Smart Rotor, calculation of the integral effects on the LCoE

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Acknowledgement

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Abstract

This report describes the method and the results of the cost analysis performed on the 5MW UPWIND or NREL Reference wind turbine that has been the basis for the project. The performance and load changes due to application of the innovation of flaps on the outboard stations of the rotor blade have been determined by Lars Bernhammer, a PhD researcher at the University of Delft, [1].

A description of the work done to determine the influence of changed loading on both the blade and the tower of the reference wind turbine and the subsequent influence these have on the respective blade and tower mass and therefore cost. The differences have been determined with engineering (cost) models of the blade and tower. Next to that, an estimate has been made on the (increased) O&M requirements and changes in the availability by adding the flaps to the system with the ECN O&M Tool. The overall effect on the Levelised Cost of Energy (LCoE) has been determined with the FLOW cost model.

The results of the work performed are: due to the predicted load reduction of 24% of fatigue equivalent flapwise blade root moment and a reduction of the static (extreme) flap and edgewise blade root moments of 8%, the blade mass can be reduced by 8.2%. Resulting in a blade cost reduction of approximately k€ 22. It is however assumed that installing a flap will increase the cost of the rotor blade by approximately k€ 60. This results in an increased cost for the rotor system of 14%.
Due to higher complexity of the rotor blades and the (assumed) chance of failure of a flap system, the O&M cost will increase by 1.5% and at the same time the availability of the wind turbine decreases with 0.5%

The total effect on the LCoE, determined with the FLOW cost model, using the results above, is an increase of the LCoE of 1.8%.

Contents

1 **Introduction** 4

2 **Description of the cost model** 6
2.1 Introduction 6
2.2 Blade cost model 7
2.3 Tower cost model 9
2.4 O&M (and availability) cost model 10

3 **Results** 13
3.1 Description of the reference machine 13
3.2 The modifications for the smart rotor applied in the blade cost model 13
3.3 The integral effect on the LCoE 17

4 **Conclusion and discussion** 19

References 21

1

Introduction

In the FLOW project “Smart Turbine” performed by TU Delft, Darwind XEMC and ECN it is required to assess the integral influence of a smart rotor on the Levelised Cost of Energy (LCoE).

The task is described as follows:

> *Task 6 (TU-Delft, XEMC-DarWind, ECN)*
> *Parallel to task 5 the effects of the design solutions are judged with respect to the impact on the Cost of Energy. ECN will use their cost model for this, in close cooperation with DarWind in order to tune this model to current practice of DarWind designed turbines. DarWind will look at a possible route to industrialisation*

The assessment is based on the results of the aero-elastic analysis performed at TUDelft, see [2, 1]. The reference wind turbine used in this project is the so called NREL/UpWind 5MW reference wind turbine, see [3]. In [2] it is shown that by applying a smart rotor, i.e. a smart trailing edge flap at the blade tip acting as a self-controlled device, the loads can be reduced substantially. The flaps reduce the blade root flapwise fatigue moments by approximately 24% while the edgewise moment is reduced by approximately 1.5%. Figure 1 gives an impression of the fatigue load changes for the blades, nacelle and tower.

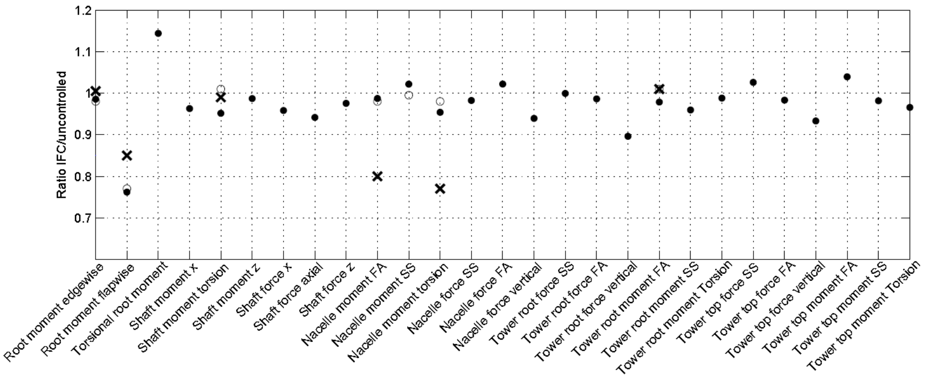


Figure 1: The fatigue load ratio with and without IFC, comparison of results (•) with Bæk IPC (o) and mode based control (x), copied from [2]

