Design Optimization of 10MW Downwind Turbines with Flexible Blades and Comparison with Upwind Turbines

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Abstract. Downwind turbines can adopt light and flexible blades because of limited risk of tower-strike. We investigate superiority of a downwind configuration in large-scale wind turbines with high extreme wind speed through comparison of optimized 10 MW downwind and upwind turbines. Blades and towers of these turbines are optimized to minimize their levelized cost of energy (LCoE) with steady state aero-structural analyses considering tower shadow and potential flow effects on power production and fatigue damage. Comparison shows that the optimized downwind turbines have an advantage in LCoE due to their lighter and more flexible blades than the upwind turbines with conventional prebend of 6 [m]. This advantage is derived from smaller thrust force, lighter rotor-nacelle-assembly, and a small distance between a tower axis and center of gravity of the rotor-nacelle-assembly. The upwind turbine requires 11 [m] prebend to obtain the comparable LCoE to the downwind turbine.

1. Introduction

Diameter of a wind turbine rotor has become larger from year to year to improve levelized cost of energy (LCoE). Blade deflection is one of the most important design constraints on recent large-scale wind turbines in upwind configuration. Since the blade deflection is limited to avoid tower-strike, blades must have high stiffness, which increases production cost of the blades and LCoE. Recent blades have prebend to make large clearance between the blades and tower. The prebend enables blade stiffness and mass to decrease. Sartori et al. proposed to install 6.5 [m] prebend to a DTU 10 MW reference wind turbine, which has 3.0 [m] prebend in the original configuration [1], to maximize rotor area at a rated condition [2]. Bortolotti et al. employed blades with 6.2 [m] prebend for a 10 MW offshore wind turbine model of International Energy Agency (IEA) Wind Task 37 [3]. However, large prebend may also require high production and transportation cost when it is applied to 10MW-scale wind turbines. One of the innovative solutions to save blade mass of the large-scale wind turbines is downwind configuration. Downwind turbines can adopt flexible blades to save mass and improve LCoE because risk of tower-strike is limited in the downwind configuration. Ning and Petch showed that the downwind turbines achieve lower LCoE than upwind turbines when they are designed under the International Electrotechnical Commission (IEC) class III condition [4]. In IEC class I condition, LCoE of the downwind turbines was higher than that of upwind turbines due to heavier towers to sustain moment loads from the weight of rotor-nacelle-assembly (RNA), which acts in the same direction as the moment from thrust force in the downwind configuration. On the other hand, Bortolotti et al. have recently showed that the tower base fore-aft moment of the downwind turbines is smaller than that of the upwind turbines in IEC wind class I [5]. The downwind turbines have another
advantage: passive yaw control to reduce a load at extreme wind speed [6]. The downwind turbines are essentially suitable for sites with IEC Class I and T where extreme wind speed is high.

In this study, we conduct design optimization of 10 MW downwind and upwind turbines under the IEC Class I condition and compare their LCoE to validate superiority of downwind configuration in large-scale wind turbine with high extreme wind speed. We also investigate effect of prebend on LCoE of upwind turbines to provide a fair comparison. The fair comparison of downwind and upwind turbines requires evaluation for tower shadow and potential flow effects on power production and fatigue damage. We propose reasonable evaluation methods based on steady state aero-structural analyses to promptly compute the power production and fatigue damage with the tower shadow effects during the optimization.

2. Aero-structural Performance Computation with Steady State Analyses

Performance and loads of the wind turbine were evaluated by the Wind-Plant Integrated System Design and Engineering Model (WISDEM) developed by the National Renewable Energy Laboratory (NREL). WISDEM computes power production, loads, and cost of wind turbines according to the blade element momentum (BEM) theory and statistic equations. The loads were computed as steady state at four rotor azimuth angles (0, 90, 180, and 270°). Power curve was obtained from these loads and rated power of the turbine. Original WISDEM does not consider the wind speed decay induced by the tower shadow and potential flow effects around the tower. We introduced tower shadow [7] and potential flow [8] models into WISDEM for reasonable LCoE comparison of downwind and upwind turbines from the points of view of power production and fatigue damage. Fatigue damage evaluation with the tower shadow and potential flow effects also requires fatigue damage equivalent load (DEL) computation for each design candidate, which has unique design variables such as tower diameter and blade shape, during the optimization process. We adopted a simple DEL computation method based on steady state loads at four rotor azimuth angles.

