Rotor and wake aerodynamic analysis of the *Hybrid-Lambda* concept - an offshore low-specific-rating rotor concept

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Abstract. The low-specific-rating rotor concept *Hybrid-Lambda* introduces a blade design with nonuniform distribution of design variables (design tip speed ratio and axial induction) along the blade span to alleviate loads of the outboard section in strong winds. In this paper, we validate aerodynamic design calculations, which were carried out with the blade element momentum theory by comparing the results to free vortex wake investigations (FVW). Furthermore, we investigate the wake behaviour with FVW and large-eddy simulations. The results show good agreements between the blade element momentum theory and FVW for integrated rotor quantities (power and thrust). Small deviations are present when the gradients of axial induction along the span are large. The wake of the *Hybrid-Lambda Rotor* shows advantages in the near-wake region (up to 4 diameters [D] downstream), especially in the outer wake annulus and in low turbulence scenarios. For further downstream positions, the wake is comparable to that of the reference turbine.

1. Introduction

Countries with a high share of wind power in the energy system suffer from low market values of wind power during periods of strong winds, whereas the market value during light-wind-days is comparably high [1]. Thus, there is a demand for turbines with an increased power capture on light-wind-days. In recent years, low-specific-rating (also referred to as "low-wind") wind turbines have received increased attention (e.g. [2]), especially onshore. Large rotors increase their power capture in light winds, but they generally come with the need for load-reduction techniques when approaching rated wind speed. This is usually done by peak shaving (pitching to feather to limit the loads) and leads to large losses in the upper partial-load range. Especially for offshore sites, this coincides with the peak of the wind speed distribution. The *Hybrid-Lambda Rotor*, introduced by Ribnitzky et al. [3] and further explained in Sec. 2, integrates the application of peak shaving into the blade design process rather than accepting it as a necessary evil. The design process is approached by balancing the two objectives of limiting power losses in the peak-shaving region and maximising power output below this region. The design features a nonuniform distribution of the axial induction along the blade span to alleviate loads of the outboard blade section in strong winds.

The enhanced wake recovery of a turbine with a nonuniformly loaded rotor was investigated by Kelley and Yang [4], [5]. They found that a blade design with larger spanwise gradients of bound circulation exhibit shorter and faster mixing far wakes. Further, Madsen [6] analysed additional benefits of low-specific-rating turbines on wind farm effects. Knauer [7] introduced a rotor design that enhances wake diffusion, using a ventilation area with negative axial induction close to the blade root.
However, the design objectives as well as the resulting blade design of the *Hybrid-Lambda Rotor* differ from the aforementioned studies, because it was designed for efficient load reduction and not primarily for enhanced wake mixing. The specific aerodynamics are of interest from a scientific point of view.

First, the nonuniform distribution of the axial induction along the blade span leads to large circulation gradients. This raises the question: To what extent is the assumption of independent blade elements in the blade element momentum (BEM) algorithm violated? The application of free vortex wake (FVW) methods would be scientifically more appropriate because they do not rely on independent blade elements. Modelling of radially varying circulation is addressed in [8]. Second, a specific wake characteristic is expected, because only a part of the rotor is designed as a low-induction rotor and the rotor disc is nonuniformly loaded. Common wake engineering models can no longer be applied. We expect additional gradients in the wake profiles, and we address the question whether those will destabilize and further diffuse the wake.

The objectives of this paper are to analyse the *Hybrid-Lambda Rotor* with high-fidelity aerodynamic simulation tools, specifically to:

(i) Investigate the *Hybrid-Lambda Rotor* with the FVW code and study the limits of the calculations made with the BEM theory. We compare integrated rotor quantities as well as spanwise resolved variables across the two methods.
(ii) Compare the wake characteristics of the *Hybrid-Lambda Rotor* with the International Energy Agency (IEA) 15-MW offshore reference turbine on different fidelity levels:
  (a) FVW simulations with a steady uniform inflow and numeric turbulent wind field
  (b) Large-eddy simulations (LES) with a neutral and stable atmospheric boundary layer (ABL)
(iii) Investigate a simplified wind farm layout in LES and compare the power output to asses the benefits of the *Hybrid-Lambda* concept.