The extreme loads are also reduced, although by a lower percentage. The blade root flapwise bending moment is reduced by approximately 8% while the blade root torsional moment is increased by that percentage. The edgewise moment is again slightly lower, in the order of 1.5%. The tower top and tower foot loading is however only slightly changed. The tower torsional moments are substantially lower due to lower a-symmetric loading in the rotor. For a more detailed impression of the extreme load changes see **Figure 2**

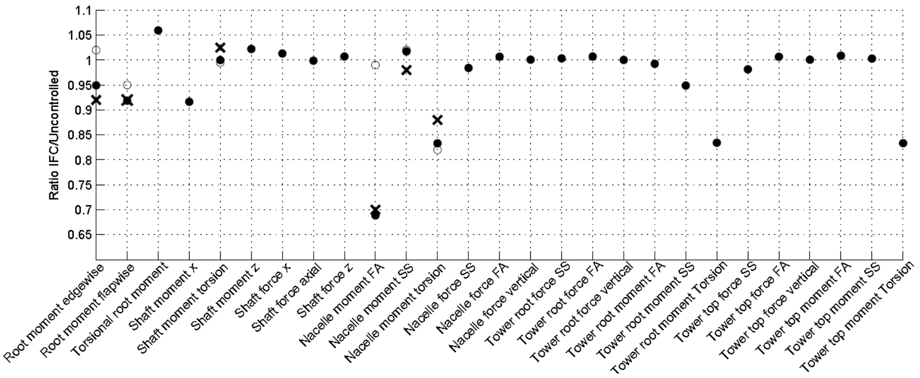


Figure 2: The ultimate load ratio with and without IFC, comparison of results (•) with Bæk IPC (o) and mode based control (x), copied from [2]

The reduced loading in the rotor does also change the loading in the hub, drivetrain, tower and foundation as can be seen in **Figure 1** and **Figure 2**.

The load spectra are determined on the basis of the IEC-61400-1 where the wind speed distribution is based on the measurements of the IJmuiden Ver meteorological mast with the Weibull scale and shape parameters values of 10.85 (a) and 2.15 (k) at the hub height. This results in an average wind speed of approximately 9.5 m/s at hub height. The assumed turbulence class is B, which is representative for off shore conditions.

The blade load reduction is mainly generated at the location of the flaps thus at the blade tips, however for the bending moments the highest reduction is achieved at the blade root. The fatigue load reduction at 33% span is 12.1% and at 2/3 of the span the reduction is reduced to 8.2%.The extreme load reduction is also less at more outboard stations, at 1/3 of the span the load reduction is 5.1% and at 2/3 of the span it is 3.8%.

The design driving loads on the tower are not that much affected by the load reduction in the rotor. The tower torsion is substantial lower and the vertical fatigue force is significantly reduced. However the axial force (FA) is showing a slight increase.

Based on the analysis of the expected load reductions stated above, the following chapters aim to give the expected reduction on the mass and therefore cost of the blades and tower elements of the reference turbine and their subsequent effect on the LCoE. Chapter 2 describes the cost model used for the tower and blades as well as a description of the O&M tool used for calculating availability. Chapter 3 gives a description of the reference machine as well as the results generated for the various models. Finally, Chapter 4 summarises the results and draws on the main conclusions of the study.

