R E G I O N E   C A M P A N I A

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C O M U N I   D I   L a c e d o n i a   (A V)   –   M o n t e v e r d e   (A V)

PROGETTO

PROGETTO DI REBLADING DEL PARCO EOLICO LACEDONIA-MONTEVERDE (39,60 MW)

PROGETTO DEFINITIVO

COMMITTENTE:

ERG Wind 4

ERG
EVOLVING ENERGIES

PROGETTISTA:

GOLDER
Via Sante Bargellini, 4
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GOLDER

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OGGETTO DELL'ELABORATO:

RELAZIONE DI VERIFICA AERODINAMICA DELLA TURBINA

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Storia delle revisioni del documento

REV.	DATA	DESCRIZIONE REVISIONE	REDATTO	VERIFICATO	APPROVATO
00	**03/2019**	PRIMA EMISSIONE	MGL	LSP	VBR

INDICE

1. PREMESSA

La presente relazione ha come oggetto l'analisi aerodinamica del rotore di una turbina eolica da 660 kW, modello Vestas V47. Si precisa che benché nel documento si faccia riferimento ad un rotore di classe IEC III, la stessa pala è in fase di riclassificazione da parte dell'ente terzo per rientrare nella classe IEC I.

La progettazione aerodinamica, effettuata da ECN per conto di ETA Blades, ha come obiettivo l'ottimizzazione della geometria del rotore al fine di massimizzare la resa energetica annua e ottenere un coefficiente di potenza Cp_{max} elevato. In fase progettuale sono stati inclusi comportamenti dinamici e problemi strutturali al fine di raggiungere un buon compromesso nel design finale.

Dal momento che la turbina è già esistente, lo scopo del lavoro è stat la progettazione di una nuova pala, eseguita col software Blade Optimization Tool (BOT). L'uso di nuovi profili alari ha permesso di ottenere una geometria più snella che, raffrontata ad una geometria di riferimento, ha mostrato evidenti miglioramenti sia in termini di produzione annua e che di valori del coefficiente di potenza Cp. Al tempo stesso, si sono raggiunte riduzioni negli sforzi assiali che permettono di incrementare la vita utile della torre. Va però sottolineato che i risultati ottenuti sono basati su simulazioni in condizioni stazionarie e assumendo che la pala sia rigida.

Confidential

Aerodynamic Design of a 660 kW Class III Wind Turbine Rotor

F. Grasso

September 2012
ECN-X--12-041

Acknowledgement

The report describes the aerodynamic analysis of a 660kW wind turbine class IEC III rotor, operating at fixed rotor speed with active pitch control. The work was done under contract with ETA-blades.

ECN project number: 6.00575

Abstract

The present report is focused on the description of the activities performed to design a new 660kW wind turbine rotor for IEC Class III.

The aerodynamic design is determined with the goal to optimize the rotor geometry for maximum annual yield and obtain high C_{pmax}. Dynamic behaviour and structural issues have been included in order to obtain a good compromise in the final design.

Contents

Introduction

ETA contracted ECN to design a new blade for 660kW wind turbine rotor, operating at fixed rotational speed with active pitch control.
The turbine is an existing one, so the project was focused on the design of a new blade for the turbine. More in details, the project is divided in three phases, detailed as below.

- Aerodynamic analysis of the existing 660kW wind turbine rotor
- Design of a new family of advanced airfoils
- Aerodynamic design of the new blade for 660kW wind turbine

The present report is focused on the description of the activities performed during the **third** phase.
The aerodynamic design is performed with the program Blade Optimization Tool (BOT) [1], which optimizes the rotor geometry for maximum annual energy yield. For this optimisation, a wind climate characterized by a Weibull form factor k = 2 and an annual mean wind speed of 7.5 m/s is used.
The initial data and the requirements for the blade design are described in chapter 1. In chapter 2 the choice of airfoils is motivated and characteristic coefficients of the airfoils are discussed. The optimisation process is discussed in chapter 3 and the results of the final design are discussed in more detail.

1 Requirements for blade design

The specific requirements of the blade design given by ETA-Blades are summarized below.

