A new approach for comparability of two- and three-bladed 20 MW offshore wind turbines

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Abstract. Wind energy plants are subject to a vast optimization process with a multitude of design parameters. While one specific three-bladed turbine type dominates the on- and offshore market, two-bladed turbines offer promising, but not yet quantified, potentials for cost savings during manufacturing, erection, and maintenance, offshore. Nevertheless, the comparability of two- and three-bladed turbines is challenging, causing an ongoing discussion within research and industry about which alternative to prefer. A new approach could be to reduce the important changes made by maintaining the exact same energy yield. This results in an increase of design changes of the two-bladed rotor, due to slightly (about 2%) longer blades to counterbalance the inevitable losses of aerodynamic efficiency. Nevertheless, it has the great advantage that subsequent comparisons of loads, masses and costs do not have to be associated with a loss of power. This could serve as a solid basis to allow drawing conclusions and considering differences in dynamical loads, masses and costs more directly and hopefully more expediently, when comparing two- and three-bladed wind turbines.

1. Introduction
Three-bladed, upwind, fixed-hub, pitch-controlled, variable-speed wind turbines are an omnipresent wind energy plant concept, originally designed for the use onshore and adapted for the offshore use. However, since environmental requirements are different, two-bladed wind turbines could be a promising alternative for the offshore wind energy market, due to cost savings in the rotor or drivetrain, faster and easier erections, potential for better accessibility by helicopter, a lighter turbine head mass, fewer components and thus a possibly smaller probability of failure [1, 2]. If two blades turn out to be superior for an offshore turbine, it will be an assessment of financial risk, resulting out of a change of technology, and the advantage of a lower levelized cost of energy (LCoE). For a clear decision, the comparability should be enhanced by reducing the most important changes made, namely by retaining the same amount of energy produced.

Most comparisons of two- and three-bladed wind turbines argue that the rotor diameter should stay unaltered (inter alia [3–10]). However, reducing the number of blades increases the distance between vortex sheds, trailing each rotating blade, by one third, if maintaining the same tip speed. A higher rotation speed would partially counterbalance the loss effects, but only until the influence of aerodynamic drag forces increases. As a result, tip losses of two-bladed turbines are generally higher, while the corresponding power coefficient $C_P$ of a similar design will inevitably be lower (derived from [11]). Hence, subsequent comparisons...
of loads or costs will always have to be associated with a loss of energy [5–9]. While this approach requires fewer design changes of the rotor, the difference in energy production effects more components and cost predictions than an insignificantly (≈ 2%) larger rotor. During the INNWIND project a comparison of two- and three-bladed turbines has been elaborated, where the two-bladed ones were equipped with 4%, 8% and 12% longer blades [12]. While the annual energy productions (AEPs) were higher, the rotors themselves had always been lighter and hence cheaper than the three-bladed reference rotor. However, the aim was not to match the exact same AEP, again creating the difficulty to compare a change of loads on the basis of unequal energy production. A new, but promising approach is to perform an iterative redesign from a three-bladed reference into a two-bladed turbine based on matching the same energy yield by duplicating the power curve while leaving most parameters and design choices unchanged, and precisely extend the blade length, subsequently (see Section 3). The major benefit is a direct comparability of all extreme and fatigue loads, without estimating whether or not the change in loads and subsequent component mass adaptations compensate the overall loss or gain of AEP. The longer blade itself might increase the costs per blade, but will be overcompensated by the reduced number of blades. Beforehand, the redesign options need to be outlined and are described in the following chapter.

2. Simplified options to redesign a three-bladed into a two-bladed turbine

![Diagram showing simplified options to redesign a three-bladed into a two-bladed turbine](image)

**Figure 1.** Comparison of only positive effects of increasing the chord or the TSR, respectively, when reducing the number of blades. Note, that each positive effect is a negative one on the other side. Thick lines mark the main advantage and the dashed line a critical border.

There are two popular philosophies for redesigning a three-bladed rotor into a two-bladed one. The respective positive implications are shown in Fig. 1, where each block implies an opposite negative attribute for the other option. The first option consists of an equal tip speed and an increased blade chord [4–7]. The most important benefit (marked thick) is the structural improvement from an exponentially growing area moment of inertia when expanding chord and thickness of the blade [13]. This results in a reduction of necessary composite material and hence in lighter as well as cheaper blades by up to 50% compared to the second redesign option [4]. The reduced weight, in turn, reduces gravitational and inertia driven, e.g. centrifugal, forces, especially regarding the comparably low rotation speed. Furthermore, the increased chord leads to a higher lift along the blade for lower wind speeds, while a blade flapwise motion induced wind speed results in a higher change in angle of attack (AoA) due to the lower rotation speed.
Hence, in combination with the decreased blade inertia, the aerodynamic damping improves, together with an increase of unfavorable sensitivity to wind gusts. The larger chord with its positive effects on the structure additionally benefits structural issues caused by increased blade loads from the tower wake of downwind turbines or larger rotors.