2. The rotor concept

The *Hybrid-Lambda Rotor* is a low-specific-rating concept for offshore siting, exemplified with a 15-MW wind turbine. The uniquely low specific rating of 180 W m^{-2} corresponds to a D of 326 m. The objective of the conceptual design is to limit the stationary loads (blade flapwise root bending moment (RBM) and thrust) to the maximum values of the IEA 15-MW reference turbine [9] (with a D of 240 m). The main idea of the concept is to design the inner 70% of the rotor differently than the outer 30% and to operate the rotor at a tip-speed ratio (TSR) of 11 in light winds and at a TSR of 9 in stronger winds. The outer portion of the blade is designed for a TSR of 11 and an axial induction of 0.21. When operated at the TSR of 9 the outer portion should produce an axial induction below 0.15. The design for a high TSR and low induction results in a much more slender outer section compared to a traditional design. The inner portion of the rotor is designed for a TSR of 9 and an axial induction of 0.21. When operated at the TSR of 11 the inner portion should produce an axial induction close to 0.33. In light wind conditions, the rotor operates at the high TSR, and the slender outer part contributes to the increased power capture. The inner part of the rotor operates like a conventional rotor

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with an axial induction factor close to 0.33. The axial induction distribution and the shift in the operating mode is shown in Fig. 1. In stronger winds (but still below the rated wind speed), the design value of the stationary RBM is reached. Then, the TSR reduces to a value of 9, and the torque generation shifts to the inner section of the rotor, which is now operating at its design point. In contrast, the outer region is significantly relieved, because it is no longer operating at its aerodynamic optimum. This reduces the lever arm of the resulting bending force, and additional peak shaving by blade pitching ensures the limitation of the loads. For further information on the *Hybrid-Lambda Rotor*, the reader is referred to [3].

3. Methods

We performed aeroelastic simulations in OpenFAST, using ElastoDyn as the elastic solver [10]. To address the first objective, i.e., the comparison of the BEM and FVW code, we simulated the *Hybrid-Lambda Rotor* using steady and uniform inflow with the standard BEM solver and the FVW module OLAF [11], [12]. We investigated three operating modes:

1) Operating point 1: Light-wind mode, defined by the high TSR of 11 and maximum wind speed just before the limiting loads are reached, which is 6.8 m s^{-1}
2) Operating point 2: Strong-wind mode, defined by the low TSR of 9 and the corresponding wind speed when the transition from the high to low TSR completes, which is 8.3 m s^{-1}
3) Operating point 3: Rated power conditions, defined by the low TSR of 9 and a wind speed of 10.2 m s^{-1}.

To investigate the wake characteristics, we first isolate the effects on the wake due to the unique aerodynamic rotor design of the *Hybrid-Lambda Rotor* in steady and uniform inflow in FVW. Then, we can evaluate if those advantages are still present in realistic inflow conditions by simulating numeric turbulent wind fields (FVW) and full ABLs (LES).

We performed FVW simulations with both the *Hybrid-Lambda Rotor* and the reference turbine. We investigated steady and uniform inflow conditions in operating points 1 and 3 and turbulent wind fields, calculated with TurbSim [13] for operating point 1. For the wind fields, we chose a relatively low turbulence intensity of 5% and a low shear exponent of 0.1. Those values are of high relevance for wake investigations, because power losses due to distinct wakes are most present in those low turbulence conditions.

We further performed LES for a single turbine with the incompressible flow solver AMR-wind [14], using its actuator line model coupled to OpenFAST. We investigated a neutral and a stable ABL for operating point 1. In this case, both turbines (the *Hybrid-Lambda Rotor* and IEA 15-MW turbine) were simulated in the same ABL precursor run, resulting in slightly different mean wind speeds and wind directions at their specific hub heights. Turbines were yawed to the exact wind direction at hub height, and the resulting wind fields were turned by the yaw angle to align the wakes of the *Hybrid-Lambda Rotor* and the IEA 15-MW. This approach corresponds to a site-specific turbine comparison, highlighting the advantages of possibly repowering existing wind farms. The LES wind fields represent operating point 1. This means the *Hybrid-Lambda Rotor* is in light-wind mode and the reference turbine is in region 1.5 with an average pitch angle of 1.6° to feather (with controllers active for both turbines). This leads to averaged thrust coefficients of 0.79 for the reference turbine and 0.75 for the *Hybrid-Lambda Rotor*. The neutral ABL shows a turbulence intensity of around 10% and the stable ABL of around 2.4%. The average shear exponents are 0.09 and 0.14, respectively. In the turbine simulations, we used grid refinements in proximity of the rotor to sufficiently resolve the nonuniform distribution of the

variables along the span of the blade. We aimed for a grid size of 3.75 m, which corresponds to 87 points along the rotor diameter for the *Hybrid-Lambda Rotor* and 64 points for the reference turbine.
The wake investigations are analysed by calculating time-averaged wake profiles, normalized to the rotor diameter of the respective turbine. We further compare the mean velocity wind fields in a horizontal plane at hub height. For averaging, an output frequency of 1 Hz is used, and the time window is set to 400 seconds.