WISDEM also evaluates some critical wind conditions for structural constraints. From our experiences in downwind turbine design, prior analyses, and the previous study [1], we assumed that ultimate loads for tower strength and out-of-plane blade deflection occur at the IEC design load case (DLC) 1.3 and those for blade strength occur at the DLC 6.1. According to Ning and Petch [4], we approximated the load with the extreme turbulence model (ETM) at the DLC 1.3 as $V_{\text{rated}} + 3\sigma_{\text{ETM}}$ where $V_{\text{rated}}$ and $\sigma_{\text{ETM}}$ are the rated wind speed and standard deviation for the ETM. The blade bending moment reaches to its maximum when lift force of the non-rotating blade becomes maximum with the extreme wind model (EWM) at the DLC 6.1. We introduced approximation method to reproduce this load.

Details of the tower shadow and potential flow models, power production and fatigue damage evaluation with them, and ultimate load approximation for the blade strength are described as follows.

2.1. Wind Profile with Tower Shadow and Potential Flow Models

Modified WISDEM only considers steady state three-dimensional wind profiles including wind shear, tower shadow, and potential flow. We assumed that wind shear is expressed as a power law as follows.

$$V(z) = V(z_{\text{ref}}) \left( \frac{z}{z_{\text{ref}}} \right)^{\alpha},$$

(1)

where $\alpha$ is the wind shear parameter, $z$ is a height from the sea level, $z_{\text{ref}}$ is $z$ at a hub height, $V(z)$ is the horizontal wind speed at $z$, and $V(z_{\text{ref}})$ is the wind speed at the hub height. We used $\alpha$ of 0.2 with the exception of 0.11 for the EWM according to [9] because cost models for onshore wind turbines were used. No turbulence was introduced to rotor plane.

The wind speed decay induced by the tower shadow was computed by the following tower shadow model for downwind turbines.
\[
V_{TS}(x, y, z) = \begin{cases} 
V(z) \left[ 1 - e \cdot \cos^2 \left( \frac{\pi y}{W_d} \right) \right] & \text{if } -\frac{\pi}{2} \leq \frac{\pi y}{W_d} \leq \frac{\pi}{2}, \\
V(z) & \text{otherwise}
\end{cases}
\]

(2)

where \( e = e_{\text{ref}} \left( \frac{x}{x_{\text{ref}}} \right)^{-\frac{1}{2}}, W = W_{\text{ref}} \left( \frac{x}{x_{\text{ref}}} \right)^{\frac{1}{2}}, x_{\text{ref}} = [x/d]_{\text{ref}} \cdot d. \)

(3)

\( V_{TS}(x, y, z) \) is the horizontal wind speed considering the tower shadow at \((x, y, z)\) and \(d\) is the outer diameter of the tower at \(z\). \(x\) and \(y\) are the horizontal distances from a central axis of the tower in wind and perpendicular-to-wind directions, respectively. \([x/d]_{\text{ref}}, e_{\text{ref}}, \) and \(W_{\text{ref}}\) are parameters to determine strength and effective region of the tower shadow. We applied these parameter values of Hitachi 2MW downwind turbines to the present 10 MW turbine optimization. These values were determined to conform the blade load of the BEM analysis with equation (2) to that of high-fidelity computational fluid dynamics analysis according to Yoshida and Kiyoki’s approach [7]. For upwind turbines, the potential flow model used in the NREL FAST was applied with a tower drag coefficient of 0.5 [8].

2.2. Power Production Evaluation

Power production is computed as an inner product of power curve and wind speed histogram following the Rayleigh distribution. We used weighted mean of torques generated by a blade at four rotor azimuth angles \((0, 90, 180, \text{ and } 270^\circ)\) to properly evaluate power curves affected by the tower shadow and potential flow models. The original WISDEM computed the power curve by simply averaging torques at the four azimuth angles. The equally weighted mean underestimates the power curve because the significantly low torque at the azimuth angle of \(180^\circ\) has quarter contribution. We employed the following equation to compute power equivalent torque \(\bar{Q}\).

\[
\bar{Q} = n_{\text{blade}} \left[ \xi Q_{180} + \frac{1-\xi}{3} (Q_0 + Q_{90} + Q_{270}) \right],
\]