On the other side, the rotor could also be redesigned for a higher tip speed ratio (TSR), utilizing the original absolute chord distribution of the three-bladed turbine [3, 8]. The most important improvement results out of a reduction of torque at the same power and consequential cost savings in the drivetrain, whether partially or fully utilized for the gearbox or generator [14]. The exact magnitude of these cost savings is highly dependent on the generator design and type. However, derived from the scaling laws of permanent-magnet direct-drive generator components described in [15], the overall generator mass reduction ratio is approximately anti-proportional to the ratio of rotation speed increase. In that case, a cost reduction of the generator around 18% would be plausible. As mentioned before, the distance of vortex sheds induced tip losses could partially be reduced by rotating faster. The lower aspect ratio of blades with a smaller chord further improves the aerodynamic performance (see e.g. [16]), increasing the power to thrust coefficient ratio, which, then again, reduces the wake deficit behind the turbine [3]. Nevertheless, wind tunnel experiments have shown that these effects on the wake deficit are only marginally different for the three-bladed turbine and both options of two-bladed turbines. In contrast, the wake recovery rate even benefits from higher turbulences and thus from increased tip losses [8]. Finally, slender blades reduce loads in parked positions due to a smaller attack surface. The worse structural properties lead to a higher wall thickness of the blade, which although increasing blade weight, reduces buckling issues. The slenderness together with the thicker blade shell could furthermore be helpful for offshore cargo.

It can be seen that the described advantages and disadvantages of the redesign options result in a multifactorial problem where many factors are not yet quantified. To summarize, no direct conclusion can be drawn at the current state, about which of the mentioned tendencies from Fig. 1 are responsible for the most reduction in LCoE. Nevertheless, the superior redesign choice is presumed to be a combination of both extremes, requiring that the proposed redesign will possess a larger chord as well as a higher TSR.

3. Designing an aerodynamically similar two-bladed wind turbine

There are innumerable ways to design a turbine. Several design proposals underline the necessity to include different disciplines, such as aerodynamics, structure, energy capture and cost estimation in one optimization process in order to achieve a superior design [17]. However, the main idea of the paper at hand is to enhance the comparability, which as been pointed out to be "notoriously difficult" [3]. Rather than completely new designed, the two-bladed turbine is redesigned out of a three-bladed reference turbine considering specific boundary conditions. One could argue that a fair comparison could be achieved as well by straightforward comparing the LCoE after performing such a multidisciplinary design optimization for a two- and a three-bladed turbine. The drawback of this approach is that causes of differences in costs do not necessarily have to relate to the change in number of blades. These differences could equally be connected to a combination of other adjustments during the design process, such as shifting the rated wind speed to a higher value or changing the drivetrain concept. While the LCoE remain the final most important decision parameter, the redesign process will be done having regard to the following principles:

(i) Component changes that are not directly affected by reducing the number of blades from three to two will be neglected in the process.

(ii) The operation strategy will remain as similar as possible resulting in a virtually equal power curve, but consequently in a slightly larger rotor diameter.
(iii) While the rotational speed could be adapted, the aerodynamic characteristics will be approximated by retaining all aerofoils, the non-dimensional aerofoil positions, relative chord distribution, relative prebend, and by adapting the same AoA along the blade for the TSRs of each turbine, respectively.

These rules lead to a clear procedure for redesigning the two-bladed turbine and grand a better overview of the improvements and drawbacks, which a reduction of one blade could offer.

As stated in Section 2, the loss in power production of the redesigned rotor could be fairly compensated by increasing either the chord or the rotation speed. In the following, a combination of both will be demonstrated, in order to benefit from structural improvements [13] as well as cost reductions in the drivetrain [14]. While the authors are aware of exponentially increasing erosion problems by all tip speeds higher than $60 \frac{m}{s}$ [18], the turbine size of 20 MW indicates a future turbine generation and thus erosion protection improvements. Therefore, a new maximum tip speed $V_{tip,2B}$ is chosen and will be set to $100 \frac{m}{s}$, which presents the maximum for commercial large scale turbines at present (see e.g. SCD advanced 6.0 MW). The ratio of three-bladed ($3B$) and two-bladed ($2B$) maximum tip speed $V_{tip}$ or TSR $\lambda$ can now be used as a rotation speed factor

$$f_{\lambda} = \frac{V_{tip,2B}}{V_{tip,3B}} = \frac{\lambda_{2B}}{\lambda_{3B}}.$$  

