are given.

Parameter	Mobilisation costs	Day-rate	Significant wave height
2 tugs	36,000	20,000	1.5
1 cargo and 1 tug	38,000	35,000	1.5
Jack-up	200,000	75,000	2.0
Construction vessel	400,000	75,000	2.0
Sheer leg	150,000	75,000	1.5
Crane barge	200,000	100,000	2.0
Directional drill	not used	35,000	N.A.
Pontoon 80x25 + crane	not used	35,000	not used
Pontoon 60x20	not used	25,000	not used
2x trenching equipment	not used	10,000	N.A.
60 MT AHT	not used	15,000	not used
35 MT AHT	not used	10,000	not used
Tow tug	not used	10,000	not used
Divers	not used	10,000	N.A.
Cargo barge (large working area)	not used	35,000	not used
Cargo barge (normal working area)	not used	25,000	not used
Submarine cutting equipment	not used	25,000	N.A.

Parameter			
Supply vessel	not used	15,000	not used
Stone vessel	not used	13,000	1.0

<u>Soil Research parameters</u>

a) Mobilisation costs. Similar to the prices of offshore equipment presented above, a PERT distribution is assumed with a mean value of €50,000. The lower and upper limits are set to the mean value ±€5,000.

b) Day-rate of equipment. Similar to the prices of offshore equipment presented above, a PERT distribution is assumed with a mean value of €50,000. The lower and upper limits are set to the mean value ±€5,000.

<u>Economic Parameters</u>

a) Annual inflation rate (Netherlands). This parameter is assumed to distribute according to a truncated Normal function with a mean value of 3% and standard deviation σ = 0.5%; The minimum value is set at 2%; the maximum value is set at 4%. See Figure 6.

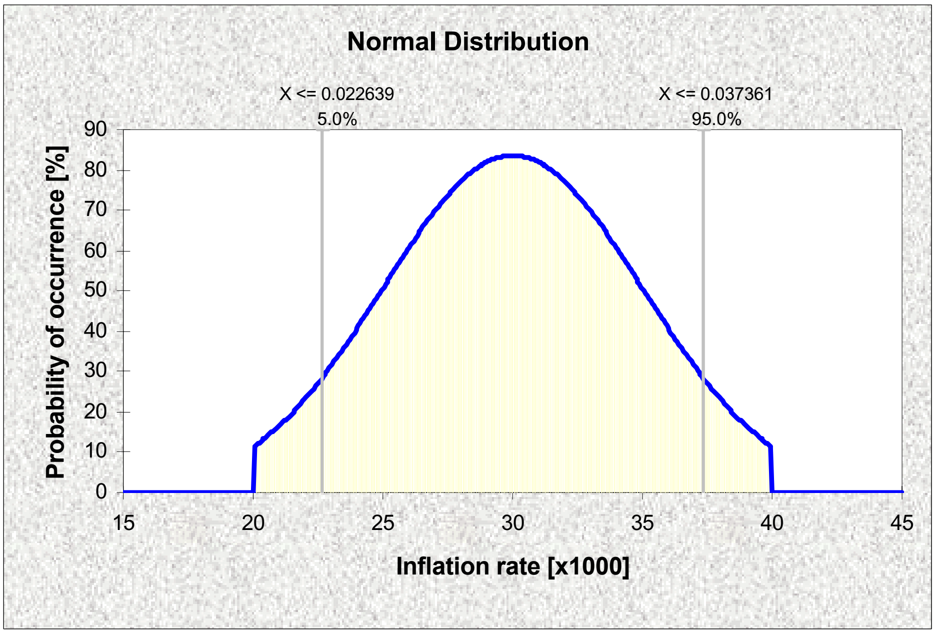

Figure 6. Normal distribution for the inflation rate.

4. STRUCTURE OF OWECOP-PROB

4.1 General

The OWECOP-Prob cost model results from the implementation of probability distributions into an Excel™ workbook using @RISK software.

In the cost model, the costs of all components defined in OWECOP are calculated and levelized to a LPC cost of energy. The LPC for wind energy is defined as the levelized costs (in € or €ct) divided by the delivered energy by the wind farm (in kWh). See reference [9] for a mathematical definition of this parameter.

Distribution functions are derived performing a certain number of Monte Carlo simulations. The following calculated parameters include a distribution function:
- LPC of wind energy;
- Gross annual electricity production (including turbine and wind farm array efficiency);
- LPC cost breakdown on level 1 (see Appendix A for wind farm components);
- Efficiency of power transport;
- Turbine availability;
- Wind farm accessibility;
- Mass of tower and monopile / tripod foundation.

In addition, for other OWECO-Prob calculated parameters, like the turbine load factor and electric infrastructure parameters, a PDF could be derived if desired.

4.2 Probabilistic Cost Model, Workbook Characteristics

The probabilistic cost model workbook consists of a number of sections organised as follows:
- An input section;
- A cost summary section;
- A calculation and database section;
- A results section, where numerical and graphical results are presented.

4.2.1 Input Section

In the input section, several types of input are required:
- GIS Parameters, i.e. parameters that depend on the chosen wind farm location;
- Turbine parameters;
- Turbine foundation parameters;
- Wind farm parameters;
- Parameters for transport and installation analysis;
- Parameters for scour protection;
- Parameters for cable installation analysis;
- Sea condition parameters;
- Electric infrastructure parameters;
- Offshore equipment prices;
- Soil research parameters;
- Economic parameters.

A snapshot of a part of the input section of the workbook is shown in Figure 7. A snapshot of a part of the section where the distribution functions are defined, is shown in Figure 8.