2

Description of the cost model

2.1 Introduction

The cost model applied to determine the effect on the LCoE is the FLOW cost model, see [4]. To run the cost model and calculate the value of the investigated innovations it is required to determine the effect of the innovation on several cost components inside the FLOW cost model. The FLOW cost model has a reference project that can be modified on project basis to evaluate the results of the different FLOW projects. The work done in this task is to determine the input for the FLOW cost model on the basis of engineering models.

The cost models used and described here are based on the Integral ECN cost model where it is assumed that the innovations investigated will only have effects on the rotor and thus the energy yield, the cost of the blades and the loads (generated by the rotor) on the tower and thus the cost of the tower (and foundation). Next to that the concept of a smart rotor will have influence on the availability of the machine in relation to the O&M effort / cost required. For the O&M only the influence of the smart rotor is taken into account. The flaps will require maintenance and might fail every now and then. This will of course influence the availability of the wind turbine and consequently the energy yield. The results of these models are input for the FLOW cost model in order to determine the effect on the LCoE.

There will also be a small effect due to the difference in wind farm efficiency effects. Applying a smart rotor in a wind farm might result in lower wake losses due to the fact that the thrust of a wind turbine with lower loads generated in the rotor will have a lower loss of impulse in the wind and can consequently lead to a higher production of the downwind wind turbines inside the wind farm. This effect is however not analysed and also not taken into account in the LCoE analysis. A lower coefficient of thrust (C_T) will result in higher wind farm efficiency.

However, in this study it is agreed by the project partners that the effects on energy yield are neglected. The study by Bernhammer, [2, 1], shows however that the integral reduction of energy yield is 3.75%, however later studies, [5], showed that this decrease can be minimised or even lead to a small increase of 0.4%.

The ECN blade and tower cost model use the wind speed distribution at 10 m height, the values are extrapolated in the model to hub height. The Weibull parameters at 10 m height used are the shape factor K of 1.65 and a scale factor of 7.75 m/s. This extrapolates to a Weibull scale parameter of 10.8 m/s and a Weibull shape factor of 2.15 at the hub height, approximately equal to the wind speed distribution used in [2].

Due to the fact that engineering cost models usually underestimate the cost of the components only the relative influences are used, i.e. the yield and the cost of rotor blades and tower are all taken relative to the result for the reference design given in [4] in the cost model.

The blade cost model and the tower cost model are describe in more detail in the following paragraphs. The results, the different yields, tower weights and blade weights are fed into the FLOW cost model to determine the influence on the Levelised Cost of Energy (LCoE).

2.2 Blade cost model

The price of the blade is determined by the weight of the blade in a simple manner:

$$Price = C_{blade} * \#_{blades} * Mass_{blade}$$

The $C_{blade,}$ i.e. the price per kg, is as given in the INNWIND.EU cost model for the year 2014, see [6], $ 1,09 * 13,084/kg = $ 14,26/kg or € 1,09/1.32 * 13,084/kg = € 10,80 / kg.

Other sources show other prices per unit of mass for rotor blades, the FLOW cost model uses € 21.50 / kg and price information that we have from the industry is that a price of € 12.5 / kg is well possible.

It is decide to use the average the 3 prices above (10,8+21,50 + 12,5) / 3 = € ~ 15 / kg for this project.

$\#_{blades}$ -= the number of blades of the wind turbine, in this case 3.

The $Mass_{blade}$ is the mass of the rotor blade of the composite parts.

The mass of a rotor blade is calculated with an engineering cost model of a rotor blade. This model consists of a simplified rotor blade design model that makes use of thin walled, slender beam theory. The loading on the blade is determined on the basis of a simplified load model that uses the IEC load conditions, class 1 B, as input.

In this model the blade is divided into three sections, the flange, the root and airfoil sections, see Figure 3. The flange cross section is cylindrical the airfoil cross section is created by an elliptical beam cross section that carries the load and thin sections in the shape of the aerodynamic profile. The root section, in between, is where the cylindrical load carrying section transforms into an ellipse.