Neglecting changes in tip or root losses, force angles, air density $\rho$ and AoA $\alpha$, the lift of each blade section $l$ should be increased by 50% for the two-bladed rotor to provide the same overall energy yield, derived from a general lift equation [3]

$$l_{2B} = 1.5 l_{3B} = \frac{\rho}{2} C_l V_{rel,2B}^2 c_{2B} = \frac{\rho}{2} C_l (f_{\lambda} V_{rel,3B})^2 f_c c_{3B} \quad \text{where} \quad c_{2B} = f_c c_{3B}.$$  

with chord length $c$, lift coefficient $C_l$, and inflow velocity $V_{rel}$. Consequently, the squared speed factor $f_{\lambda}$ should be anti-proportional to the chord factor $f_c$ by the factor of 1.5. Since changes of induction and losses cannot be ignored in the final design, the chord factor has to be defined iteratively together with the corresponding blade twist distribution $\vec{\theta}_{2B}$, utilizing, e.g., a blade element momentum (BEM) based turbine model simulation with the three-bladed turbines twist $\vec{\theta}_{3B}$ as initial twist $\vec{\theta}_{2B,init}$ and

$$f_{c,init} = \frac{1.5}{f_{\lambda}^2}.$$  

as initial chord factor (see part A of Fig. 2). The key to achieve a similar aerodynamic behavior of the blades is to use the same, presumably optimal, glide angle of the aerofoils. Therefore, the difference in AoA along the blade $\Delta \vec{\alpha}$ has to be added to the twist of the last iteration step $\vec{\theta}_{2B,old}$ to receive the twist for the next iteration

$$\vec{\theta}_{2B,new} = \vec{\theta}_{2B,old} + \Delta \vec{\alpha} \quad \text{with} \quad \Delta \vec{\alpha} = \vec{\alpha}_{2B} - \vec{\alpha}_{3B}.$$  

Is the sum of all absolute differences $|\Delta \alpha_i|$ finally smaller than a chosen accuracy $\epsilon$, the optimal TSR $\lambda_{2B,\text{opt}}$ has to be determined. If it does not match the desired TSR $\lambda_{2B}$ from eq. (1) within the accuracy margin $\pm \epsilon$, the chord distribution of the last iteration $\vec{c}_{old}$ has to be re-factored by

$$\vec{c}_{new} = \vec{c}_{old} (\frac{\lambda_{2B,\text{opt}}}{\lambda_{2B}})^2.$$  

Is the redesign of the two-bladed rotor with an equal diameter accomplished, the loss in absolute power at rated $P_r$ can be counterbalanced by scaling the rotor radius $R$ with the factor

$$f_r = \sqrt{\frac{P_{3B,r}}{P_{2B,r}}} = \frac{R_{2B}}{R_{3B}}.$$
based on the same rated conditions regarding wind speed and density as the reference turbine. The complete iterative procedure is illustrated in a flow chart in Fig. 2. Note, that the turbine is simulated rigid since the initial blade stiffnesses and masses have to be adapted later based on the resulting static blade forces.

A first estimation of blade mass and thus costs could be accomplished by approximating the main spar, consisting of spar caps and shear webs, with a quadratic profile \[4\]. Equal to Larsen et. al. \[4\], but with a factor \(f_\sigma\) for the loads, here mainly driven by the flapwise bending moments \(M_{y,2B}\) and \(M_{y,3B}\), one can set loads and sectional modulus \(W\) in equilibrium to

\[
 f_\sigma = \frac{M_{y,2B}}{M_{y,3B}} \equiv \frac{W_{2B}}{W_{3B}} \approx \frac{b_{2B}h_{2B}t_{2B}}{b_{3B}h_{3B}t_{3B}} + \frac{1}{3} \frac{h_{2B}^2t_{2B}}{h_{3B}^2t_{3B}} + \frac{t_{2B}}{t_{3B}} f_c^2, \tag{7}
\]

where height \(h\) and width \(b\) of the quadratic profile have been scaled by the chord factor \(f_c\) analog to the chord in eq. (2). The wall thickness \(t\) has to be adapted according to eq. (7),
to achieve an equal stress level in the most stretched regions of the structure. Note, that the stiffness ratio of the blade equals the load ratio , multiplied by another . The resulting stiffness will hence exceed the necessary value for the boundary condition of, e.g., tip tower clearance by the factor . Introducing a mass factor and approximating the mass with the cross-section area of the quadratic profile [4], the mass factor could be estimated together with eq. (7) by

\[ f_m = \frac{m_{2B}}{m_{3B}} = \frac{A_{2B}}{A_{3B}} = \frac{2(b_{2B} + h_{2B})l_{2B}}{2(b_{3B} + h_{3B})l_{3B}} = \frac{t_{2B}}{t_{3B}}f_c = \frac{f_\sigma}{f_c}. \]  

(8)

According to rules of scaling, the mass increases cubically to the length factor [19].