1.1 Geometrical parameters

Rotor Diameter [m]:	49*
Hub Radius [m]:	1.1
Number of Blades	3
Max. Chord [m]:	3
Position of Max. Chord [m]:	-
Max. Twist [deg]:	-
Tilt Angle [deg]:	-
Cone Angle [deg]:	-

*The initial value for the rotor diameter was 47m, but after the first design iteration, it has been increased to 49m.

1.2 Operational parameters

IEC Class:	3
Cut in Wind Speed [m/s]:	3
Nominal Wind Speed [m/s]:	7.5
Cut Out Wind Speed [m/s]:	25
Rotor Speed [rpm]:	28.5
Max. Tip Speed [m/s]:	75

Max. Power [kW]:	660
Power Control:	active pitch
Optimal Cp (mech.)	>0.49

During the design, the ECN software BOT has been used. One of the inputs of the design is the mechanical and electrical losses; in absence of data provided by the customer, the following values have been assumed, based on previous experience.

Fixed Mechanical and Electrical Losses [kW]:	10
Variable Mechanical and Electrical Losses [%]:	4

1.3 Additional requirements

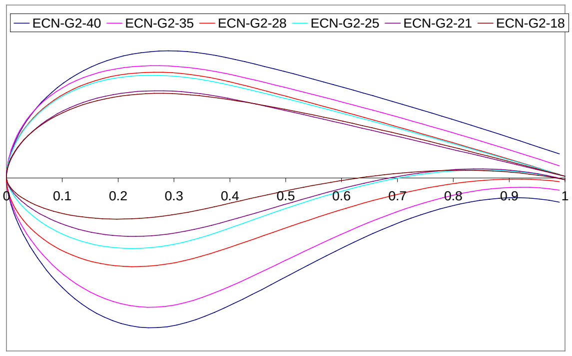
The new blade should be suitable as replacement for an old blade in an existing turbine. The design should be performed in such way that no adjustments/modifications are need for the other components/sub-systems of the turbine. In particular, the performance of the blade should be satisfactory with the existing control system/algorithm.

2

Airfoils selection

The selection of the airfoils to be installed along the blade plays a crucial role during the design of a blade. In the present project, instead of existing airfoils, special airfoils have been used, specifically designed for this blade. The complete discussion about these geometries (named ECN-G2-xx) can be found in [2]; here, only the shapes and the main aerodynamic characteristics are illustrated.

Figure 1: ECN-G2-xx airfoils. Comparison between the geometries



Thickness (%)	Airfoil ID
40	ECN-G2-40
35	ECN-G2-35
28	ECN-G2-28
25	ECN-G2-25
21	ECN-G2-21
18	ECN-G2-18

Figure 2: Lift curves of the ECN-G2-xx airfoils

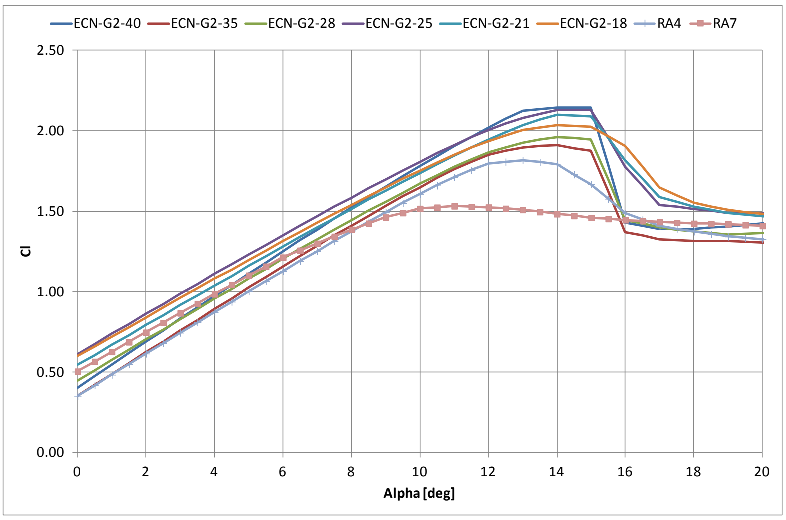
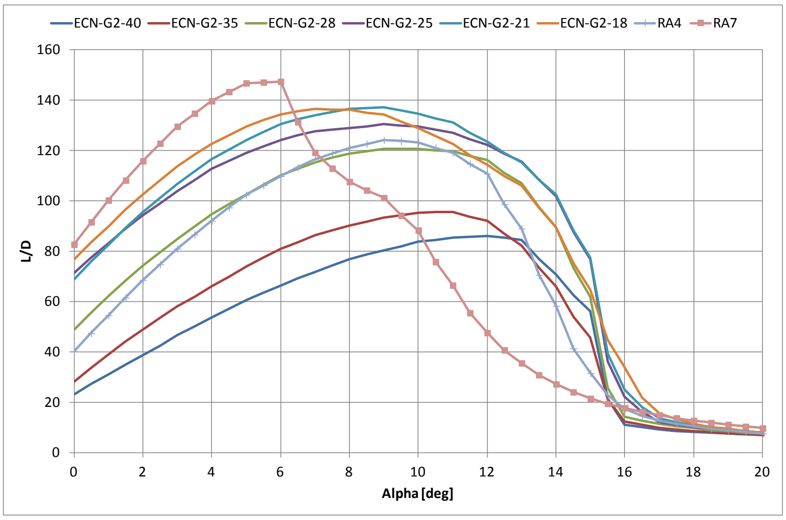