USER'S INPUT

GIS PARAMETERS			
Reference height for average wind speed	ref_height	**85.0**	[m]
Distance of grid cell to electrical grid on shore	D_grid	**25**	[km]
Distance of grid cell to harbour	D_harbour	**25**	[km]
Water depth, distance below MSL	water_depth	**25**	[m]
Grid size (square)	grid_size	**1**	[km]
		20	

TURBINE PARAMETERS			
Robustness	reliability	**state-of-the-art**	
cut in wind speed	cut_in	**3**	[m/s]
cut out wind speed	cut_out	**25**	[m/s]
cp-max (aerodynamic)	cp_max	**0.495**	[-]
wind speed bin	wind_bin	**0.25**	[m/s]
nominal turbine power	P_turbine	**6000**	[kW]
speed indicator (variable slip, - speed, or constant speed)	speed_indicator	**VSP**	
specific power	specific_power	**475**	[W/m^2]

TURBINE FOUNDATION PARAMETERS			
minimum wall thickness monopile	min_wall_monopile	**0.04**	[m]
maximum wall thickness monopile	max_wall_monopile	**0.08**	[m]
maximum monopile tower diameter	D_tower_max	**6.0**	[m]
corrosion excess	corrosion_excess	**0.003**	[m]
annual average design wind speed	V_avg_design	**10**	[m/s]
Axial aerod. coefficient for 50 yr extreme wind speed	cd_ax_50yr	**1.4**	[-]
load factor	load_factor_fndtn	**1.5**	[-]
yield stress	sigma_02	**240,000,000**	[N/m^2]
material density	rho steel	**7850**	[kg/m^3]
increase factor support weight due to miscellaneous components	factor_support_weigh	**1.10**	[-]
tripod: rige slenderness (length / diameter)	rige_slenderness	**40**	[-]

Figure 7. Input section of OWECOP-Prob

DISTRIBUTIONS INPUT

GIS PARAMETERS			min.	most likely	max.	std dev
Average wind speed at reference height	V_ave_ref	9.350000 [m/s]	0	9.35	10.7525	0.6
Vertical wind shear exponent	shear_exponent	0.080000 [-]	0.06	0.08	0.1	0.01
Weibull shape factor at hub height, air	Weibull_shape	2.065000 [-]	1.88		2.25	
50 year return significant wave height	sign_wave_height ..	9.333333 [m]	8.00	9.00	12.00	

TURBINE FOUNDATION PARAMETERS			min.	most likely	max.
Material cost factor for monopile and tower	mat_cost_pile	2.466667 [€ / kg]	1.80	2.00	5.00
Material cost factor for tripod	mat_cost_supports	3.666667 [€ / kg]	3.00	3.50	5.00

WIND FARM PARAMETERS			min.	most likely	max.
Farm availability	park_availability	0.980000 [-]	0.95	0.985	0.99
Farm array efficiency	wind_deficit	-0.153517 [-]	0.05	0.14	0.30
Farm electric efficiency	park_efficiency_elec	0.976667 [-]	0.95	0.98	0.99

PARAMETERS FOR TRANSPORT AND INSTALLATION			TRANSPORT AND INSTALLATION min.	most likely	max.
Probability of good weather for transport	P(benign)_tr	0.80000 [-]	0.70	0.80	0.90
Probability of good weather for installation	P(benign)_inst	0.80000 [-]	0.70	0.80	0.90
Percentage of waveves below 1.0 m	Waveper	66.83333 [%]	60	66.5	75

PARAMETERS FOR SCOUR PROTECTION COSTS			SCOUR PROTECTION min.	most likely	max.
Unit costs of scour protection rocks	rock_price	25.00 [Euro/MT]	20	25	30

WAVE PARAMETERS			min.	most likely	max.
Moment coefficient	cm_wave	1.93333 [-]	1.80	1.95	2.00
Drag coefficient	cd_wave	1.35000 [-]	1.00	1.40	1.50
Weibull shape factor for wave height	Kweibull	1.49700 [-]	1.42	1.49	1.61
Weibull scale factor for wave height	Cweibull	0.81033 [-]	0.49	0.84	1.01

ELECTRIC INFRASTRUCTURE PARAMETERS			ELECTRIC INFRASTRUCTURE min.	most likely	max.
AC power loss per km	power_loss_AC	0.002175 [1 / km]	0.0020	0.0022	0.0024
DC power loss per km	power_loss_DC	0.000092 [1 / km]	0.00008	0.00009	0.00010

Figure 8. Snapshot of definition of distributions in OWECOP-Prob.

4.2.2 Cost Summary Section

The cost summary section of the workbook is a compilation of the wind farm costs according to the following classification:
- Wind farm design;
- Hardware;
- Assembly, transport and installation;
- Annual operation and maintenance;
- Retrofit and overhaul;
- Decommissioning.

Each of these main groups is defined to be in level 1 of the cost breakdown. Subdivision in subsequent levels gives a more detailed cost breakdown into component level. A complete list of components according to their respective levels is presented in Appendix A.

4.2.3 Calculation and Database Section

In this section, all turbine component dimensions and weights and their respective costs are calculated. These costs are based on a price per kg of material used or are derived from empirical formulas from different sources.
Another type of calculation is the type and cost of electric infrastructure. These are optimised based on costs of electric hardware, installation costs of components and electric efficiencies of the cable types.

Finally, the wind distribution over the year, the energy yield of the wind farm and the turbine availability and accessibility are estimated. These results are further used to calculate the LPC of the wind farm.

4.2.4 Results Section

Results obtained with OWECOP-Prob are presented in section 5.

5. EVALUATION OF RESULTS

5.1 General

In this section, some results obtained with the model costs are presented. These results are derived for a wind farm design with characteristics as presented in 5.2.
It should be noticed that, if desired, other kind of probabilistic results are also possible with slight change(s) to the cost model. The results presented here must be considered as an example. Some typical results of the probabilistic analysis are presented in 5.3.

5.2 Characteristics of the Analysed Wind Farm

Only the most relevant parameters are presented in this section. A complete list of all input parameters is presented in Appendix B.

<u>Wind Farm Design</u>	
Wind farm power	480 [MW]
Number of turbines in the farm	80 [-]
Number of turbines per group	10 [-]
Mean spacing between turbines	8x Rotor Diameter
Distance to shore	25 [km]
<u>Turbine Design</u>	
Nominal power of turbine	6 [MW]
Specific power of turbine	475 [W/m^2] ➔ Rotor radius = 63.4 [m]
<u>Environmental Parameters</u>	
Water depth at site	20 [m]
<u>Economic Parameters</u>	
Economic lifetime	12.5 [years]
Interest rate on debts	6.5 [%]

5.3 Some Output Obtained with the Probabilistic model

The results obtained with the probabilistic model follow after 3000 Monte Carlo simulations. The results have converged, that is, the results obtained from the statistics of the software changed less than 1.5% after the 3000 simulations. In this section the levelized production costs of wind energy (LPC) and the gross annual electricity production are analysed as an example.