4. Results

The turbine taken as a study example is the INNWIND 20 MW reference wind turbine (RWT) [20], which is the result of an upscaling from the DTU 10 MW [21]. All simulations have been performed in DNV GL’s Bladed v4.8.0.63. To ensure the accuracy of turbine model properties and simulation settings, the bladewise power and thrust coefficient propagation has been compared to the ones of the DTU 10 MW [21], matching them perfectly. To provide a better overview of influence from the consecutive parts – redesign and rotor size scaling – both will be shown on the plots and tables, labeled as ”2B factorized” (Fig. 2 part A) and ”2B lengthened” (Fig. 2 part A + B), respectively. Following the design process of Fig. 2, all models possess the same AoA at the respective design TSRs, requiring an adjustment during part A of the two-bladed turbine’s twists. Their main properties, together with the ones of the three-bladed reference turbine, are listed in Table 1. Visible is a 3.6% lower power coefficient for both two-bladed turbines. Still, the lengthened turbine reaches an equal absolute power at the same rated wind speed as the three-bladed reference.

|                              | 3B RWT | 2B factorized | 2B lengthened |
|------------------------------|--------|---------------|---------------|
| number of blades             | 3      | 2             | 2             |
| rotor diameter \( R \) in m  | 252.2  | 252.2         | 257.4         |
| maximum \( C_P \)            | 0.472  | 0.455         | 0.455         |
| max tip speed in m/s         | 90     | 100           | 100           |
| maximum rotor speed in rpm   | 6.79   | 7.194         | 7.063         |
| design TSR                   | 7.5    | 8.333         | 8.333         |
| rated wind speed \( V_r \) in m/s | 11.4   | 11.4          | 11.4          |
| all losses in the drivetrain | 94%    | 94%           | 94%           |
| power at \( V_r \) in MW     | 20     | 19.3          | 20            |
| speed factor \( f_\lambda \) | 1      | 1.111         | 1.111         |
| chord factor \( f_c \)       | 1      | 1.208         | 1.208         |
| length factor \( f_r \)      | 1      | 1             | 1.0206        |
| approx. blade weight in t    | 117.85 | 142.49        | 151.48        |

To further describe the differences in aerodynamic performance, normed power and thrust curves are plotted in Fig. 3. The dotted blue line "2B factorized” in plot 3a) shows a delay of power \( P \) for the redesign with the usual approach of maintaining an equal rotor diameter (inter alia [3–8]), reaching the same rated power at a 0.14 m/s higher wind speed. This is a result of the lower maximum power value, visible in plot 3b), which, in turn, is caused by
higher tip losses, described in Section 1 and [11]. If increasing the blade length by 2.06% (green stars), the absolute power of the three-bladed reference could be perfectly matched. Due to the increased losses of the two-bladed rotor, the thrust $T$ is 2.39% higher for an equal power design. In contrast, if maintaining the same rotor diameter, the thrust in partial load even becomes 1.47% lower than the reference case. However, if increasing the power output of the case ”2B factorized” beyond the reference rated wind speed of 11.4 m/s until 11.54 m/s, the thrust in full load operation is always highest due to a delayed pitching to feather (3c) dashed blue line).

Figure 3. Power (a) and thrust (c) curves with fixed TSR for partial load operation and with variable TSR for a constant wind speed of 11.4 m/s (b) and (d), normed by the respective power and thrust value of the three-bladed reference turbine at rated wind speed and TSR.

Note, that the curves ”3B reference” (red triangles) and ”2B factorized” (dotted blue) in plot 3b) and 3d) have a high similarity to normed $C_P$- and $C_T$-curves, due to an equal blade length. The upscaled case of ”2B lengthened” (green stars) basically scales the curves to higher ordinate values while maintaining the same progressions. The important difference is, that it clarifies the magnitude of influence of the otherwise lower power and thrust values of the two-bladed case ”2B factorized”. While one could argue that a two-bladed turbine design with an equal rotor diameter possesses a lower thrust, the green stars line shows that the advantage in
thrust (3d) is just a consequence of a lower power output (3b). If the three-bladed reference blade would be reciprocally scaled down to match the same power curve as the two-bladed turbine ”2B factorized”, the overall thrust value would be lower. This elucidates that a lower thrust is not a general advantage of a two-bladed turbine, but rather a result of design point, which could be outmatched with ease by a three-bladed turbine if this benefit is truly desired.

| 3B reference | 2B factorized | 2B lengthened (2.04%) | 2B fact. / 3B ref. (fσ) |
|--------------|---------------|-----------------------|-------------------------|

**Figure 4.** Flapwise bending moment over wind speed (a) and over relative blade length at 11.4 m/s wind speed (b), normed by the maximum value of the three-bladed reference.