Figure 3: Efficiency curves of the ECN-G2-xx airfoils



3

Blade design

The rotor blade is optimized for a maximum annual energy production (with a given wind climate). The program BOT , used for blade design, has an option for optimizing the rotor geometry (chord and twist) for a given Weibull wind distribution, characterized by its scale factor *A* and form factor *k*. Instead of *A*, the annual mean wind speed $\overline{U}$ can be used, since

$$\overline{U} = A\Gamma\left(1 + 1/k\right) \approx 0.89A$$

for common values of *k* (Γ is the complete gamma function). This option maximizes the value of

$$E = \int_{U_{\text{in}}}^{U_{\text{out}}} P(U)\, f(U; A, k)\, dU,$$

where *f*(*U*; *A*, *k*) is the Weibull wind distribution. Wind turbine class III has an annual average wind speed $\overline{U}$ of 7.5 m/s. The present design is optimized for this average wind speed and k = 2. *P*(*U*) is the calculated turbine power, after correction for the mechanical and electrical losses. In BOT these losses have been modeled by a constant loss plus a percentage of the aerodynamic power (see operational parameters in section 1.2).
Without restrictions, the resulting blade geometry from BOT is the one that gives maximum annual energy yield for the specific wind climate defined.
For a specific tip speed ratio, the maximum power is achieved for one optimal combination of the chord and twist distribution. This optimal combination is found when every blade section operates at the optimal angle of attack (i.e., at the maximum lift over drag ratio) while the value of the axial induction factor is *a* ≈ 1/3.

3.1 Design results

In this section, the results of the design are illustrated and discussed. For comparisons, the Reference Wind Turbine (RWT) provided by ETA-Blades and analyzed has been used as reference. The details about the RWT can be found in [3].

3.1.1 Geometry

Figures 4-6 show chord, twist and thickness distributions of the new (indicated NEW in the graphs) blade compared to the RWT. Apart from the length of the blade (increased in the new one), the biggest differences between the new blade and the RWT are in terms of chord and thickness distributions. This is a direct consequence of the properties of the used airfoils; the ECN-G2 airfoils have been developed with the goal to produce high lift in order to be effective also at low speed condition. During the design of the blade this characteristic lead to a sensible reduction in chord, and consequently in wetted area.
In table 1, the geometrical properties of the new blade are summarized.