To address the performance of the *Hybrid-Lambda Rotor* in a wind farm configuration, we performed LES with two aligned turbines. In order to investigate the opportunity of the *Hybrid-Lambda Rotor* to be used as a repowering solution for existing wind farms, we chose a fixed absolute spacing of 6 of the reference turbine's diameters for both turbine simulations. This results in a relative spacing of 4.4 D for the *Hybrid-Lambda Rotor*. This simulation setup corresponds to a wind farm design problem when the given surface area is restricted and the ratio of rated power to surface area is kept constant rather than the relative turbine spacing.

4. Results

In this section, we first compare the BEM and FVW results for the *Hybrid-Lambda Rotor*. In the second and third part, we address the wake investigations using the FVW code and LES.

4.1. Comparison of BEM and FVW results

We performed aeroelastic simulations for the *Hybrid-Lambda Rotor* for operating points 1 and 2 using BEM and FVW methods. Results show that, for steady uniform inflow, the integrated rotor quantities (power and thrust) are in very good agreement for the two methods. For the light-wind mode, the aerodynamic power exactly matched, whereas the FVW code computed about 0.5% higher thrust. For the strong-wind mode, the FVW code computed 1.5% higher power and 0.75% higher thrust.

Next, we compare the radially resolved axial induction factor (as shown in Fig. 1). For the light-wind mode, the FVW code computed an axial induction factor that is about 5% lower for the inner part of the rotor and up to 15% higher for the outer part of the rotor compared to the BEM results. Thus, the FVW code predicts a smaller change of induction between the two blade regions. The observed differences might be due to additional vortices, which are created by the strong gradients of the circulation distribution at a 0.7 nondimensional blade length. These vortices increase the induction on the outer part of the rotor and decrease the latter on the inner part. Looking at the strong-wind mode this trend persists but is much less distinctive. The axial induction distribution is in good agreement for the strong-wind mode among the two methods. As the gradients in the axial induction distribution at a 0.7 nondimensional blade length are reduced in the strong-wind mode, weaker vortices are created, which leads to reduced differences between the BEM and FVW results compared to the light-wind mode. The angle of attack distribution in Fig. 1 shows similar results. In the light-wind mode, the higher axial induction outboards (computed by the FVW code), leads to slower axial velocity components. Consequently, the angle of attack is reduced for the outer part of the blade in the FVW calculations. For the inner part of the blade, a similar line of arguments can be applied vice versa. Again, the differences in the angle of attack distribution in the strong wind mode between the two codes are very mild.

In summary, the FVW simulations confirm that the aerodynamic design ideas of the *Hybrid-Lambda Rotor* are applicable, although they reach the limit of the assumptions made in the BEM theory. The assumption of independent blade elements is violated in the transition region of the two blade regions, as strong gradients in the circulation are present. These gradients introduce additional vortices, but they act in favour of the *Hybrid-Lambda* concept, as the aerodynamic power computed by the FVW code slightly increased.

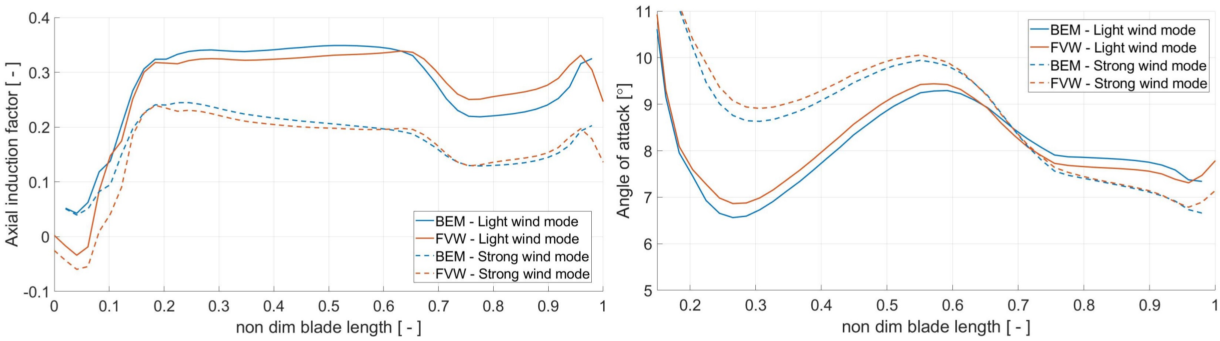

Figure 1: Axial induction distribution (left) and angle of attack distribution (right) for operating point 1 (solid lines) and operating point 2 (dashed lines), comparing BEM (blue) and FVW (red)