<u>LPC of Wind Energy</u>

From the samples taken from the results, a probability distribution function can be fitted for the LPC. As an example, Figure 9 shows an Extreme Value approximation to this PDF and Figure 10 shows a Gamma PDF of the same.
Note that every time a new run with @RISK software is performed, (slightly) different results and figures may be obtained. This is due to the nature of Monte Carlo simulations.

From Figure 9 it can be seen that the probability of LPC being lower than € 0.10087 is 95%.

For this distribution, this probability could also be calculated as follows: The distribution of an Extreme Value distribution is given by the next formula (see Appendix C).

$$F(x) = \exp\left[-\exp\left(-\frac{x-a}{b} \right) \right]$$

This means that with the parameters a = 7.45152 and b = 0.88731 of the Extreme Value distribution, the probability of LPC being smaller than 0.1 € may be approximated by:

$$p(LPC \leq 10) = F(10) = \exp\left[-\exp\left(-\frac{10-7.45152}{0.88731} \right) \right]$$

$$\Rightarrow p(LPC \leq 10) = \exp[-\exp(-2.8721)] = 0.9450 = 94.5\%$$

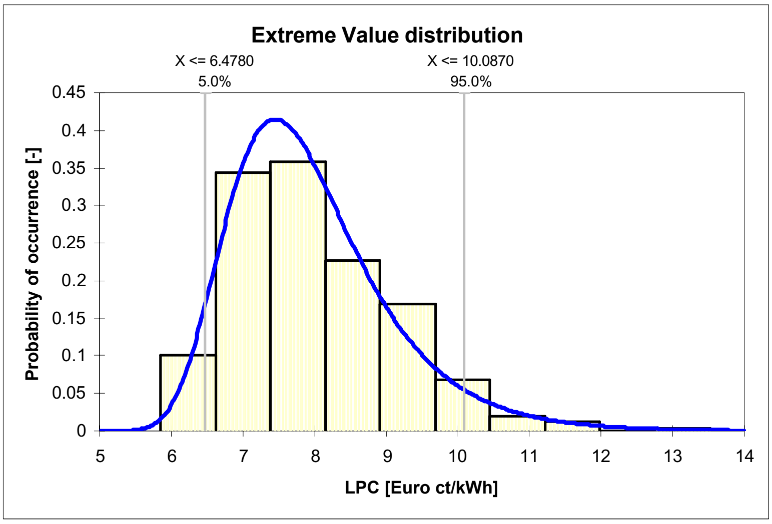

Figure 9. Example of "Extreme Value" PDF for LPC.

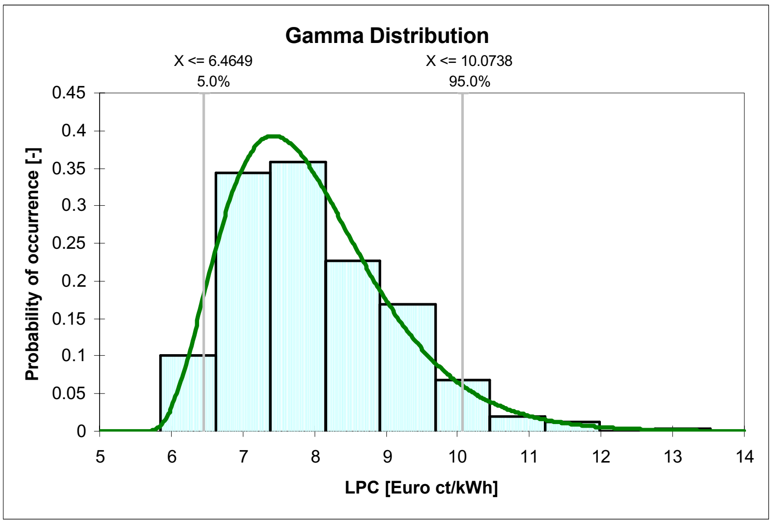

Figure 10. Example of "Gamma" PDF for LPC.

There is no analytical representation for a Gamma distribution function. Therefore, the probability of exceeding with the Gamma distribution cannot be calculated with an algorithm.

Another way of presentation of the results may be done through a cumulative distribution. An example of a cumulative distribution for the LPC of wind energy is given in Figure 11.

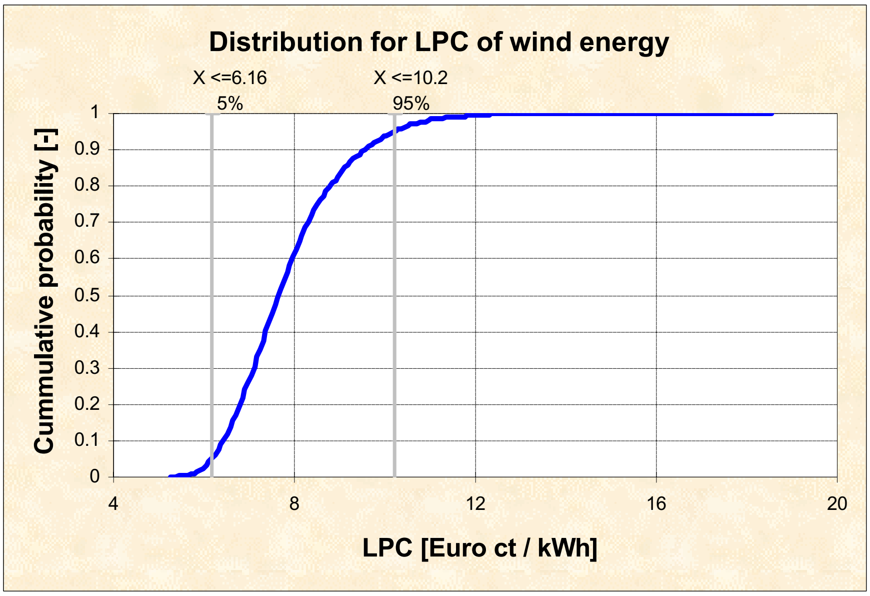

Figure 11. Example of cumulative distribution for LPC.

