Investigation of Innovative Rotor Concepts for the Big Adaptive Rotor Project

Nick Johnson,[1] Pietro Bortolotti,[1] Katherine Dykes,[1] Garrett Barter,[1] Patrick Moriarty,[1] Scott Carron,[1] Fabian Wendt,[1] Paul Veers,[1] Josh Paquette,[2] Chris Kelly,[2] and Brandon Ennis[2]

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Technical Report
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List of Abbreviations and Acronyms

AEP	annual energy production
BAR	Big Adaptive Rotor
BEMT	blade element momentum theory
BOS	balance of system
CapEx	capital expenditures
CF	capacity factor
DOE	U.S. Department of Energy
IPC	individual pitch control
LCOE	levelized cost of energy
MTL	manufacturing, transportation, and logistics
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
O&M	operation and maintenance
OpEx	operational expenditures
R&D	research and development
Sandia	Sandia National Laboratories
TCC	turbine capital costs
TRL	technology readiness level
TSR	tip-speed ratio

Executive Summary

For the past few decades, substantial reductions in the cost of wind energy have come from large increases in rotor size. Larger rotors capture substantially more energy through greater swept area and access to increased wind speeds at higher above-ground levels. Another benefit of this rotor growth has been higher capacity factor turbines and wind plants, yielding less variability in power production. With limited land-based high wind resource sites remaining in the United States, future development will depend in part on deployment in lower wind resource sites, requiring further increases in rotor size for cost-effective energy production. The objective of the Big Adaptive Rotor (BAR) project is to identify and develop the necessary technology to enable the development of a land-based 5-megawatt turbine with a 200-m rotor designed for International Electrotechnical Commission Class III A conditions. This configuration yields a specific power of 150 W/m^2. Research has shown that low specific power rotors, with correspondingly higher capacity factors, could lead to higher economic value (Wiser and Bolinger 2017).

In 2018, U.S. national laboratory researchers conducted a literature review and developed a catalog of 16 innovative technology concepts that had the potential to enable land-based blades over 100 m in length. An experts' workshop was convened in August 2018 to evaluate the performance of each concept according to levelized cost of energy, capacity factor, and balance of station costs. Additionally, the experts identified and evaluated the science and engineering challenges associated with each concept in the areas of blade aerodynamics, turbine elasticity, aeroacoustics, blade structure, materials, manufacturability, and transportation logistics, among others. The evaluation consisted of a qualitative assessment and comments about each concept. After the experts' workshop, an internal national laboratory team consisting of researchers from Sandia National Laboratories and the National Renewable Energy Laboratory evaluated each of the concepts in the same manner.

The assessments for the performance metrics and science and engineering challenges were used to complete a qualitative analysis to determine which concepts had the potential to make the largest impact on next-generation turbine design. The analysis favored technologies that had a higher performance impact and more open science and engineering challenges. Based on the rankings of the innovative technology concepts, six concepts were identified for future research and development opportunities, namely downwind turbines, distributed aerodynamic devices, multielement airfoils, highly flexible blades, high tip-speed-ratio blades, and inflatable blades. The objective of this report is to summarize the innovative technology concepts considered in the study, summarize the findings of the workshop, and provide a qualitative analysis on the workshop results.

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1 Introduction

Wind turbine rotor diameters continue to increase in size for several reasons, including greater power capture, ability to capture more energy at lower wind speeds, and economies of scale (both capital and operational expenditures) associated with fewer turbines for the same or greater overall power capture. Wiser and Bolinger (2017) have tracked the increase in wind turbine size over time and have shown a continued increase in rotor size. However, limitations on transportation and logistics of blades reaching 65 m or longer for land-based applications may limit future growth (Cotrell et al. 2014).

Another impact of this rotor growth has been higher capacity factor (CF) wind plants, yielding less variability in power production. With limited high wind resource sites, future land-based wind energy development will depend partly on deployment in lower wind resource sites, requiring further increases in rotor size for cost-effective energy production. However, the technologies required to enable the next generation of rotors have not been fully validated, including large blade manufacturing and transportation, novel rotor design concepts and features, and turbine controls. In addition, numerous fundamental scientific questions and challenges remain to be solved for some innovative concepts.

The Big Adaptive Rotor (BAR) project is funded by the U.S. Department of Energy (DOE) Wind Energy Technologies Office and has the objective of researching and developing innovative technologies that enable large land-based rotors that have the potential to produce a 10% increase in CF over current technology. The innovative technologies must have a reduction in specific power to at least 150 W/m^2 at an International Electrotechnical Commission Class III wind site for a 5-megawatt (MW) or higher rating and maintain a competitive levelized cost of energy (LCOE) compared to current technology.

The purpose of this document is to:

1. Identify and classify innovative BAR concepts
2. Evaluate the concepts in terms of their potential to impact wind plant LCOE and other performance metrics of interest and identify science and engineering challenges that would limit the commercialization of these concepts
3. Quantitatively analyze and compare the BAR concepts.

2 BAR Concept Catalog

The national laboratory team, consisting of experts from the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (Sandia), conducted a literature review and developed a catalog of 16 innovative technology concepts that had the potential to enable very large land-based blades. The concepts considered are shown in Table 1. There is a large range of technology configurations that span from the more conventional to those with completely different topologies compared to modern commercial turbines.