The elliptical beam section consist of two elliptical shapes the outer contour and an elliptical inner contour. By subtracting the inner contour from the outer contour a thin walled beam remains. The outer dimensions of this beam are determined by the chord and profile thickness. The height of the beam, on the outside, is assumed to be 95% of the profile thickness and the width of the beam is assumed to be a certain percentage of the chord. This percentage can be varied along the span in a linear trend. This beam is designed at each element section for fatigue and static strength. The entire beam is designed to meet Eigenfrequency and stiffness requirements.

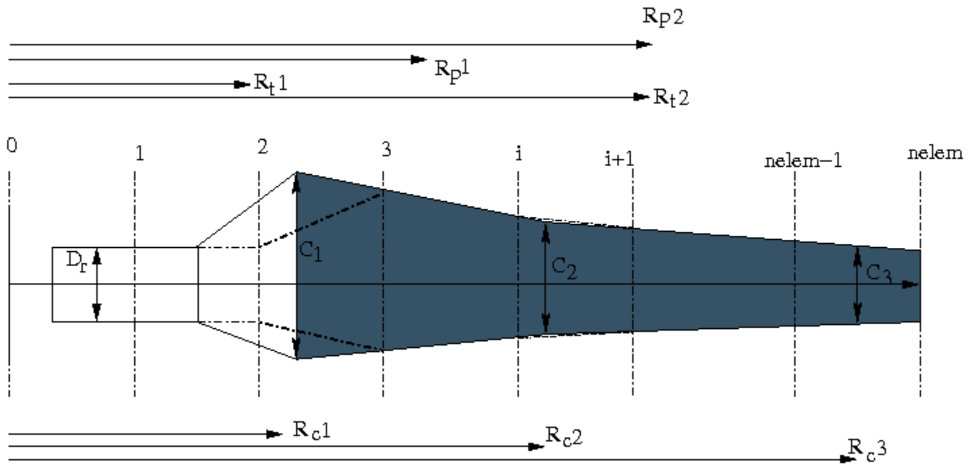


Figure 3: The blade model

The load spectrum for the rotor blade is calculated in a simplified manner, based on the Dutch Wind handbook part 3, [7]. The load spectrum is determined for 64 deterministic gusts that are based on the wind conditions defined in the input of the analysis. The wind spectrum for the load calculations can, and is in this case, based on the IEC wind conditions, IEC Class I B, ie. for an average wind speed of 10 m/s at hub height and the low turbulence class.