From the above graph, it can be seen for instance, that there is a probability of 90% that the LPC adopt a value between 6.16 €ct and 10.20 €ct.
From the obtained graph with the @RISK software, it can also be calculated that the probability of the LPC lying between 7.0 €ct and 9.0 €ct equals 56.7%. The probability of LPC being higher than 8 €ct equals 61.5%.

Another result that can be obtained with the analysis is the so-called tornado diagram. An example of this diagram is presented in Figure 12.

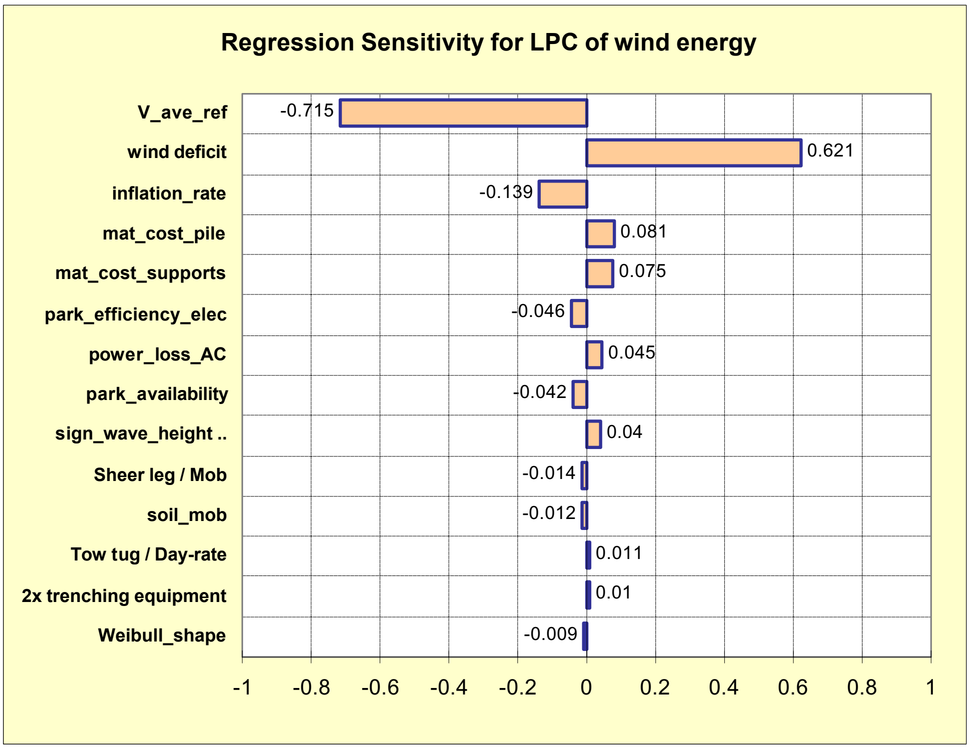

Figure 12. Tornado diagram for LPC of wind energy.

In this diagram, the influence of the defined input parameters of the cost model on the LPC is quantified. This diagram reads as follows: a positive unit change of one of the input parameters of the left column causes an increase of the LPC. If the value plotted is negative, an increase of the input variable causes a decrease of the LPC.

To understand the significance of the values, the inflation rate is chosen as an example. If the inflation rate increases by one standard deviation (of its own distribution), the value of the LPC decreases by the factor 0.139 times the standard deviation of LPC.

In our example, the standard deviation of the inflation rate is obtained from its distribution. The estimated value of the standard deviation of the inflation rate is 0.0044. The estimated standard deviation of the LPC equals to 1.2455. An increase of the inflation rate from 0.03 to 0.0344 (3.44% instead of 3%) means that the LPC value will change from 7.84 €ct (its mean value) to 7.84 - 0.137 x 1.2455 = 7.669 €ct.

From the tornado diagram, it can also be read that the influence of the inflation rate is larger than the influence of for instance the farm availability.

Note that the presented tornado diagram is just an example. Tornado diagrams of other defined outputs may also be obtained when these outputs get a probabilistic distribution function. An example of another tornado diagram is given by Figure 13.

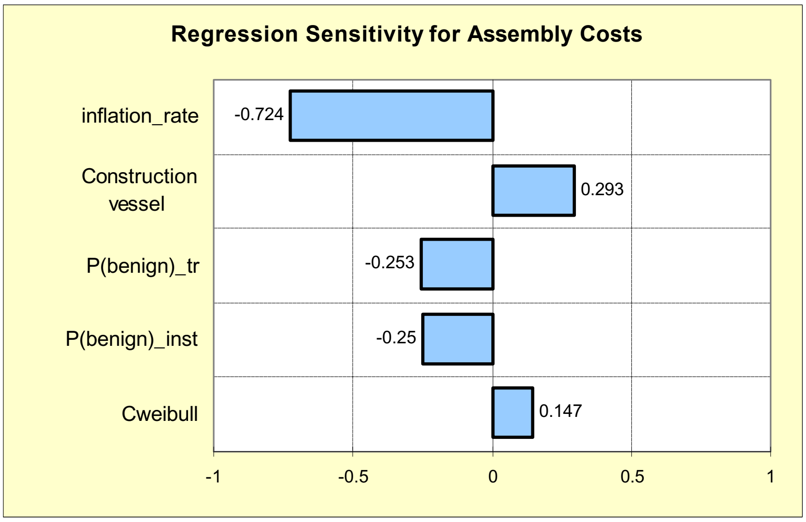

Figure 13. Tornado diagram for assembly costs

<u>Gross Annual Electricity Production</u>

From the cumulative distribution obtained for the gross annual electricity production (see Figure 14), it can be seen that there is a chance of 90% that the realised electricity production lies between $15.37 \cdot 10^6$ and $25.13 \cdot 10^6$ kWh. This production range is valid for one (average) turbine, in the defined wind farm, in one year. From this graph, it is also possible to derive what the possibility is that a minimum specified electric production is achieved by this turbine.