Regarding loads, plot a) and b) of Fig. 4 illustrate the propagation of normed flapwise blade bending moments of all three cases over wind speed and relative blade length, respectively. The gray line visualizes that the turbine ”2B factorized” possesses a load factor $f_\sigma$ (see eq. (7)) of 1.482 for all wind speeds as well as all blade positions if the pitch to feather starts at 11.4 m/s. Using eq. 8 the blade mass could be calculated to be 22.7% higher for the factorized and 30.4%

| 3B ref; 2B: | $V_{tip} = 90\frac{m}{s}$ | $V_{tip} = 95\frac{m}{s}$ |
|--------------|--------------------------|--------------------------|
| $V_{tip} = 100\frac{m}{s}$ | $V_{tip} = 105\frac{m}{s}$ | $V_{tip} = 110\frac{m}{s}$ |

**Figure 5.** $C_p$-curves for different design tip speeds a) and corresponding factors for chord, mass and loads for each tip speed, respectively b).
increased for the lengthened case. If the factorized turbine wouldn’t start pitching to feather until the reference power of 20MW is reached, shown with the dashed blue line in 4a), the load factor increases (dashed gray line) and changes the mass prediction.

To answer the question, about how dependent the estimated redesigned rotor mass is on the chosen tip speed, Fig. 5 shows power propagations over TSRs for design tip speeds of 90\(\frac{\text{m}}{\text{s}}\), 95\(\frac{\text{m}}{\text{s}}\), 100\(\frac{\text{m}}{\text{s}}\) (alias “2B factorized”), 105\(\frac{\text{m}}{\text{s}}\), and 110\(\frac{\text{m}}{\text{s}}\). As a result of better aerodynamic efficiency by spinning faster [11], the maximum \(C_P\)-values increase marginally for higher design tip speeds in 5a), while the tip thrust coefficient slightly decreases together with the load factor \(f_\sigma\) in 5b).

What does increase vastly with the design tip speed is the mass factor \(f_m\), due to the reduction of blade thickness and chord: While the 50% increased static flapwise blade root bending moment per blade of a two-bladed turbine could be roughly compensated with a turbine blade of the same weight for a speed factor \(f_\lambda\) of 1.0 (see also [4]), the blade mass of a design with \(f_\lambda\) of 1.22 (e.g. [3]) would be increased by about 48%. Here, the former would offer a great reduction in rotor costs on the one side, while the later has a rotor mass almost equal to the three-bladed reference, but a good potential of reducing drivetrain costs on the other side [14]. However, the effect of both alternatives, separately or in combination, on the final costs of a whole turbine is highly dependent on the cost model itself and on consequences of differing unsteady loads. These loads, in turn, vary vastly depending on the control strategy used [2] or on the passive load reduction method utilized, such as a teetering system [22]. Hence, the respective assessment will be left for future work. Nevertheless, the method at hand could provide a good start in a redesign process with a huge amount of variables, where diverging values of, e.g., loads or masses can already be evaluated at a much earlier design stage, than their final LCoE, all because the comparison is based on an equal amount of absolute energy yield.

5. Conclusions and outlook
Two- and three-bladed turbines possess aerodynamic and structural differences, which can be seen and compared in a variety of ways. The proposed new approach could clarify design choices and serve as a solid basis for future comparisons of two- and three-bladed large-scale offshore wind turbines regarding dynamical loads, FEM-structure and -stability analyses, and finally costs more directly without association to lower energy yields. Hence, it could be a new fundament for the ongoing question within research and industry if two-bladed or three-bladed horizontal axis wind turbines are the better technology for the energy production offshore.

Considering future work, setting the energy yields to an equal level is merely the first part in a long row of design and investigation steps. The rough estimation of blade mass has to be evaluated with high fidelity methods, together with the first assumptions of scaled stiffness. The more harmful dynamics of two-bladed turbines should be analyzed by a servo-aero-elastic tool and countermeasures deduced. An accurate cost model should serve as guidance exposing important choices during the design process as well as for the final determination of levelized cost of energy.

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