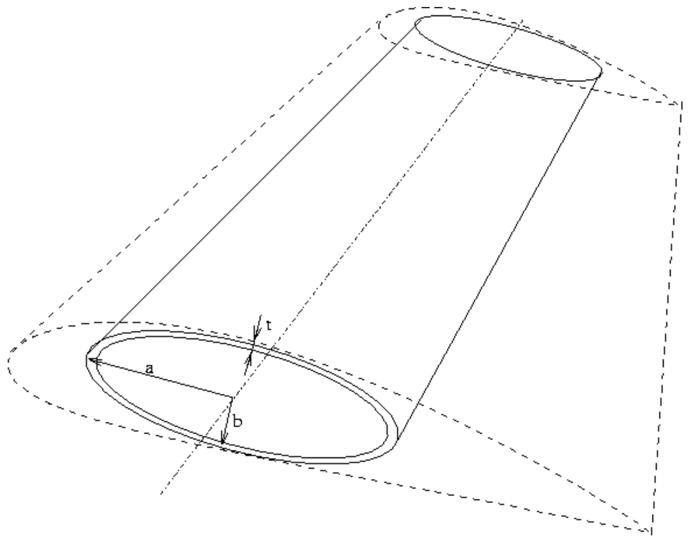


Figure 4: Airfoil section with a load carrying beam

The load spectrum is determined without initially modelling dynamics for the blade. The mass and stiffness are initially not known. On the basis of the flapwise and lead wise (aerodynamic) loads on the tip, the wall thickness of the tip element is determined and in the design loop, the weight component in the lead wise load direction is added. At the end of the initial design loop, when all blade elements from tip to flange have been designed, the mass and stiffness distribution of the blade is known and the Eigenfrequency of the rotor can be calculated. With this and the rotor RPM versus wind speed, the dynamic amplification factor for the stationary loads can be determined. Increasing the loads and design loop is made once again changing the mass/stiffness distribution. This design loop is repeated until the outcome does not change anymore. This design loop results in a “final” mass and stiffness distribution of the blades. The mass of the blades is used in the cost model to determine the influence on the LCoE. Due to the fact that the cost model is an approximation and as mentioned previously, engineering cost models usually under estimate the prices only the relative results are used. Thus the blade mass of the reference machine, without the innovation is used as the bases and the relative improvement is used in the overall cost model of FLOW.

2.3 Tower cost model

The tower cost is determined on the basis of the tower mass in a simple manner:

$$\text{Price} = c\_c\_1 * \text{Mass}_{\text{tower}}$$

The value of c_c_1 is 1,74 * \$ 2,5/kg = 1,74/1,32 * 2,5 = € 3,3 / kg.

The tower weight is determined with a tower design model, which is based on a simple engineering model. This means that the tower dimensions, tower radius and wall thickness distribution is determined in such a way that the mass of the tower is minimal with the following design restrictions:

Four strength and frequency requirements are implemented:

1. extreme loads,

2. fatigue loads,
3. buckling,
4. Eigenfrequency does not conflict with the rotor rotational speed.

The tower design varies the taper of the diameter and the wall thickness linearly with the height.

Assumptions in the design model are that:

- ✓ Diatop = 1. + c_Dia_top * Dia,
- ✓ T_towerTop = 0.02 [m],
- ✓ diameter varies linearly with the height,
- ✓ wall thickness varies linearly with the height.

The model of the tower is shown in **Figure 5**.

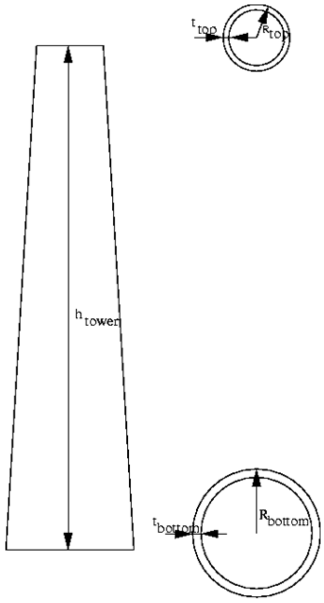


Figure 5: Tower model

Tower resonance requirements are shown in the table below:

soft-soft	ν_{tower}	$<$	$a \,.\, \Omega_{min}$				
stiff-soft	ν_{tower}	$>$	$b \,.\, \Omega_{max}$	&	ν_{tower}	$<$	a . **# blades** Ω_{min}
stiff-stiff	ν_{tower}	$>$	c . **# blades** . Ω_{max}				

The model results in a simple tower design described with the tower taper and the wall thickness taper which together with the tower height and the top diameter gives a complete description of the tower. The resulting design complies with the given constraint w.r.t. Eigenfrequency and has sufficient strength w.r.t. the given material strength parameters.

The engineering model results in:

- ✓ Mass_{tower}
- ✓ ν_{tower}
- ✓ Tower foot diameter
- ✓ Tower footwall thickness.

2.4 O&M (and availability) cost model

To determine the influence of the blade flaps modification on the O&M and consequently on the availability of the wind turbine an analysis will be performed with the ECN O&M Tool V.4-4, [8]. This is a tool implemented in Excel and is certified by Germanischer Lloyd.

To determine the differences due to the smart rotor a reference case, a wind farm, has been modelled in the tool. The reference wind farm consist of a 100, 5 MW wind turbines, which are located close to the shore.

To model the smart rotor in the O&M Tool it will be required to determine the additional failure options that are linked to the application of the smart flaps on the rotor.