4.2. Wake investigations using FVW
In this section, we investigate the wake behaviour of the *Hybrid-Lambda Rotor* simulated by the FVW model. We first address steady and uniform inflow to identify general characteristics of the near wake. The FVW method is not ideal to investigate the far wake, and the reader is referred to section 4.3 for further information about the far wake. In the FVW simulations, the wake becomes unstable beyond 2.5 D. Beyond this distance, the wake profiles should be considered with care, because OLAF does not account for viscous diffusion. Further, the nacelle is not modelled in FVW, which led to an overspeed in the center of the wake within the first 1 D downstream. Nacelle effects were modelled in the LES investigations (Sec. 4.3).
Figure 2 compares the wake of the *Hybrid-Lambda Rotor* with the reference turbine for the light-wind mode and rated wind speed. The inner 70% of the rotor is displayed with a black bar, whereas the outer part of the rotor, which is designed for low induction, is displayed with a white bar. The axial induction distribution of the *Hybrid-Lambda Rotor* is reflected in the wake velocity. For the light-wind mode, the outer part of the blade causes less deceleration of the flow, which led to an outer annulus of the wake with a higher wind speed. The strong-wind mode further revealed the potential for wind farm power to increase, because the flow in the wake did not decelerate as much as the reference turbine. This is not only due to the aerodynamic rotor design but also due to operation at lower thrust coefficients in the peak-shaving region. Still, it highlights a major advantage as wake deficits are greatly reduced close to rated wind speed.

Figure 3 compares the wake deficit profiles for operating point 1 and 3 at different downstream locations. The profiles show a slightly higher wake deficit for the *Hybrid-Lambda Rotor* for the inner rotor part, compared to the reference rotor. This is also in line with the blade design, as the axial induction for the inner rotor (0.33 for the *Hybrid-Lambda Rotor*) is slightly higher compared to the reference turbine (0.3 for the IEA 15-MW). Further, the gradients to the inner wake core are relatively strong in the near wake and smooth out at around 3 to 4 D downstream. For rated wind speed (operating point 3), a similar behaviour can be recognized, but the gradients in the wake profiles are reduced, which is in line with the axial induction distribution (see Fig. 1). The wake deficit is only almost half as strong as it is for the reference turbine in the near wake, which highlights the clear advantages in the wake deployment of the *Hybrid-Lambda Rotor*. The wake of the *Hybrid-Lambda Rotor* also shows a straight outline in the strong-wind mode. In contrast, a significant wake extension can be observed for the reference turbine, leading to a wake width (95% of the free stream velocity) of about 1.3 D at a downstream position of 4 D, whereas the the wake width of the *Hybrid-Lambda Rotor* is still only around 1.1 D.