(4)

where \(Q_{AZ} (AZ = 0, 90, 180, 270)\) is the torque generated by one blade and computed from the steady state BEM analyses at the azimuth angle of \(AZ\), \(\xi\) is a weight for \(Q_{180}\) which is affected by the tower shadow and potential flow models, and \(n_{\text{blade}}\) is the number of blades installed \((n_{\text{blade}} = 3\) in this study). \(\xi\) is determined beforehand to balance wind kinetic energy through the rotor plane (integral of the cube of local wind speed in the rotor plane) computed from the azimuth angles discretized into four and 360. We determined values of \(\xi\) for tower shadow and potential flow models by computing this wind kinetic energy for our wind turbines though suitable \(\xi\) depends on the wind shear parameter \(\alpha\), rotor diameter, tower diameter, hub height, etc. In this study, \(\xi = 0.18\) and 0.15 were used for tower shadow and potential flow models, respectively. These values should give reasonable approximation of \(\bar{Q}\) for 10 MW turbines.

2.3. Fatigue Damage Evaluation

WISDEM evaluates fatigue damage constraint as follows.

\[
n/N < D_{\text{limit}},
\]

(5)

where \(D_{\text{limit}}\) is an allowable fatigue damage, \(N\) is the number of cycles to failure when the load whose amplitude equals DEL acts on the blade, and \(n\) is the number of cycles to compute DEL. Note that only \(N\) is a variable computed from DEL and the blade design while \(D_{\text{limit}} \leq 1\) is a design parameter and \(n\) is an arbitrary constant \((n = 20 \times 365.25 \times 24 \times 60 \times 60 \text{ in this study})\). \(N\) for blade structural components including spar cap and trailing edge (TE) panel can be computed as

\[
N = \left( \frac{\varepsilon_{\text{ult}}}{\gamma_{\text{del}} \varepsilon_{\text{del}}} \right)^{m},
\]

(6)
\[\varepsilon_{\text{del}} = \frac{M_{\text{del}}\gamma_{\text{str}}}{E I_{\text{str}}}.\]  

(7)

\(\varepsilon_{\text{ult}}\) is a ultimate strain of the blade material, \(\gamma_{\text{del}}\) is a total safety factor, \(m\) is a slope of a S-N curve, \(M_{\text{del}}\) is DEL of the bending moment in an evaluation direction (flapwise for spar cap and edgewise for TE panel), \(\gamma_{\text{str}}\) is a moment arm between a blade pitch axis and an evaluation point on the spar cap or TE panel, and \(E I_{\text{str}}\) is bending stiffness of the blade in the evaluation direction. \(\varepsilon_{\text{ult}}, m,\) and \(\gamma_{\text{del}}\) can be determined from material properties and standards. \(\gamma_{\text{str}}\) and \(E I_{\text{str}}\) can be computed from structural design of the blade. Original WISDEM gives \(M_{\text{del}}\) of a reference turbine though load difference between the optimized and reference blades is ignored in this way.

In this study, we estimated \(M_{\text{del}}\) from steady state loads at four rotor azimuth angles. Let \(M_{\text{AZ}}(r, V)\) be the bending moment in the evaluation direction when the azimuth angle, blade position, and hub wind speed are \(\text{AZ}, r,\) and \(V,\) respectively, moment amplitude \(\Delta M(r, V)\) can be computed as

\[\Delta M(r, V) = \frac{1}{2} \left[ \max_{\text{AZ}} \left( M_{\text{AZ}}(r, V) \right) - \min_{\text{AZ}} \left( M_{\text{AZ}}(r, V) \right) \right] \quad (AZ = 0, 90, 180, 270).\]  

(8)

\(M_{\text{AZ}}(r, V)\) is evaluated from the BEM analyses considering blade pitch angles described later, and \(M_{\text{180}}(r, V)\) includes the tower shadow and potential flow effects. \(M_{\text{del}}\) at \(r\), \(M_{\text{del}}(r),\) is estimated from \(\Delta M(r, V)\), normalized wind speed histogram \(\varphi(V)\) [-], and rotational speed of the rotor \(\omega(V)\) [min\(^{-1}\)] as

\[M_{\text{del}}(r) = \frac{1}{n} \int_{V_{\text{in}}}^{V_{\text{out}}} \Delta M(r, V) \frac{\varphi(V) \omega(V) n_{\text{time}} dV}{m},\]  

(9)

where \(V_{\text{in}}\) and \(V_{\text{out}}\) are cut-in and cut-out wind speeds and \(n_{\text{time}} = 20 \times 365.25 \times 24 \times 60\) [min]. We should include turbulence and vibration effects on DEL in \(\gamma_{\text{del}}\) because equation (9) ignores them.