Next to that each failure option should have a probability of occurrence and a description of the consequences and requirements to repair. Thus e.g. when a flap failure is described:

- ✓ Probability of occurrence, e.g. once every 7 years (or 3 times in the lifetime of the wind turbine).
- ✓ The wind turbine will be shut down above rated wind speed.
- ✓ It will be required to send 4 mechanics capable of using rope access to inspect the blade and possibly replace the flap.
- ✓ The cost of the replacement components.
- ✓ The cost of the equipment and personnel.
- ✓ The weather requirements, e.g. the wind speed should be lower than 8 m/s at the hub height.

With the O&M tool it will be determined what the waiting time will be and what the cost of the repair will be, i.e. the lost production and the cost of the maintenance crew.

3

Results

3.1 Description of the reference machine

The wind turbine model used in the study is the 5 MW NREL / UPWIND reference wind turbine, see [3]. This model is a well-developed and often used calculation model based on the DOWEC 5 MW wind turbine.

Table 1: Turbine specifications NREL offshore 5-MW baseline wind turbine

Parameter	**Value**
Rotor diameter	126 m
Hub height	90 m
Rated power	5 MW
Power regulation	Variable speed, collective pitch control system
Pitch regulation	Electrical
Generator	Direct-Drive Permanent Magnet

3.2 The modifications for the smart rotor applied in the blade cost model

The smart rotor is for the modelling of the cost mainly the change in the rotor blade structure. At the tip of the rotor blade a flap or flaps will be installed. The location and dimensions of the flap are, between 78% and 98% of the rotor radius and has a width of 10% of the local chord, which is ~2.78 m (@ 78% R – 49.15 m) and ~1.75 m (@ 98% R – 61,74m). This makes a flap of the dimensions as follows, a length of 12.6 m with a chord between 0.287 m and 0.175 m) and an approximated surface of 2.85 m^2, see **Figure 6**

The load reduction that is of interest for the cost study is the reduction in blade loading.

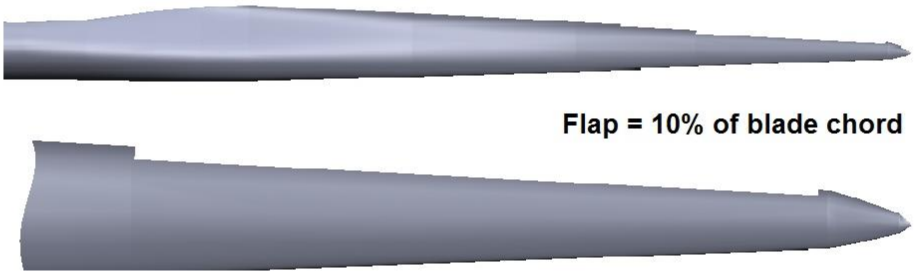


Figure 6: A graphic representation of the flap

The load reduction for the rotor blades root sections are calculated and reported in [2]. The distribution of the load reductions along the span, communicated via email, is shown in the **Table 2**, and **Figure 7**.

Table 2: Load reduction in the blades as a function of the span

	Flapwise		Edgewise	
	Nm		**Nm**	
R	Fatigue	Extreme	Fatigue	Extreme
%R	%	%	%	%
0.00	-24.	-8.	-1.5	-8.
33.33	-12.1	-5.1	-1	-5.33
66.67	-8.2	-3.8	-0.5	-2.67
100.00	0.	0.	0.	0.