The probability that the electricity production becomes more than $25.13 \cdot 10^6$ kWh is just 5%.

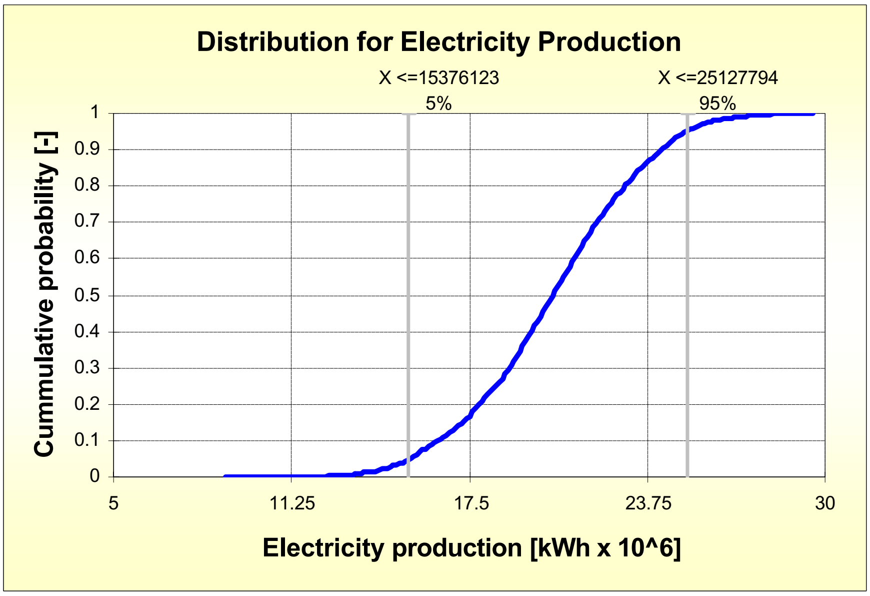

Figure 14. Cumulative distribution for electricity production.

For all other parameters where a probabilistic distribution function is derived, similar questions to those presented for the LPC and the gross electric production could be answered. These analyses are not presented here.

5.4 Analysis of Obtained Output

An analysis of some results is presented in this section. Analysis of other output variables can be achieved similarly by coupling the desired output calculation to the defined PDF's. The results presented here are based on the tornado diagram obtained in the previous section. They are intended as an example.

The four parameters that have the largest influence on the LPC of wind energy, as calculated in the cost model for the wind farm design as presented in section 5.2 (see Figure 12) are:

- Wind speed at reference height;
- Wind deficit;
- Inflation rate;
- Material cost of piles and tower;

The influence of these parameters is explained here briefly. The calculated standard deviation of the distribution function for LPC used for this analysis is 1.2926, while the mean value is 7.987. These values may change slightly every time a @RISK simulation is run, although the results will be very similar.

Wind Speed at Reference Height

The wind speed at reference height depends on the location of the wind farm. At different locations, different roughness of the seawater surface may be found, influencing the wind speed at a certain height. At a determined location, the wind speed may vary during the day or season of the year due to changes in, for instance, the ambient temperature. In other words, the wind speed is a stochastic variable that influences the LPC of wind energy by its variability. For this parameter, a Normal PDF is used (see section 3.3).

From the wind speed at the reference height, the speed at hub height is calculated. An increase of the mean wind speed at hub height level (taken over the whole year) will mean that the total delivered energy of the wind turbine will increase over a year. Increasing of

the delivered energy of the turbine without increasing the total costs will reduce the LPC of wind energy.
The amount of reduction of the LPC, can be estimated from the tornado diagram:

- Std. deviation for wind speed distribution = 0.5962 [m/s];
- Mean wind speed at reference height = 9.35 [m/s];
- Change of reference wind speed from 9.35 to 9.41 [m/s] results in a change of LPC from 7.987 [€ct/kWh] to 7.987 – 0.715*1.2926 = 7.063 [€ct/kWh].

<u>Wind Deficit</u>
The wind deficit is caused by the mutual interference of the wind turbines. It depends among other factors, on the way the wind turbines are distributed in the farm and the magnitude of the wind speed direction distribution during the year. The wind deficit is a stochastic parameter. By giving a distribution function to this parameter, the influence of its uncertainty on the LPC can be quantified. The PDF used for this parameter is a PERT distribution, see section 3.3.

The influence of the wind deficit into the LPC is similar to the influence of the reference wind speed discussed above. The array efficiency is defined as {1-wind_deficit}. The array efficiency of the wind farm is directly related to the mean wind speed at hub height level. The last one is a function of the reference speed, the hub height, the wind shear exponent and the array efficiency.
An increase in wind deficit means that the array efficiency will decrease, decreasing in return the wind speed at hub level and the delivered energy of the wind turbine. This will cause the LPC to increase.
The amount of increase of the LPC, can be estimated from the tornado diagram:

- Std. deviation for wind deficit = 0.0465 [-] (= 4.65%);
- Mean wind deficit = 0.1510 [-] (= 15.1%);
- Change of wind deficit from 15.1% to 19.75% results in a change of LPC from 7.987 [€ct/kWh] to 7.987 + 0.621*1.2926 = 8.790 [€ct/kWh].

<u>Inflation Rate</u>
The inflation rate is an economic parameter that changes depending on the economic market. For the cost model, it is a parameter with an unknown value. For this parameter, a Normal PDF is used in the cost model, see section 3.3 for details.

The inflation rate influences the real interest rate at which a loan is issued. By an increase of the inflation rate, the real interest rate decreases, decreasing the relative value of the loan. By a rise of the inflation rate over the years, the LPC will decrease.
The amount of reduction of the LPC, was already estimated from the tornado diagram in section 5.3:

- Std. deviation for inflation rate distribution = 0.0044 [-];
- Mean inflation rate = 0.03 [-];
- Change of inflation rate from 3% to 3.44% [-] results in a change of LPC from 7.987 [€ct/kWh] to 7.987 – 0.139*1.2926 = 7.807 [€ct/kWh].