The blade pitch angles above rated wind speed (region 3), where pitch control is mainly applied, were estimated by comparing rotational forces at a blade cross-section in the rated condition and region 3. The rotational force, \(F,\) induced by local lift force of an airfoil at \(r\) is as follows if drag force and induced velocities are disregarded.

\[F = C_l \frac{1}{2} \rho c [V^2 + (r \omega_{\text{rated}})^2] \sin(\phi),\]  

(10)

where

\[C_l = C_{l0} + \frac{\partial C_l}{\partial \alpha}(\phi - \theta).\]  

(11)

\(\rho, c, \omega_{\text{rated}}, \phi, \theta, C_l, C_{l0},\) and \(\partial C_l/\partial \alpha\) are air density, chord length, rotational speed of the rotor in the region 3, flow angle to rotor plane, pitch angle, lift coefficient, lift coefficient at a zero angle of attack, and lift slope, respectively. We assumed that \(F\) in the region 3 is the same as that at the rated wind speed. Let a subscript “\(\text{rated}\)” be values at the rated wind speed, this assumption gives the following equation to estimate \(\theta\) in the region 3.

\[\theta = \phi + C \left[ 1 - \frac{[(V_{\text{rated}} - V_0)^2 + (r \omega_{\text{rated}})^2] [1 + \frac{\phi_{\text{rated}}}{\varphi^2 + (r \omega_{\text{rated}})^2}] \sin(\phi_{\text{rated}})}{\sin(\phi)} \right].\]  

(12)

where

\[C = C_{l0} \left[ \frac{\partial C_l}{\partial \alpha} \right]^{-1}, \phi = \tan^{-1} \left( \frac{V}{r \omega_{\text{rated}}} \right), \phi_{\text{rated}} = \tan^{-1} \left( \frac{V_{\text{rated}} - V_0}{r \omega_{\text{rated}}} \right), V_0 = 1 \text{ [m/s]}.\]  

(13)

We replaced \(r\) by rotor radius \(R, V_0\) is a gap between the rated wind speed \((V_{\text{rated}})\) and the wind speed at which the pitch control begins \((V_{\text{rated}} - V_0)\). Equation (12) can include the effects of induced velocities by multiplying \(\phi\) and \(\phi_{\text{rated}}\) by 2/3 though we ignored them due to better estimation accuracy in 10 MW turbines without it. The parameter \(C\) was determined by fitting equation (12) to pitch schedules of the NREL 5 MW reference turbine and some other turbines. Figure 1 shows original and estimated pitch schedules of the NREL 5 MW reference turbine. Equation (12) enabled to estimate \(M_{\text{AZ}}(r, V)\) with reasonable accuracy in the region 3.
2.4. Ultimate Load Approximation

We assumed that the ultimate load for the blade strength occurs when lift force of the non-rotating feathered blade becomes maximum with the EWM and instantaneous yaw misalignment due to turbulence. This condition can be happened in both DLC 6.1 and DLC 6.2. We approximated the ultimate load in the DLC 6.1 because the DLC 6.1 includes normal safety factor of 1.35 and results in severer load than the DLC 6.2. In our prior analyses, a non-rotating blade of the NREL 5MW reference turbine showed its maximum lift force at a blade tip angle of attack of 19°. Thus, we computed blade loads at the blade tip angle of attack of 19°, hub wind speed of 1.4\(V_{\text{ref}}\) \((V_{\text{ref}} = 50 \text{ [m/s]} \text{ for IEC class I turbines in this study}),\) and rotor azimuth angle of 0° with steady state BEM analyses as the ultimate loads with the 50-year EWM. Kiyoki et al. measured yaw misalignment of a 2 MW downwind turbine at an extreme wind condition caused by a typhoon and revealed that the instantaneous yaw misalignment around 19° frequently appeared [6]. The blade tip angle of attack should reach 19° in this condition.