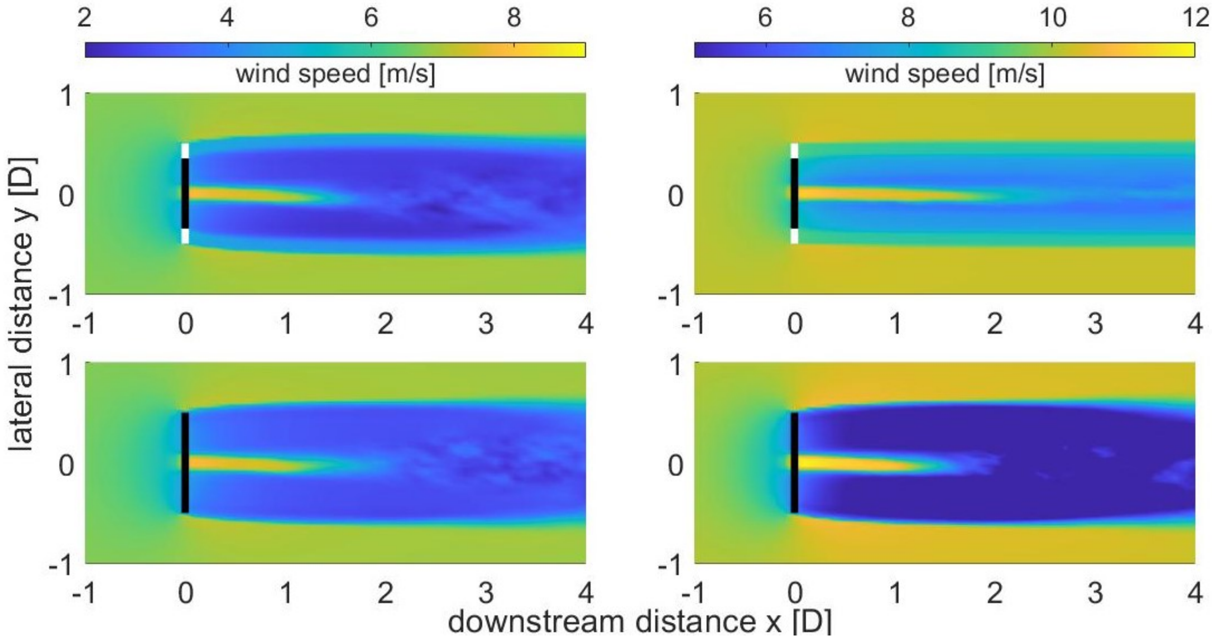

Figure 2: Averaged axial velocity component for steady uniform inflow (FVW). Top: *Hybrid-Lambda Rotor*; bottom: IEA 15-MW turbine; left: Operating point 1 ($6.8\,\mathrm{m\,s^{-1}}$); and right: Operating point 3 ($10.2\,\mathrm{m\,s^{-1}}$).

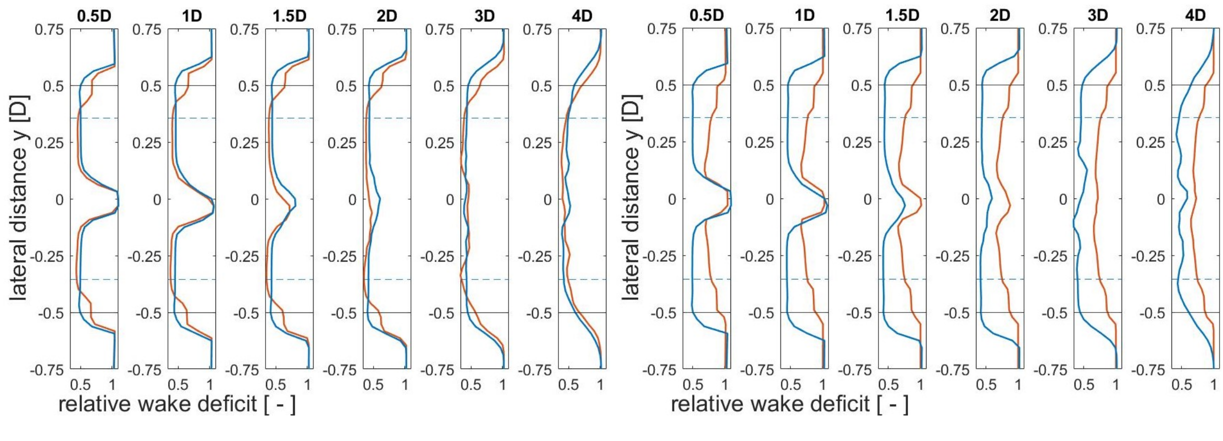

Figure 3: Normalized wake deficit profiles (FVW, steady uniform) for operating point 1 (left) and 3 (right). Dashed lines indicate 70% rotor radius. Red: *Hybrid-Lambda Rotor*; and blue: IEA 15-MW turbine.

Steady and uniform inflow does not reflect reality, but it helped us to identify and understand some basics in the wake characteristics of the *Hybrid-Lambda Rotor*. Next, we used numeric turbulent wind fields with the FVW code to evaluate if the characteristics, identified in the steady and uniform case, are still present when turbulence is considered. The results are shown in Fig. 4. The reduced wake deficit in the outer annulus is still present, but it smooths out much faster (compared to the steady case) beyond a downstream position of 1.5 D. Turbulence is the main driver for wake diffusion and the wakes of both turbines mix much faster compared to the steady-inflow case. The wake profiles indicate a marginally better recovery for the *Hybrid-Lambda Rotor* at around 3 D downstream. For positions further downstream, both wakes seem almost fully recovered, but note that this is related to the truncation of the wake in the FVW code and does not represent a realistic behaviour for a turbulence intensity of 5%.