Figure 4: Chord distribution

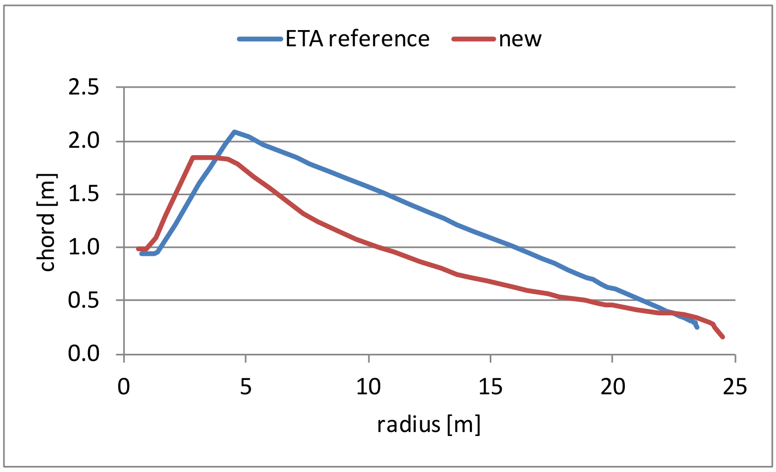


Figure 5: Twist distribution

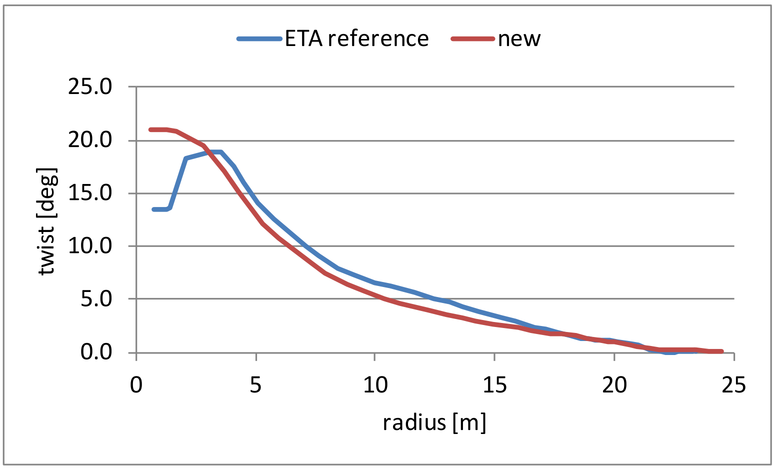
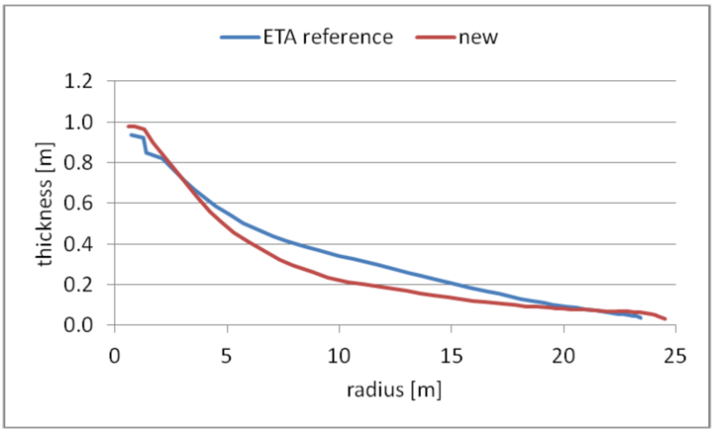


Figure 6: Thickness distribution



Tabel 1: Geometrical characteristics of the new blade

Radius [m]	*Chord [m]*	*Twist [deg]*	*Thickness [m]*	*Percentage thickness [-]*
0.6000	0.9800	21.0034	0.980	1.00
0.9000	0.9800	21.0034	0.980	1.00
1.2930	1.0921	20.9904	0.963	0.88
1.7000	1.3000	20.8925	0.900	0.69
2.8000	1.8368	19.4385	0.750	0.41
3.6526	1.8368	17.0172	0.632	0.34
4.2653	1.8296	15.1083	0.560	0.31
4.6867	1.7834	13.8753	0.510	0.29
5.3109	1.6600	12.0721	0.457	0.28
5.9484	1.5500	10.6930	0.409	0.26
7.3546	1.3200	8.3123	0.323	0.24
7.9280	1.2434	7.4909	0.296	0.24
8.8089	1.1561	6.4677	0.262	0.23
9.4946	1.0825	5.8106	0.235	0.22
10.3923	1.0075	5.0997	0.213	0.21
11.0603	0.9539	4.6460	0.202	0.21
12.1478	0.8620	3.9840	0.182	0.21
12.9840	0.7988	3.5122	0.169	0.21
13.6358	0.7527	3.1819	0.154	0.21
14.2015	0.7193	2.9341	0.146	0.20
14.9003	0.6831	2.6674	0.137	0.20
15.9890	0.6266	2.2784	0.120	0.19
16.5349	0.5990	2.0839	0.114	0.19
17.3375	0.5611	1.8122	0.105	0.19
17.8277	0.5399	1.6821	0.098	0.18
18.3713	0.5181	1.5205	0.093	0.18