3. Design Conditions and Optimization Problem Definition

Design optimization was conducted for onshore 10 MW downwind and upwind turbines under the IEC class IA condition. To investigate the effect of prebend on LCoE of the upwind turbines, two design cases were prepared. Case-1 assumed realistic prebend up to 6 [m] according to [2, 3] while Case-2 allowed the upwind turbines to have optimal prebend up to 20 [m] balancing power production and cost reduction. The downwind turbines did not have prebend to keep large clearance between the blades and tower and prevent the blades from striking to the tower at shutdowns. In both downwind and upwind turbines, tilt and cone angles of the rotor were fixed at 6° and 4°, respectively, as well as Pietro et al. [3]. The tilt and cone angles of downwind turbines were applied in a direction to increase the clearance between the blades and tower. This clearance was computed from blade deflection, prebend, tilt and cone angles, hub overhang, and tower diameter to evaluate a clearance constraint for upwind turbines and the tower shadow and potential from effects. We adopted two-stage optimization to take the blade deflection into account with minimal computational cost because rigorous deflection computation required convergence calculation with iteration for each wind speed. In the first stage, optimization in the Case-1 was conducted without the deflection, and tentative deflection at 70% of the rated wind speed, which gave reasonable approximation of annual energy production (AEP) [4], was obtained. Then, the tentative deflection was introduced to the second stage of optimization in the Case-1 and 2. The Case-1 introduced 90% of the tentative deflection of the downwind turbines and 100% of the tentative deflection of upwind turbines to the corresponding turbines while the Case-2 introduced 90% of the tentative deflection of downwind turbines to the upwind turbines. 90% of the tentative deflection gave reasonable approximation in flexible blades.

The objective function, constraints, and design variables of the design optimization were summarized in Table 1. Design of blade and tower was optimized to minimize LCoE while drivetrain
with a three-stage gearbox was implicitly optimized to minimize its mass through DriveSE in WISDEM. The optimization was conducted with various blade lengths from 75 to 105 [m]. LCoE minimization was the only one objective function in this study. We utilized onshore cost model in WISDEM [10] to evaluate LCoE due to its reliability even though 10MW wind turbines are usually employed at offshore sites. Onshore cost model did not affect optimization results because most parts of the cost models except turbine cost were functions of rated power fixed at 10 MW. Hence, LCoE was minimized by minimizing the turbine cost and maximizing AEP.

Most of the constraints were same as those used by Ning and Petch [4] although material properties and safety factors were modified as shown in Table 2. We used the material properties provided by WISDEM and the Sandia National Laboratories [11]. The ultimate strength of blades was evaluated as strain by dividing the ultimate stress by the elastic modulus. We introduced a partial safety factor of 2.0 for the fatigue load as DEL correction to include turbulence and vibration effects. There were five constraints we added and modified: fatigue strength, angle of attack, tip speed, blade root diameter, and deflection. The DEL estimation was added for the blades while fatigue damage of the tower, which was an inactivated constraint, was eliminated. We utilized airfoils in Table 3, where \( l/d \) and \( C_l \) are lift-to-drag ratio and lift coefficient, respectively, under their allowable angles of attack to avoid stall. The maximum tip speed was limited below 100 [m/s]. The blade root diameter should be greater than 90% of hub diameter which was 5% of the blade length. The maximum blade tip deflection should be smaller than 70% of clearance between the unloaded blades and tower for upwind turbines.

The design variables were mainly related to the blades and tower because the drivetrain was implicitly optimized in WISDEM. Spar cap and TE panel thicknesses were used as design variables while shell and spar web were simply scaled up from those of the NREL 5MW reference turbine. The number of design variables was 42 for downwind turbines and 45 for upwind turbines (including three for prebend). The hub height was not a design variable and computed as \( R + 20 \) [m]. The overhang was approximated as a sum of the hub diameter and tower top radius.

The nondominated sorting genetic algorithm II (NSGA-II) was used as optimizer due to its robustness and gradient-free property to adopt airfoil distribution as the design variables. The population and generation counts in NSGA-II were both 200.

### Table 1. Objective function, constraints, and design variables of design optimization.

| Objective function               | LCoE (minimization) |
|---------------------------------|---------------------|
| Constraints                     |                     |
| Blade:                          | Ultimate, buckling, and fatigue strength, natural frequency, angle of attack, tip speed, root diameter, and deflection (upwind) |
| Tower:                          | Ultimate and buckling strength, natural frequency, manufacturability, and weldability |
| Design variables                |                     |
| Blade:                          | Chord, twist, airfoil, spar cap thickness, TE panel thickness, and prebend (upwind) |
| Tower:                          | Outer diameter, wall thickness, and waist position |
| Others:                         | Tip speed ratio, rated rotational speed |