<u>Material Cost of Piles and Tower</u>
The cost of material directly influences the LPC of wind energy. The value of this parameter is derived from past projects and the expected upper and lower limits of it are estimated based on expected market variability. The used PDF for this parameter is a PERT distribution, see section 3.3 for details.

By increasing the cost of materials, the LPC of wind energy will increase. The amount of increase of the LPC, can be estimated from the tornado diagram:

- Std. deviation for material cost parameter = 0.4912 [-];
- Mean material cost parameter = 2.4667 [-];

- Change of material cost parameter from 2.47 to 2.96 results in a change of LPC from 7.987 [€ct/kWh] to 7.987 + 0.081*1.2926 = 8.092 [€ct/kWh].

Note that depending on the characteristics of the wind farm to be analysed, the parameters having the largest influence on the LPC of wind energy may vary.

For a wind farm located for instance at a long distance from shore, costs of cable laying equipment become more significant for the LPC costs than for a wind farm located near shore. The same conclusion is applicable for other input parameters like for instance the economic lifetime of the wind farm.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

1. OWECOP-Prob enables a probabilistic analysis of the cost and potential of offshore wind energy as calculated by OWECOP. The implementation of this probabilistic model may replace all what-if analysis, by variation of the input parameters in OWECOP. The OWECOP-Prob model also gives a good insight of the relative effects of the input parameters.

2. OWECOP-Prob is especially suited for site-specific analysis of wind farms. A global approach for a sector of the Dutch EEZ, like for instance in the deterministic version, is not possible because the model is not coupled to a GIS database. OWECOP-Prob could however quantify some useful boundaries for the outcome of the GIS database approach.

3. To implement the probabilistic model into OWECOP, all user-defined variables were separated into wind farm design parameters and wind farm unknowns. All wind farm unknowns include a probabilistic distribution function.

4. If desired, other user-defined variables may easily be represented by a probabilistic distribution function. The same applies to other output variables, making OWECOP-Prob a flexible tool.

5. The probabilistic distribution functions have a shape that has been derived from expert opinions. The probabilistic model helps to visualise the influence of the variables on the results.

6. Depending on the characteristics of the wind farm to be analysed, the parameters having the largest influence on the LPC of wind energy may vary.

7. In expectation of results of studies about the variability of Operation en Maintenance costs, a probabilistic analysis of O&M has not yet been performed with OWECOP-Prob.

8. In this report, a 480 MW wind farm (80 x 6MW turbines) at a water depth of 20 metres has been used as an example. In the analysis performed, the uncertainty of the wind characteristics, the mutual influence of the wind turbines and the inflation rate have the major influence on the LPC calculation.

6.2 Recommendations

Based on the results presented in section 5 and the conclusions presented here above, the following recommendation is given:

- Introduce a probabilistic analysis of Operation and Maintenance costs.
- Search and implement a possible correlation between some defined parameters. Example of correlated parameters could be wind speed and Weibull factors for wind, and Wave height and Weibull factors for wave conditions.

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APPENDIX A. LIST OF COMPONENTS OF A WIND TURBINE FARM

	Level 1	Level 2	Level 3	Level 4
DESIGN	Wind Farm Design			
		Management		
		One-off Insurance Premium		
		Feasibility		
			Environmental Study	
			Technical Feasibility	
			Social Feasibility	
		Site Assessment		
			Environmental	
			Geophysical	
			Geotechnical	
		Acquisition		
			Tendering	
			Quotations	
			Contract	
		Engineering		
			Design	
			Certification	
HARDWARE	Hardware	(including transport onshore)		
		Management		
		Measuring Tower		
			Support Structure	
				Foundation
				Tower
				Platform
				Access Facilities
				Lifting Equipment
				Other
			Measurement System	
				Hut
				Measurement Equipment
				Computers
				Other
		OWEC		
			Support structure	
				Foundation
				Tower
				Platform
				Access Facilities
				Lifting Equipment
				Other
			Nacelle	
				Housing
				Drive Train
				Main Shaft
				Gear System
				Bearings
				Generator

	Level 1	Level 2	Level 3	Level 4
HARDWARE				Electr. Conversion
				Yaw System
				Mainframe
				Computer and Sensors
				Break-Coupling System
				Electr. Cable
				Cooling System
				Miscellaneous
			Rotor	
				Blades
				Hub
				Pitch Control System
		Electric Collection System		
			Power Conversion	
			Collection Cable	
		Central Platform		
			Support Structure	
			Platform	
			Other	
		Transmission System to Shore		
			Cable Platform	
			Transformer Station	
			Transmission Cable	
			Power Conversion	
			Intermediate Components	
			Grid Connection	
			Onshore Transformer Station	
		Purchased Auxiliary Equipment		
		Onshore Transport		
		Pre-assembly		
		Onshore Premises		
ASSEMBLY, TRANSPORT AND INSTALLATION	Assembly, Transport and Installation			
		Management		
		Assembly Onshore		
			Measuring Tower	
			OWEC	
			Electric Collection System	
			Central Platform	
			Transmission System to Shore	
			Rent of Quay side	
			Rent of Storage Onshore	
			Testing Onshore	
				Measuring Equipment
				OWEC Lifting Equipment
				Other OWEC Components
				Electric Collection System
				Transmission System to Shore
		(De)mobilisation Costs		
		Transport Offshore		
			Measuring Tower	
			OWEC	
			Electric Collection System	
			Central Platform	
			Transmission System to Shore	

	Level 1	Level 2	Level 3	Level 4
ASSEMBLY, TRANSPORT AND INSTALLATION		Offshore Storage		
		Assembly Offshore		
			Measuring Tower	
			OWEC	
			Electric Collection System	
			Central Platform	
			Transmission System to Shore	
		Installation		
			Measuring Tower	
				Foundation
				Tower
				Measurement Equipment
			OWEC	
				Foundation
				Tower
				Nacelle & Rotor
				Access Facilities
			Electric Collection System	
				Offshore Electric Cabling
				Cable Tie-in
			Central Platform	
			Transmission System to Shore	
				Platform(s)
				Transformer Station
				Offshore Electric Cabling
				Cable tie-in
				Grid Connection
				Onshore Electric Cabling
				Onshore Transformer Station
		Seabed Preparation / Scour Protection		
			Measuring Tower	
			OWEC	
			Electric Collection System	
			Central Platform	
			Transmission System to Shore	
				Cable Platform
				Transmission Cable
		Commissioning		
			Measuring Tower	
			OWEC	
			Electric Collection System	
			Central Platform	
			Transmission System to Shore	
OPERATION AND MAINTENANCE	Yearly Operation & Maintenance			
		Management		
		Inspection Subsea Works		
		Preventive Maintenance - Crews		
		Preventive Maintenance - Equipment		
		Preventive Maintenance - Spare Parts & Consumables		
		Corrective Maintenance - Crews		
		Corrective Maintenance - Equipment		
		Preventive Maintenance - Spare Parts & Consumables		
		Annual Insurance Premium		
		Administration (Sales, Distribution, etc.)		