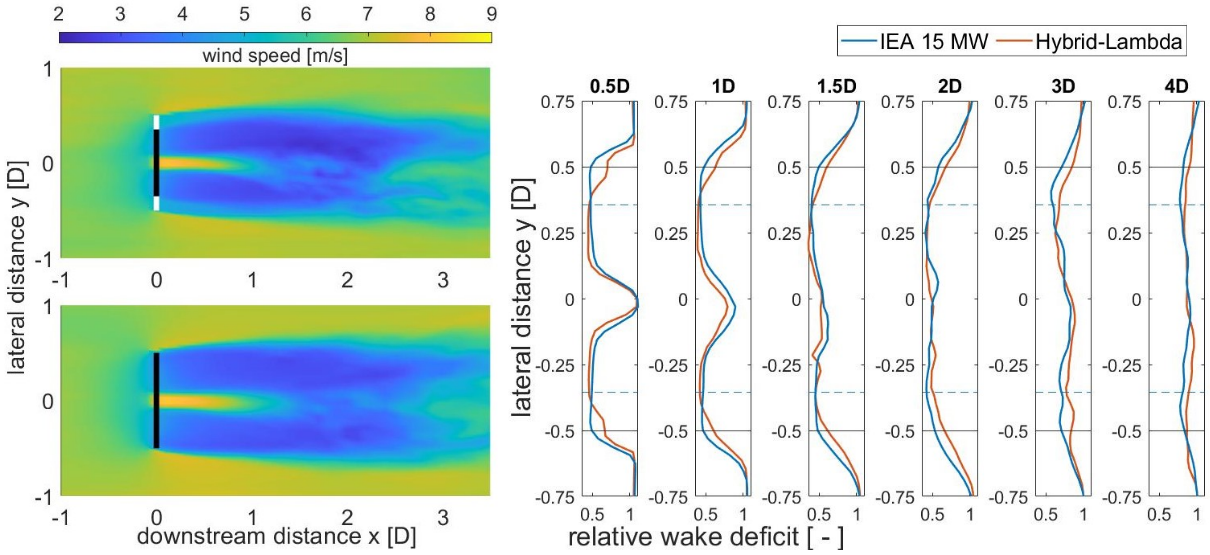

Figure 4: Left: Averaged axial velocity component for numeric turbulent wind field (FVW), light-wind mode (top: *Hybrid-Lambda Rotor*; bottom: IEA 15-MW turbine); right: Normalized wake deficit profiles

4.3. Wake investigations using LES and actuator line model

In a final step, we investigate the wake characteristics with LES coupled to an actuator line model and OpenFAST. We compare the wake of the two turbines and further distinguish between a neutral and a stable ABL stratification.

Starting with the neutral stratification, the corresponding wake profiles are displayed in Fig. 5. The gradients in the wake of the *Hybrid-Lambda Rotor* are comparable to the ones obtained with the FVW simulations. However, they smooth out more quickly compared to the FVW investigations. Advantages are especially distinct up to a distance of 4 D downstream and the recovery of the outer 30% of the wake is improved. In general, higher wind speeds are observed in the wake of the *Hybrid-Lambda Rotor*.

Comparing these results to the stable stratification is of high interest, because wake losses are most prominent in such atmospheric conditions with a very low turbulence intensity. The results are shown in Fig. 6. The major driver for wake diffusion, atmospheric turbulence, is reduced, which results in wider and longer wakes. For downstream positions greater than 3 D the wake profiles for both turbines are wider and more plateau-like, compared to the neutral case. Further, the additional gradients in the wake of the *Hybrid-Lambda Rotor* persist longer. At downstream positions of 1 and 1.5 D (compare Fig. 5 and 6), the gradients are already smoothed out in the neutral case but still noticeable in the stable stratification. In Fig. 7, the averaged velocity fields are normalized with the same reference diameter for both turbines. This visualisation emphasis the different absolute size of the wakes.

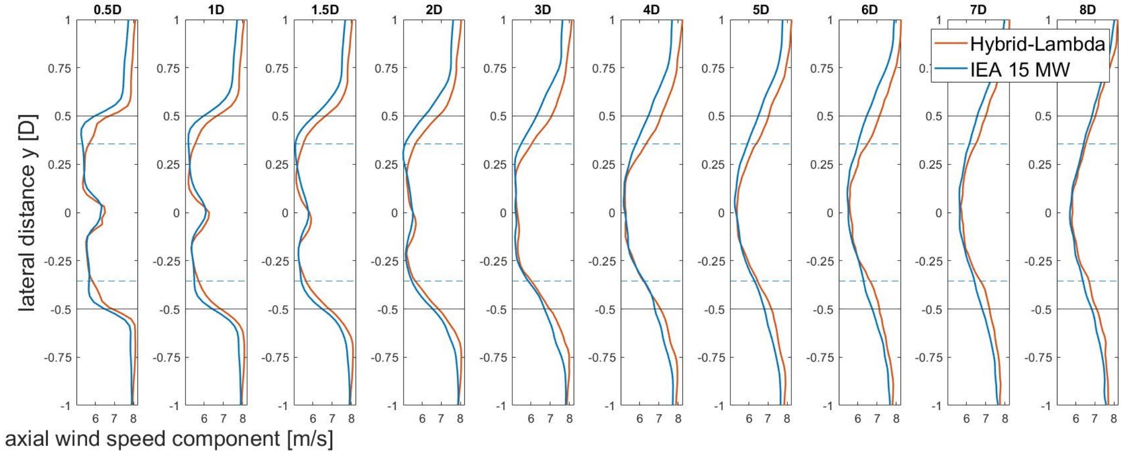

Figure 5: Neutral stratification: Normalized wake deficit profiles from LES (light-wind mode)