18.8793	0.4977	1.3317	0.090	0.18
19.3998	0.4765	1.1302	0.086	0.18
19.7102	0.4640	1.0296	0.084	0.18
19.9813	0.4534	0.9196	0.082	0.18
20.3204	0.4408	0.7946	0.079	0.18
20.6498	0.4293	0.6816	0.077	0.18
20.9682	0.4189	0.5742	0.075	0.18
21.4444	0.4041	0.4236	0.073	0.18
21.8919	0.3914	0.3132	0.070	0.18
22.3899	0.3791	0.2493	0.068	0.18
22.8919	0.3680	0.2181	0.066	0.18
23.1666	0.3603	0.2339	0.065	0.18
23.4271	0.3460	0.1937	0.062	0.18
23.9468	0.3006	0.1548	0.054	0.18
24.0824	0.2803	0.1521	0.050	0.18
24.1868	0.2556	0.1521	0.046	0.18
24.5023	0.1666	0.1519	0.030	0.18

3.1.2 Performance

As mentioned in the section 1.3, the new blade should produce satisfactory performance with an existing control system in use. The pitch control used as reference change the pitch angle of the blade according to internal presets for low wind speeds and to limit the power for high wind speeds. The values of pitch angle for each wind speed have been provided by ETA-Blades and can be found in [3]. The performance are evaluated considering the pitch system active.
Table 2 shows a comparison between the general performance of the new blade with the RWT. It should be noticed that the radius of the RWT is 1 meter shorter, so this has also impact on the comparisons.

Tabel 2: General performance summary

	RWT	NEW	Δ (%)	
Yield [GWh/yr]:	2.155	2.272	5.4	Annual yield
P_{rated} [kW]:	660			Rated power
U_{rated} [m/s]:	11.5			Rated wind speed
C_{Pmax} (mech):	0.4859	0.4971	2.3	Maximum mechanical power coefficient

In table 3 instead, the detailed performance for each wind speed are listed. The data reported in bold for the pitch angle are the ones imposed by the pitch control algorithm, while the others are automatically adjusted in order to maximize the performance of the blade. In figures 7-11, the comparisons between these data and the ones related to the RWT are shown.