	Level 1	Level 2	Level 3	Level 4
RETROFIT AND OVERHAUL	Retrofit & Overhaul			
		Management		
		Preventive Maintenance - Crews		
		Preventive Maintenance - Equipment		
		Preventive Maintenance - Spare Parts & Consumables		
		Corrective Maintenance - Crews		
		Corrective Maintenance - Equipment		
		Preventive Maintenance - Spare Parts & Consumables		
DECOMMISSIONING	Decommissioning			
		Management		
		(De)mobilisation costs		
		Removal of Structures		
			Measuring Tower	
			OWEC	
			Electric Collection System	
			Central Platform	
			Transmission System to Shore	
		Transport to Shore		
		De-assembly		
		Salvage		

APPENDIX B. COMPLETE INPUT LIST FROM THE COST MODEL

USER'S INPUT

GIS PARAMETERS

Reference height for average wind speed	ref_height	**85.0**	[m]
Distance of grid cell to electrical grid on shore	D_grid	**25**	[km]
Distance of grid cell to harbour	D_harbour	**25**	[km]
Water depth, distance below MSL	water_depth	**20**	[m]
Grid size (square)	grid_size	**1**	[km]

TURBINE PARAMETERS

Robustness	reliability	**state-of-the-art**	
Cut in wind speed	cut_in	**3**	[m/s]
Cut out wind speed	cut_out	**25**	[m/s]
Cp-max (aerodynamic)	cp_max	**0.495**	[-]
Wind speed bin	wind_bin	**0.25**	[m/s]
Nominal turbine power	P_turbine	**6000**	[kW]
Speed indicator (variable slip, - speed, or constant speed)	speed_indicator	**VSP**	
Specific power	specific_power	**475**	[W/m^2]

TURBINE FOUNDATION PARAMETERS

Minimum wall thickness monopile	min_wall_monopile	**0.04**	[m]
Maximum wall thickness monopile	max_wall_monopile	**0.08**	[m]
Maximum monopile tower diameter	D_tower_max	**6.0**	[m]
Corrosion excess	corrosion_excess	**0.003**	[m]
Annual average design wind speed	V_avg_design	**10**	[m/s]
Axial aerod. coefficient for 50 yr extreme wind speed	cd_ax_50yr	**1.4**	[-]
Load factor	load_factor_fndtn	**1.5**	[-]
Yield stress	sigma_02	**240 E6**	[N/m^2]
Material density	rho steel	**7850**	[kg/m^3]
Increase factor support weight due to miscellaneous components	factor_support_weight	**1.10**	[-]
Rige slenderness (length / diameter) of tripod	rige_slenderness	**40**	[-]

WIND FARM PARAMETERS

Number of turbines in the farm	N_OWEC	**80**	[-]
Number of turbines in a group	Nturb_per_group	**10**	[-]
Number of cable platforms present in the farm	Ncplat	**0**	[-]
Spacing (x); distance in a line of turbines	spacing_x	**7**	[diameters]
Spacing (y); distance between the turbine lines	spacing_y	**9**	[diameters]
Farm orientation (direction of line turbines)	park_orientation	**120**	[deg]
air density	air_density	**1.25**	[kg/m^3]
Operational life time wind farm	life_time_park	**20**	[years]

USER'S INPUT

PARAMETERS FOR TRANSPORT AND INSTALLATION

Number of vessels used for transport	Nvess_tr	**1**	[-]
Number of vessels used for installation	Nvess_inst	**1**	[-]
Transport "fixed" time between turbines	t_fix_tr	**1.5**	[days]
Installation "fixed" time between turbines	t_fix_inst	**2**	[days]

PARAMETERS FOR SCOUR PROTECTION COSTS

Number of mobilisation days	Nmob	**8**	[-]
Travelling speed of stone vessel	Vship	**11**	[km/hr]
Maximum cargo of stones of stone vessel	Scargo	**1000**	[MT/load]
Density of rocks used	rho_steen	**2.2**	[MT/m3]
Layer thickness of applied scour protection	t_layer	**1.5**	[m]
Number of days in one operational season	season	**183**	[days]
Quantity of rocks at each cable crossing	Nrocks	**500**	[MT]
Distance of horizontal drilling	Ddrill	**500**	[m]

PARAMETERS FOR CABLE INSTALLATION COSTS

Number of cable crossings (cable to shore)	Ncross	**3**	[-]

WAVE PARAMETERS

Water density	rho_water	**1025**	[kg/m^3]

ELECTRIC INFRASTRUCTURE PARAMETERS

Factor direct distance / effective cable length to grid connection	D_grid_factor	**1.25**	[-]
Voltage of cable to shore	HVac	**150**	[kV]
Maximum current of cables AC	Imax	**800**	[A]
Cosinus of phase (by approximation)	cos_phi	**0.8**	[-]

SOIL RESEARCH PARAMETERS

Number of points to be investigated	Points	**7**	[-]

ECONOMIC PARAMETERS

Preparation period	preperation_period	**2**	[years]
Construction period	construction_period	**1**	[years]
Economic operational life time of the park	life_time_economic	**12.5**	[years]
Percentage of equity capital	capital_equity	**20.0%**	[-]
Percentage of private capital	capital_private	**0.0%**	[-]
Percentage of capital loan	capital_loan	**80.0%**	[-]
Interest rate on equity capital	interest_equity	**15.0%**	[-]
Interest rate on private investment	interest_private	**0.0%**	[-]
Annual interest rate on debts (loan / green funds)	interest_loan	**6.5%**	[-]

APPENDIX C. PROBABILITY DISTRIBUTION FUNCTIONS

Normal PDF as stated in @RISK manual:

Normal Page 1 of 1

Normal

NORMAL(μ,σ)

Applications

Distribution of characteristics of a population (height, weight); size of quantities that are the sum of other quantities (because of the central limit theorem).