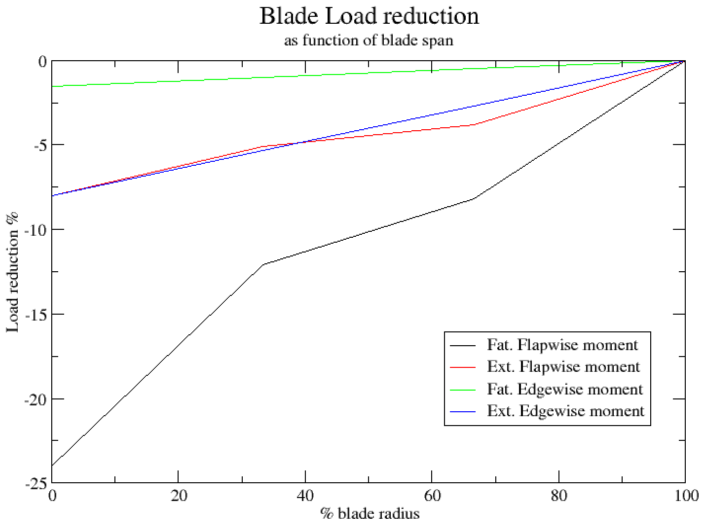


Figure 7: The reduction of the blade loads as a function along the span

The additional cost of adding a flap to the rotor blade is estimated at k€ 60. The cost of the flap is estimated at k€ 40, [9], and the cost to modify the blade is estimated at k€ 20, half that of the cost of a flap.

The results of the analysis with the blade cost model show that the blade weight will be reduced with 8.2% due to the lower loading. The blade weight of the NREL blade is according to [3] 17,740 kg. A blade mass reduction of 8.2% results in a weight reduction of 1454 kg or a reduction of the price (in €'s) when the cost of a blade is € 15,00 / kg, [6], of € 21.810. The blades of the NREL 5 MW wind turbine are estimated to cost (only the composite structure) 17,740 kg or k€ 266,100 each. The cost of the blade including the flaps is estimated to be 0.918 * 17,740 * € 15 + € 60.000,= k€ 302,280.

The price increase for the rotor is assumed to be 302,280/266,100 = 1.14 or 14 % higher.

The rotor blades of a rotor with flaps are 14% more expensive compared to the reference wind turbine.

The tower fore aft bending moments is actually not significantly changed; see **Figure 1** and **Figure 2**. The (only) tower loadings that are substantially reduced are the fatigue equivalent vertical force and torsional moments. These are however not a design driving loads.

This results in a minimal change in the cost of the tower.

The tower mass and cost of wind turbine with flaps is assumed to be equal to the reference wind turbine

3.2.1 The O&M cost effects due to the application of a smart rotor and the consequences on the availability of the wind turbine.

To determine the influence of the smart rotor flaps on the O&M cost and the availability resulting from that Darwind-XEMC performed a preliminary FMEA (Failure Mode & Effect Analysis), [9]. For practical reasons Darwind – XMEC performed the analysis as if the modification was used on the Darwind – XEMC 5 MW, which has a rotor diameter of 115 m.

Three new failure cases are defined:

1. A defective load transducer inside the flap, with an occurrence of once every 10 years with a repair time of 2 hrs and additional cost of € 150 for the transducer. The crew required is 3, one using rope access to the flap and 2 inside the nacelle.
2. A small failure in the flap, which can be replaced by a refurbished flap, with an occurrence of once every 10 years, with a repair time of 8 hrs and the cost of the refurbished flap of k€ 10, a quarter of the estimated cost of a flap. The crew required is 4, 2 using rope access to the flap and 2 inside the nacelle.
3. A large failure of the flap, which needs to be replaced by a new flap. The failure description is identical to #2 but this time a new flap will be installed with a cost of k€ 40.

Each failure has been modelled in the OM Tool resulting in the following increases (**Table 3**) in the cost per kWh and decreases in the availability of the wind turbine.