Tabel 3: Performance of the new blade

U [m/s]	P_{elec} [kW]	P_{dyn} [kW]	P_{mech} [kW]	θ_{blade} [°]	λ [-]	η [-]	Ω [rpm]	$C_{P\,mech}$ [-]	$C_{P\,elec}$ [-]	C_T [-]	F_{ax} [kN]	$M_{bl.root}$ [kNm]
3.00	(-0)	0.8	(-14)	0.00	24.376	0.000	28.500	-0.4643	0.0271	1.5610	16.2	95.2
3.50	(-0)	5.1	(-7)	0.20	20.894	0.000	28.500	-0.1489	0.1021	1.2690	18.0	100.9
4.00	5.6	15.4	16.2	**1.40**	18.282	0.344	28.500	0.2194	0.2080	1.0275	19.0	104.9
4.50	24.3	32.3	35.7	**1.35**	16.251	0.680	28.500	0.3390	0.3066	0.9733	22.8	123.6
5.00	46.4	55.0	58.8	**1.10**	14.625	0.790	28.500	0.4069	0.3807	0.9430	27.2	145.8
5.50	74.1	82.7	87.6	**1.02**	13.296	0.846	28.500	0.4557	0.4302	0.8992	31.4	166.3
6.00	105.6	115.0	120.4	**0.95**	12.188	0.877	28.500	0.4824	0.4610	0.8559	35.6	186.3
6.50	140.2	151.9	156.4	**0.83**	11.250	0.896	28.500	0.4930	0.4788	0.8172	39.9	206.6
7.00	178.8	193.4	196.7	**0.60**	10.447	0.909	28.500	0.4964	0.4880	0.7873	44.6	228.8
7.50	222.5	239.1	242.2	**0.23**	9.750	0.919	28.500	0.4970	0.4907	0.7667	49.8	253.9
8.00	271.3	288.5	293.0	**-0.18**	9.141	0.926	28.500	0.4954	0.4878	0.7480	55.3	280.0
8.50	324.8	339.9	348.7	**-0.59**	8.603	0.931	28.500	0.4915	0.4791	0.7286	60.8	306.1
9.00	383.6	391.1	410.0	**-1.07**	8.125	0.936	28.500	0.4868	0.4643	0.7120	66.6	333.6
9.50	444.0	439.5	473.0	**-1.29**	7.698	0.939	28.500	0.4775	0.4437	0.6853	71.5	355.7
10.00	509.4	483.1	541.1	**-1.60**	7.313	0.942	28.500	0.4684	0.4182	0.6629	76.6	379.3
10.50	578.7	520.8	613.2	**-1.95**	6.965	0.944	28.500	0.4585	0.3894	0.6419	81.8	403.2
11.00	642.1	552.0	679.3	**-1.84**	6.648	0.945	28.500	0.4418	0.3590	0.6074	84.9	416.8
11.50	660.0	577.2	697.9	0.37	6.359	0.946	28.500	0.3972	0.3285	0.5210	79.6	384.8
12.00	660.0	597.1	697.9	2.59	6.094	0.946	28.500	0.3496	0.2991	0.4423	73.6	349.4
12.50	660.0	612.4	697.9	4.39	5.850	0.946	28.500	0.3093	0.2714	0.3821	69.0	321.9
13.00	660.0	624.1	697.9	5.95	5.625	0.946	28.500	0.2750	0.2459	0.3342	65.2	299.2
13.50	660.0	632.9	697.9	7.35	5.417	0.946	28.500	0.2455	0.2227	0.2950	62.1	279.6
14.00	660.0	639.6	697.9	8.63	5.223	0.946	28.500	0.2202	0.2018	0.2623	59.4	262.5
14.50	660.0	644.5	697.9	9.82	5.043	0.946	28.500	0.1982	0.1830	0.2347	57.0	247.1
15.00	660.0	648.2	697.9	10.95	4.875	0.946	28.500	0.1790	0.1663	0.2111	54.9	233.2
15.50	660.0	651.0	697.9	12.01	4.718	0.946	28.500	0.1622	0.1513	0.1908	53.0	220.5
16.00	660.0	653.1	697.9	13.03	4.570	0.946	28.500	0.1475	0.1380	0.1732	51.2	208.8
16.50	660.0	654.7	697.9	14.00	4.432	0.946	28.500	0.1345	0.1262	0.1579	49.7	197.9
17.00	660.0	655.9	697.9	14.93	4.302	0.946	28.500	0.1230	0.1156	0.1445	48.2	187.8
17.50	660.0	656.8	697.9	15.83	4.179	0.946	28.500	0.1127	0.1061	0.1326	46.9	178.4
18.00	660.0	657.4	697.9	16.71	4.063	0.946	28.500	0.1036	0.0976	0.1221	45.7	169.6
18.50	660.0	658.0	697.9	17.55	3.953	0.946	28.500	0.0954	0.0900	0.1128	44.6	161.2
19.00	660.0	658.4	697.9	18.37	3.849	0.946	28.500	0.0881	0.0831	0.1044	43.5	153.4
19.50	660.0	658.7	697.9	19.17	3.750	0.946	28.500	0.0815	0.0769	0.0969	42.6	145.9
20.00	660.0	658.9	697.9	19.95	3.656	0.946	28.500	0.0755	0.0713	0.0902	41.7	138.8
20.50	660.0	659.1	697.9	20.70	3.567	0.946	28.500	0.0701	0.0662	0.0841	40.8	132.4
21.00	660.0	659.2	697.9	21.44	3.482	0.946	28.500	0.0652	0.0616	0.0786	40.0	126.0
21.50	660.0	659.3	697.9	22.17	3.401	0.946	28.500	0.0608	0.0574	0.0736	39.3	119.9
22.00	660.0	659.4	697.9	22.87	3.324	0.946	28.500	0.0567	0.0536	0.0690	38.6	114.1