### Table 2. Material properties and safety factors (strain for blade and stress for tower).

| Parts                  | Blade spar cap     | Blade TE panel      | Tubular tower |
|------------------------|--------------------|---------------------|---------------|
| Material               | Uni-direction carbon| Uni-direction glass | Steel         |
| Elastic modulus [GPa]  | 114.5              | 41.80               | 210.0         |
| Ultimate tensile stress [MPa] | 1546        | 972.0               | 450.0         |
| Ultimate compressive stress [MPa] | 1047       | 702.0               | 450.0         |
| Ultimate strain for fatigue (\( \epsilon_{ult} \)) | 0.01132 | 0.02002             | -             |
| Safety factor for ultimate load | 2.977 = 1.35×2.205  | 1.485 = 1.35×1.1    | -             |
| Safety factor for fatigue load | 3.920 = 2.0×1.0×1.960 | -                  | -             |
| Slope of S-N curve (m)  | 14                 | 10                  | -             |
4. Results and Discussion

4.1. Performance of optimized wind turbines

The optimized downwind turbines and upwind turbines in the Case-1 and 2 after the two-stage optimization were compared to validate superiority of the downwind turbines with the flexible blades in the IEC class IA condition. Figure 2 shows various aspects of performance of downwind and upwind turbines: LCoE, rotor AEP, blade mass, RNA mass, tower mass, blade tip deflection at 70% of the rated wind speed, maximum blade tip deflection, and blade tip prebend. The downwind turbines with rotor diameter over 164 [m] show the superiority in LCoE to the upwind turbines with conventional prebend (Case-1) and achieve their lowest LCoE at the rotor diameter of 194.75 [m]. This is derived from 15-17% lighter and more flexible blades installed in the downwind turbines. These lighter blades also decrease the RNA mass including hub and nacelle components by 5-7%. On the other hand, blade structure of the upwind turbines in the Case-1 is constrained by the clearance between the blades and tower although prebend up to 6 [m] is fully applied.

Another advantage of the downwind turbines with the flexible blades is smaller thrust force due to the rotor tilt and cone angles and deflection toward downstream whereas AEP is also reduced. This smaller thrust force enables the downwind turbines to have comparable tower mass to the upwind turbines. The other important feature is a smaller distance between a tower axis and center of gravity of the RNA (1 [m]) than that in the 5 MW turbines (2 [m]). The smaller distance is derived from the nacelle as heavy as the tower. This will be the main difference with the results of Ning and Petch [4], where heavier towers of the 5MW downwind turbines increased their LCoE.

In the downwind turbines, we should consider the deflection toward the tower at the shutdowns. Figure 2 (g) includes the clearance between the unloaded blades and tower of the downwind turbines. The tower-strike can be avoided by designing a suitable shutdown process because the clearance is greater than 90% of the maximum blade tip deflection. Besides, the downwind turbines can adopt larger tilt and cone angles or prebend toward downstream to make additional clearance [12, 13]. In fact, commercial downwind turbines have tilt and cone angles of 8° and 5°, respectively [14]. These angles give additional 5 [m] clearance to the downwind turbine with the rotor diameter of 194.75 [m].

The upwind turbines with optimal prebend (Case-2) have comparable LCoE to the downwind turbines and achieve the lowest LCoE at the rotor diameter of 184.5 [m] although the upwind turbine with the lowest LCoE requires significantly large prebend of 11 [m]. These two took different ways to achieve their lowest LCoE. The downwind turbines, which can adopt the lighter rotor with lower thrust, utilize lighter RNA to achieve lower cost while the upwind turbines keep AEP higher. The downwind turbines may have advantage when turbines are installed in offshore farms or farms with earthquakes. Smaller thrust force will reduce bending moment and cost of structures under the sea in offshore farms. In earthquake regions, the lighter RNA can reduce the tower mass and cost which are dominated by ultimate load of earthquakes instead of the DLC 1.3 in this study.