Table 3: Effects on O&M cost and availability due to the Smart rotor

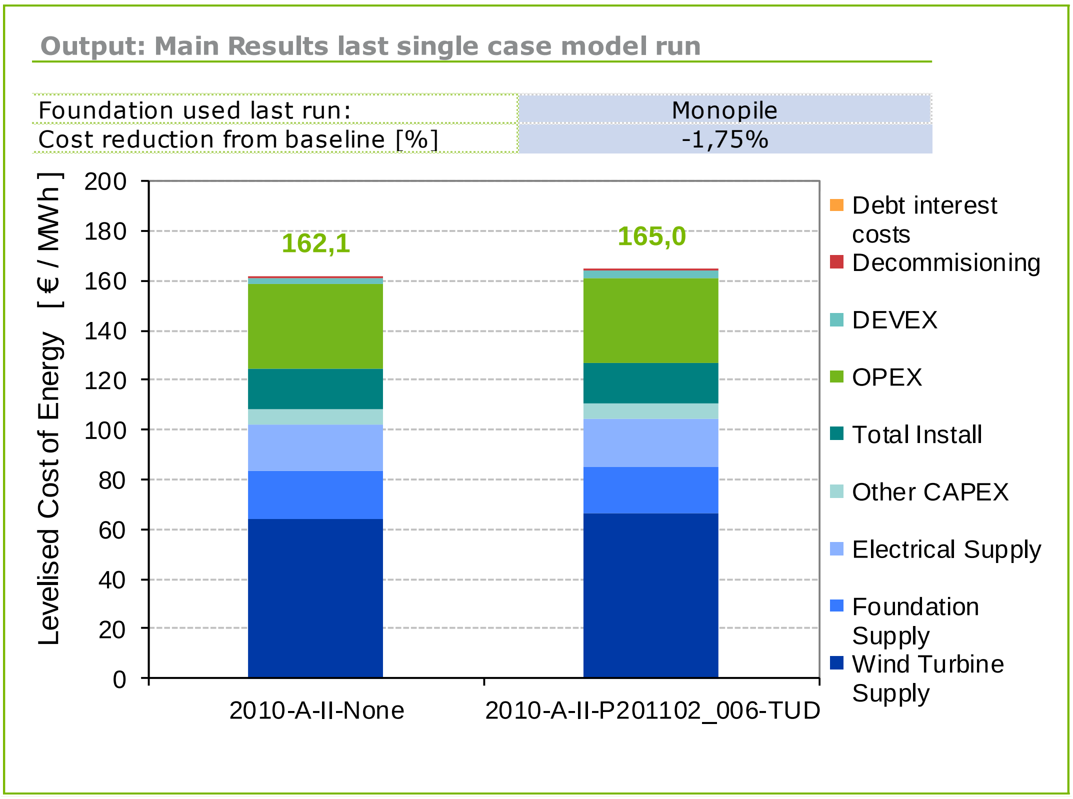
	Ratio of Smart Rotor WF / Reference WF
Relative effect on O&M Cost	1,016
Relative effect on Availability	0,996

3.3 The integral effect on the LCoE

The integral cost effect is determined with the Flow cost model, [4], using the results from the ECN cost model as input.

The parameters that are changed due to the analysis in paragraph 3.2 are

- The rotor blades increased in price 14%
- The tower is unaltered
- The increase in O&M cost is 1.5%
- The decrease in availability is 0.5%



Output: Main Results last single case model run

Foundation used last run:	Monopile
Cost reduction from baseline [%]	-1,75%

Figure 8: The overall result on the LCoE of the reference case WF A (Hollandse Kust) and Turbine type II (5 MW).

The overall cost effect of the application of the smart rotor is that the cost increases from € 162.1 / MWh to 165.0 / MWh which is an increase of 1.8%.

4

Conclusion and discussion

The application of a smart rotor on an offshore wind turbine, at the moment and on the basis of the assumptions mentioned in this report, does not have a favourable effect on the cost of energy. Due to the fact that the rotor blades increase in price quite substantially, with more than 14% and at the same time the O&M cost increase slightly by 1.5 % and an also very small reduction of the availability of the wind turbine of approximately 0.4% the outcome of the integral analysis is, not surprisingly[1], an increase of the LCoE of approximately 1.8%

The results are determined with a substantial number of estimated parameters. The cost of the flap and the cost of change in the rotor blade construction of in total k€ 60 is substantial on the total assumed cost of a rotor blade. To make the cost of the flap equal to the cost reduction due to weight reduction the total cost of adding a flap to a rotor blade should not be higher than € 22.000.

But even if the assumptions are too high the cost of energy would still become higher although with a lower percentage.

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[1] Not surprisingly due to the fact that all determined inputs indicate a higher LCoE.

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