22.50	660.0	659.5	697.9	23.57	3.250	0.946	28.500	0.0530	0.0501	0.0649	37.9	108.5
23.00	660.0	659.6	697.9	24.25	3.179	0.946	28.500	0.0497	0.0469	0.0610	37.3	103.2
23.50	660.0	659.6	697.9	24.91	3.112	0.946	28.500	0.0466	0.0440	0.0576	36.7	98.0
24.00	660.0	659.6	697.9	25.56	3.047	0.946	28.500	0.0437	0.0413	0.0544	36.2	93.1
24.50	660.0	659.7	697.9	26.20	2.985	0.946	28.500	0.0411	0.0388	0.0514	35.6	88.4
25.00	660.0	659.7	697.9	26.83	2.925	0.946	28.500	0.0387	0.0365	0.0487	35.2	83.9

Where:

U [m/s]:	Wind speed
P_{elec} [kw]:	Electrical power
P_{dyn}[kW]:	Dynamic power (electric + turbulence)
P_{mech} [kW]:	Mechanical power
θ_{blade}[deg]:	Blade pitch angle
λ[-]:	Tip speed ratio
μ[-]:	Efficiency of the mechanical system
Ω[RPM]:	Rotational speed
Cp_{mech} [-]:	Mechanical power coefficient
Cp_{elec}[-]:	Electrical power coefficient
Ct [-]:	Aerodynamic thrust coefficient
F_{ax} [kN]:	Axial force
Mbl_{root} [kNm]:	Root bending moment

Figure 7: Power curve of the new blade compared to the reference geometry

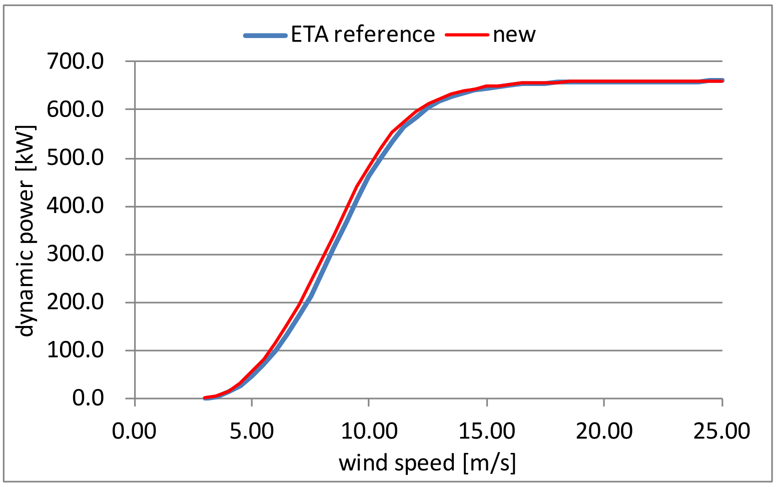


Figure 8: Power curve of the new blade compared to the reference geometry. Detail

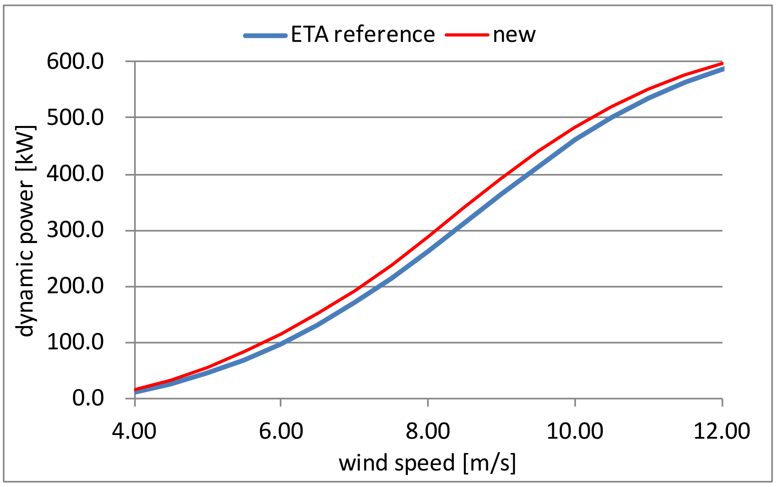


Figure 9: Power coefficient curve of the new blade compared to the reference geometry