Figure 2 (f) compares the 90% and 100% of tentative deflection used in load computation and blade tip deflection obtained in the second stage of the optimization. The deflection of downwind and upwind turbines is well approximated while underestimation sometimes occurs.
In this study, the only DLC 1.3 and DLC 6.1 were approximated by steady state aero-structural analyses though all DLCs should be evaluated in the real wind turbine design. Thus, feasibility of the optimized wind turbines at the other DLCs represented by the DLC 1.4 and DLC 5.1, where the tip deflection of upwind turbines and deflection toward the tower for downwind turbines can be maximum, respectively, should be validated with unsteady aero-structural analyses. Gusts with direction change at the DLC 1.4 may increase the angle of attack and maximum tip deflection of the upwind turbine blade. This is because DLC 1.3 approximated by $V_{\text{rated}} + 3\sigma_{\text{ETM}}$ increases the angle of attack at the 80% blade position by 14° in the present design condition, which is too large for the airfoils to have their highest $C_l$. On the other hand, the large clearance comparable to the maximum tip deflection at $V_{\text{rated}} + 3\sigma_{\text{ETM}}$ with the ETM may prevent the downwind turbines from tower-strike at the DLC 5.1 as it assumes emergency shutdowns with the normal turbulence model.

**Figure 2.** Performance of optimized wind turbines: LCoE (a), rotor AEP (b), blade mass (c), RNA mass (d), tower mass (e), blade tip deflection at 70% of the rated wind speed (f), maximum blade tip deflection (g), and blade tip prebend (h).
4.2. Optimized blade shapes and characteristics
To reveal features of the optimized downwind turbine, we compared blade shapes and characteristics of the representative downwind and upwind turbines with rotor diameter of 184.5 [m] where the upwind turbines achieve their lowest LCoE. Figure 3 shows chord length, twist angle, spar cap thickness, total deflection (tentative deflection minus prebend), edgewise DEL, and flapwise DEL of the representative turbines. The downwind turbine has clearly different features compared to upwind turbines. Chord length of the downwind turbine is smaller than upwind turbines. Smaller chord length derives lighter blades while it requires smaller twist angle to increase the angle of attack. The angles of attack of downwind and two upwind (both Case-1 and 2) turbines at their outboard is approximately 5° and 4°, respectively. The upwind turbine in the Case-1 has small angle of attack around 3° at the blade tip to reduce flapwise bending moment and deflection. Besides, the downwind turbine can adopt thinner spar cap than the upwind turbines as shown in figure 3 (c). The blade structure of the downwind turbine is mainly constrained by the ultimate compressive strength at the spar cap and fatigue damage at the TE panel. On the other hand, activated constraints in the two upwind turbines are the maximum blade tip deflection for the spar cap and buckling at the TE panel.

Estimated DEL in figures 3 (e) and (f) reflects the design feature of each wind turbine. The edgewise DEL follows the mass of the blades though the downwind turbine with the smallest edgewise DEL is severely constrained by the fatigue damage at the TE panel. This is because the small chord length significantly decreases edgewise stiffness and increases strain amplitude. The flapwise DEL is correlated with the wind speed decay induced by the tower shadow and potential flow. The upwind turbine in the Case-1 has the largest flapwise DEL due to the smallest clearance between the loaded blades and tower, which is derived from prebend canceled by deflection as shown in figure 3 (d). The upwind turbine in the Case-2 has smaller flapwise DEL than that in the Case-1 because the large prebend of 11 [m] is not canceled by deflection of 8 [m] and makes additional 3 [m] clearance. Flapwise DEL of the downwind turbine is as small as that of the upwind turbine in the Case-2. Its flexible blades make large clearance to alleviate the wind speed decay induced by the tower shadow.

Figure 3. Blade shapes and characteristics of the representative wind turbines: chord (a), twist (b), spar cap thickness (c), total deflection (d), edgewise DEL (e), and flapwise DEL (f).
5. Conclusions
To investigate the superiority of the large-scale downwind turbines with high extreme wind speed, the blades and towers of 10 MW downwind and upwind turbines were optimized to minimize LCoE in the IEC class IA condition. We introduced the tower shadow and potential flow models and DEL estimation method for a fair comparison of AEP and fatigue damage between downwind and upwind turbines. The optimized downwind turbines achieved better LCoE than the upwind turbines with conventional prebend due to its lighter and flexible blades. Since these blades also decreased the thrust force and RNA mass, the downwind turbines had advantage in cost at the sacrifice of AEP. The tower mass of the downwind turbines was comparable to that of the upwind turbines. This feature was derived from the small thrust force and RNA mass, besides, the small thrust force and RNA mass may give the downwind turbines a cost advantage in offshore farms and farms with earthquakes, respectively. The upwind turbines required significantly large prebend of 11 [m] to obtain comparable LCoE to the downwind turbines.

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