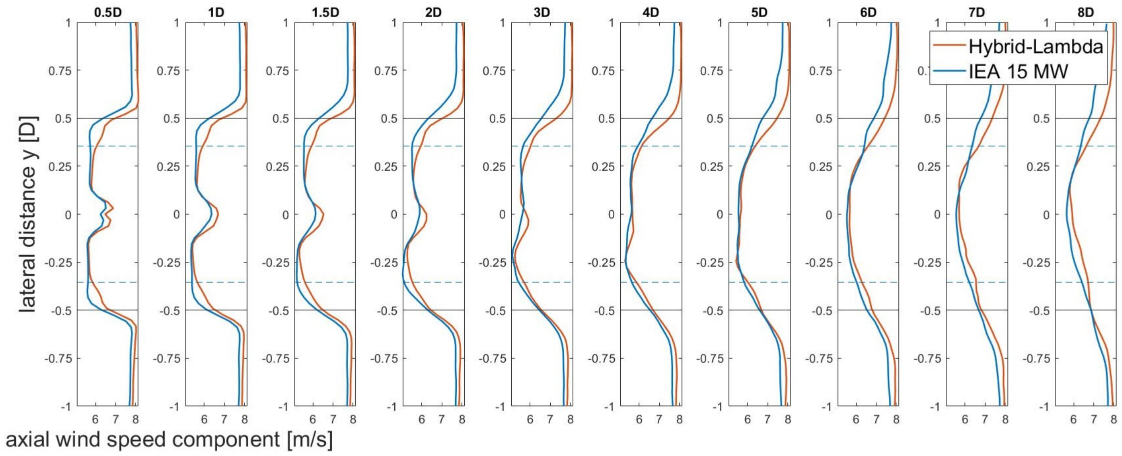

Figure 6: Stable stratification: Normalized wake deficit profiles from LES (light-wind mode)

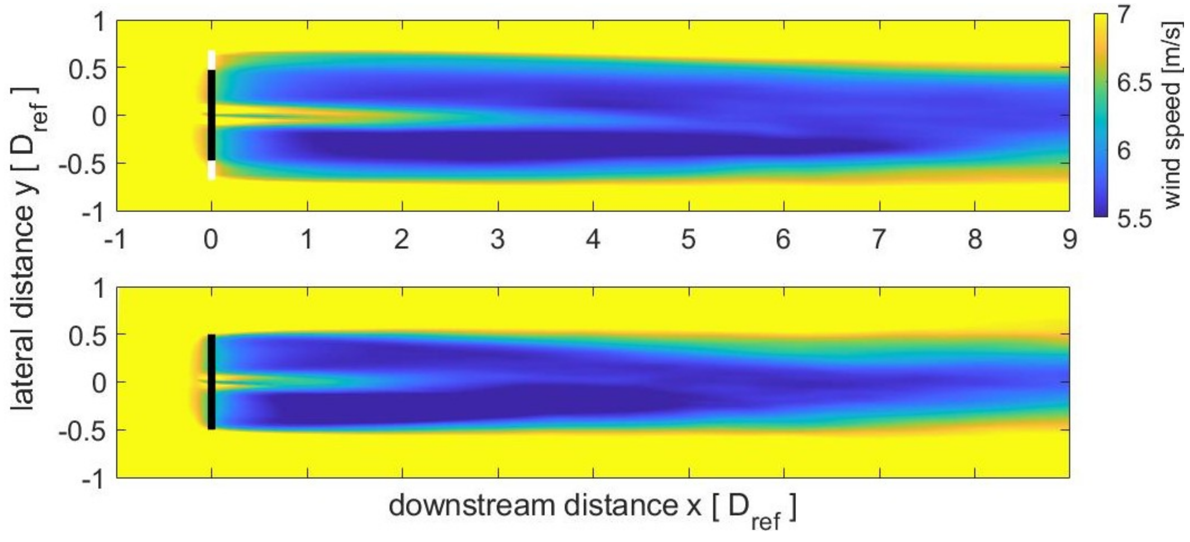

Figure 7: Stable stratification: Averaged axial velocity component for LES (light-wind mode); top: *Hybrid-Lambda Rotor*; and bottom: IEA 15-MW turbine with coordinates normalized with the diameter of the IEA 15-MW rotor for both plots