Density

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

Distribution

No closed form

Parameters

$\sigma > 0$

Domain

$-\infty < x < \infty$

Mean

μ

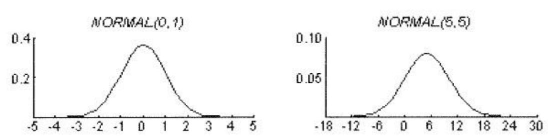
Mode

μ

Variance

σ^2

Normal Graphs



mk:@MSITStore:C:\Program%20Files%202\Dtools\SYSTEM\pdf4.chm::/htm/normal.htm 3/14/02

Uniform PDF as stated in @RISK manual:

Uniform   Page 1 of 1

Uniform

UNIFORM(min,max)

Applications

Quantities that variy uniformly between two values.

Density

$$f(x) = \frac{1}{max - min}$$

Distribution

$$F(x) = \frac{x - min}{max - min}$$

Parameters

$min \le max$

Domain

$min \le x \le max$

Mean

$$\frac{min + max}{2}$$

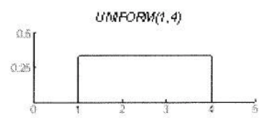
Mode

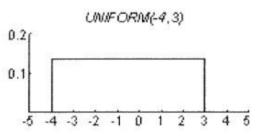
No unique mode

Variance

$$\frac{(max - min)^2}{12}$$

Uniform Graphs





mk:@MSITStore:C:\Program%20Files%202\Dtools\SYSTEM\pdf4.chm::/htm/uniform.htm 3/14/02

PERT PDF as stated in @RISK manual:

Pert

PERT(min,most likely,max)

Applications

Rough modeling when actual data is absent, approximate activity time in a PERT network.

Density

$f(x) = f_B(x', \alpha_1, \alpha_2)$

where

f_B *is the density of a BETA distribution*

$$x' = \frac{x - min}{max - min}$$

$$\mu = \frac{min + 4 * mostlikely + max}{6}$$

$$\alpha_1 = \frac{(\mu - min)(2 * mostlikely - min - max)}{(mostlikely - \mu)(max - min)}$$

$$\alpha_2 = \alpha_1 \frac{max - \mu}{\mu - min}$$

Distribution

$F(x) = F_B(x', \alpha_1, \alpha_2)$

where F_B *is the distribution of a BETA function*

Parameters

min < most likely < max

Domain

$min \le x \le max$

Mean

μ

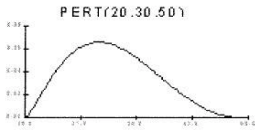
Mode

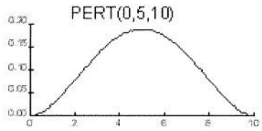
most likely

Variance

$$\frac{\alpha_1 \alpha_2 (max - min)^2}{(\alpha_1 + \alpha_2)^2 (\alpha_1 + \alpha_2 + 1)}$$

PERT Graphs





Extreme Value

EXTVALUE(a,b)

Applications

The limit, as n tends to infinity, of the maximum value of n independent random variates with the same continuous distribution. Also called the Gumbel distribution.

Density

$$f(x) = \left(\frac{1}{b}\right) \mathbf{exp}\left(-\frac{x-a}{b}\right) \mathbf{exp}\left[-\mathbf{exp}\left(-\frac{x-a}{b}\right)\right]$$

Distribution

$$F(x) = \mathbf{exp}\left[-\mathbf{exp}\left(-\frac{x-a}{b}\right)\right]$$

Parameters

$b > 0$

Domain

$-\infty < x < \infty$

Mean

$a - b\Gamma'(1)$

where $\Gamma'(n) = \frac{d\Gamma(n)}{dn}, \Gamma'(1) \cong -0.57721$

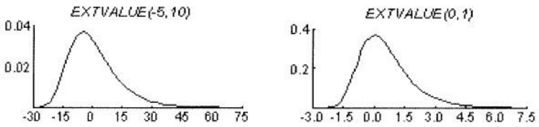
Mode

a

Variance

$$\frac{b^2\pi^2}{6}$$

Extreme Value Graphs


EXTVALUE(-5,10)
0.04
0.02
-30 -15 0 15 30 45 60 75
EXTVALUE(0,1)
0.4
0.2
-3.0 -1.5 0.0 1.5 3.0 4.5 6.0 7.5

	Date: May 2002	Number of report: ECN-I--02-007

Title	Implementation of a Probabilistic Cost Model into OWECOP
Author(s)	S.A. Herman
Principal(s)	-
ECN project number	7.4159
Principal's order number	-
Programme(s)	ECN - Basis

Abstract

A computer program named OWECOP (Offshore Wind Energy Cost and Potential) has been developed by ECN in order to quantify the energy production costs of offshore wind energy. This program couples a Geographic Information System (GIS database) with an Excel™ workbook.

This report describes a probabilistic analysis implemented into the OWECOP cost model. Therefore the @RISK software package for probabilistic analyses is implemented into the Excel workbook of OWECOP. The cost model obtained bears the name OWECOP-Prob.

Some typical results of the OWECOP-Prob model are: probabilistic distribution functions (PDF) for the energy yield, PDF's for overall offshore wind energy implementation costs and tornado diagrams showing the relative influence of the uncertain parameters. These results are obtained by Monte Carlo simulations.

In expectation of results of the variability of Operation en Maintenance costs, a probabilistic analysis of O&M has not yet been performed with OWECOP-Prob.

Key words:

Offshore, wind energy, cost model, probabilistic model, @RISK.

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