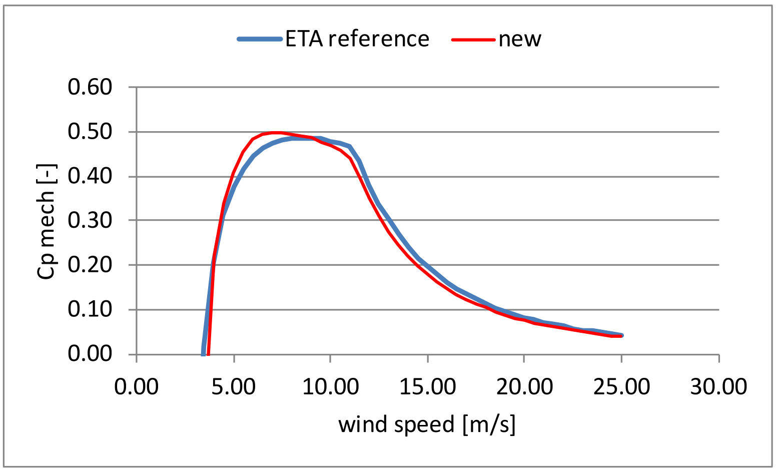


Figure 10: Axial force curve of the new blade compared to the reference geometry

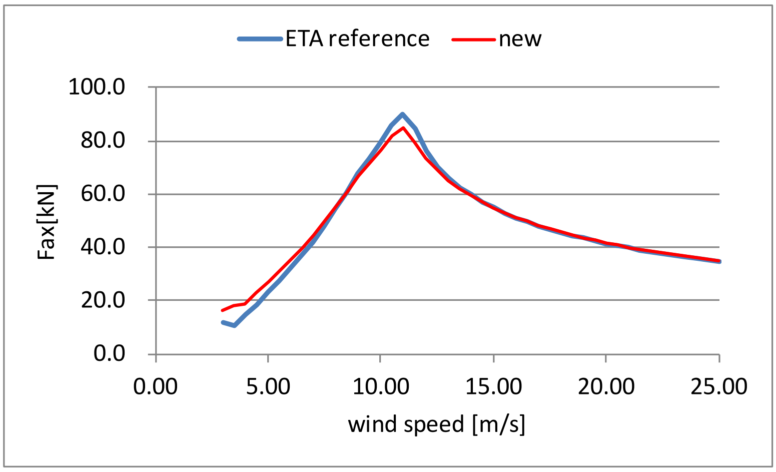
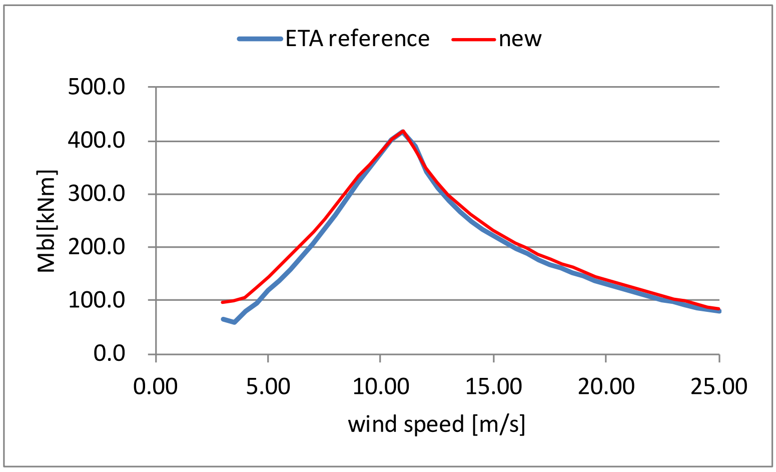


Figure 11: Root bending moment curve of the new blade compared to the reference geometry



From figure 8 it can be noticed that the power produced by the new blade is larger than the RWT over the complete range of low-medium wind speeds; for high wind speed, the control system limits the power to the rated value. The annual yield production is increased of 5.4% with a better value of C_{pmax} (+2.3%). At the same time, the maximum root bending does not exceed the one of the RWT (-0.1%) and the maximum of the axial force is 5% smaller. This has positive impact on the tower since the forces acting on the top of the tower, due to the rotor are less intense.

4 Conclusions

The design of a 660kW IEC class III rotor has been performed. New airfoils have been used that led to a slender geometry. Comparisons with a reference geometry showed significant improvements in terms of annual yield production and Cp with less wetted area and chord distribution. At the same time, reduction regarding the axial force have been reached that are beneficial for the life time of the tower. However, it should be kept in mind that the analyses presented in this report are performed in steady conditions, under the assumption that the blade is rigid.

References

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