Finally, we compare configurations with two turbines in both stratifications, neutral and stable. First, we compute the energy yield by integrating the sum of the power output of the two turbines over the simulation time. The two *Hybrid-Lambda Rotors* can yield 1.85 times more energy in the neutral ABL and 1.91 in the stable ABL compared to the two reference turbines, respectively. Those findings are in line with the previous investigations of the wake profiles, because the advantages of the *Hybrid-Lambda Rotor* are more distinct in a stable ABL with a low turbulence intensity. We further compare this number to the expected scaling ratio, which results from the increase in the swept rotor area (1.84). The additional energy yield results, apparently, from the improved wake recovery of the *Hybrid-Lambda Rotor*. We further compare the power ratio of the downstream and upstream turbines in Table 1. In the neutral ABL, the downstream *Hybrid-Lambda Rotor* produces 48.9% of the upstream turbine, whereas the downstream reference turbine only produces 46.8% of the upstream reference turbine. A similar trend is observed for the stable ABL with power ratios of 46.1% and 43.9%, respectively.

Table 1: Comparing the power ratio of downstream and upstream turbines in LES (operating mode 1)

	Neutral	**Stable**
Hybrid-Lambda Rotor	0.489	0.461
Reference Turbine	0.468	0.439

5. Discussion

The *Hybrid-Lambda Rotor* was not designed with the objective of enhanced wake mixing. Nevertheless, the design with a nonuniform distribution of the axial induction raises interesting scientific questions on how this affects the wake deployment. In this study, we compared two rotors of different diameters. This is a challenging comparison, but the reduction in the specific rating is the first step in the design concept of the *Hybrid-Lambda Rotor*. This step enables increased power capture in light winds, which is highly important for the future path of decarbonization. Blades of this size come with the need for load-reducing techniques. But applying peak thrust shaving also significantly reduces wake losses close to the turbine rated wind speed. This coincides with the maximum in the Weibull wind speed distribution (offshore) and will further increase the annual energy production on a wind farm level. Even for the light-wind mode, when no peak shaving is applied, advantages in the wake recovery are identified. To fully support this thesis, further case studies considering higher turbulence intensity and bigger farm layouts with various spacings and inflow directions should be analysed.

6. Conclusions

In this study, we validated the aerodynamic design concept of the *Hybrid-Lambda Rotor* with high-fidelity aerodynamic simulations, FVW and LES, and compared the results to the ones predicted by BEM theory. We identified its characteristic wake behaviour and compared it to the wake of the IEA 15-MW reference turbine.

The FVW investigations support the design principles of the *Hybrid-Lambda Rotor* that were originally identified using the BEM theory. The integrated rotor quantities (power and thrust) obtained with the FVW and BEM methods are in very good agreement, deviating by a maximum of 1.5%. Discrepancies in the radius resolved variables are most distinct when the gradients along the blade span are large. In the light-wind mode, differences of about 15% in the axial induction distribution are observed between BEM and FVW. In the strong-wind mode, the deviations are less prominent, as the gradients along the blade span are reduced.

The wake of the *Hybrid-Lambda Rotor* has unique characteristics, and it shows advantages, especially in the near-wake region (up to 4 D downstream). In detail, these are higher wind speeds in the outer-wake annulus and decreased wake expansion and significantly reduced wake deficits in the strong-wind mode. Those characteristics are observed fairly consistently with both methods (FVW and LES). The advantages are most prominent in low turbulence conditions and can smear out in higher turbulence which is still the main driver for wake diffusion.

In summary, the design of a blade with strong gradients along its span is possible with the BEM theory, but a verification with a FVW code is advisable. Gradients in the axial induction distribution are reflected in the wake and can be beneficial for the wake recovery. The advantages found in this study favour an application of low-specific-rating turbines in a scenario with close spacing and low turbulence conditions. In a simplified wind farm configuration with two turbines in a fixed absolute spacing, the *Hybrid-Lambda Rotor* was found to yield almost twice the energy as the reference turbine (noting that both turbines have the same power rating but different diameters). Further, the ratio of the downstream to upstream turbine power production increases for the *Hybrid-Lambda Rotor*. This could open opportunities for repowering existing offshore wind farms with low-specific-rating turbines. Maintaining the given farm layout will save costs due to the reuse of existing infrastructure but leads to a reduced relative spacing of the larger turbines. An innovative turbine concept, like the *Hybrid-Lambda Rotor*, is promising for mitigating wake losses as it is better suited for close spacing.

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