Table 1. BAR Concepts Broken Down by Innovation Category

Rotor Topology	Orientation	Blade Configuration	Blade Design Features	Hub Configuration
Three-bladed	**Upwind**	**Scaled conventional blade**	**No advanced features**	**Normal hub**
Two-bladed	Downwind	Slender, high tip-speed-ratio blades	Multielement airfoils	Large hub radius
Dual-rotor		Highly flexible blades	Segmented/modular blades	
Multirotor		Low-induction rotor	Inflatable blades	
		Wake-optimized rotor	Variable coned rotor	
			Variable diameter rotor	
			Winglets	
			Distributed aerodynamic controls	

The first row (in red) shows the current dominant configuration for modern commercial land-based wind turbine technology. The following lines show variations from the current configuration grouped into categories by design considerations. Some of the categories reflect fundamentally different topologies from the current dominant design configuration (e.g., the dual rotor or multirotor), while others are design features that could apply to numerous concepts (i.e., blade segmentation is compatible with machines of two or three blades with upwind or downwind orientations). For the purposes of isolating and exploring the potential of each innovation, all of the above concepts were treated separately. In the following subsections, each concept is described at a high level in terms of the concept definition as well as potential benefits and challenges of the technology from a BAR project perspective.

2.1 Rotor Topology: Two Bladed

One way to reduce rotor capital cost is to reduce the number of blades from three to two. In the early stages of wind energy development, multiple two-bladed rotor concepts were developed, installed, and tested. A key motivation for pursuing this path in early modern wind turbine technology development was the high cost of the blade relative to the other turbine components (Dykes 2016). In addition, the removal of one blade reduces the overall weight of the rotor and the gravity loads transmitted to the rest of the system, potentially allowing weight and cost reductions for other turbine components. The two-bladed wind turbines designed for optimal aerodynamic performance also have higher tip-speed ratios (TSRs). Because two-bladed turbines have inherently higher TSRs for optimal operation, they provide similar benefits of higher operational rotor speeds for a given wind speed, which reduces drivetrain torque and may allow for reduced gearbox size for geared machines and/or smaller generators for geared or direct drive machines (Ning and Dykes 2014; Dykes et al. 2014). However, higher TSRs can also be associated with blade erosion and higher loads; these considerations need to be weighed against the advantages. Additionally, reducing the number of blades will have a significant impact on blade transportation, logistics, and installation costs, which are a major part of project capital costs and must be considered before the industry adopts very large rotors.

Figure 1. Early design of a two-bladed rotor. *Photo from National Atmospheric and Space Administration*[1]

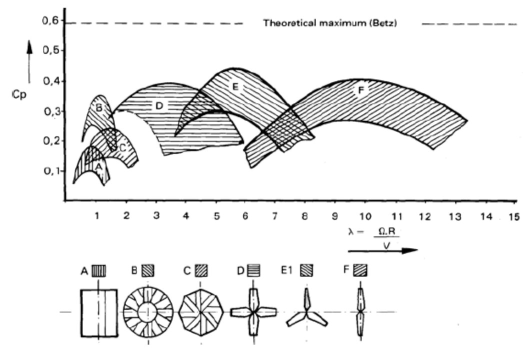

Figure 2. Influence of rotor solidity on Cp versus lambda. *Image from Lysen (1983)*

Nonetheless, three-bladed rotor wind turbine designs became the industry standard from the 1980s up to the present day due to several challenges for reliable design and operation of two-bladed systems. First, three-bladed systems can be designed for a slightly higher aerodynamic efficiency, which translates to increased power capture compared to two-bladed machines. In addition, because two-bladed wind turbines typically operate with higher TSRs, they will have increased aeroacoustic tip noise as compared to a three-bladed turbine for the same wind speed. Finally, and perhaps most importantly, the two-bladed configuration suffers from asymmetric mass moment of inertia as a function of the azimuthal position of the rotor and experiences complex dynamics and gyroscopic loading during yaw that present control design and reliability challenges (Schorbach, Haines, and Dalhoff 2016).

2.2 Rotor Topology: Dual Rotor

Hub losses extend to about 25% of span, regardless of length, due to the need for thick structural cross sections and geometry that are heavily constrained by additional manufacturing and transportation constraints. This leads to poor aerodynamic performance of the inboard section, with an estimated 5% loss of net aerodynamic efficiency due to the hub region alone (Rosenberg, Selvaraj, and Sharma 2014). The inboard sections of the rotor therefore are a lost opportunity for power production that grows proportionally to the rotor diameter.

[1] http://www.nasa.gov/images/content/149600main_1987_05991.jpg

This power could be reclaimed with co-axial, multiple-stage rotors. In this concept, a small diameter rotor is placed ahead of the larger rotor and rotates in the same direction as the larger rotor. Researchers that optimized a two-stage co-axial rotor found that the smaller rotor should be approximately 25% of the diameter of the larger rotor (Rosenberg, Selvaraj, and Sharma 2014). In the preliminary studies, the smaller rotor is modeled to spin more quickly to achieve an optimal TSR. The smaller rotor produces power in the region that would otherwise escape through hub losses of the larger rotor. Additionally, the different rotor diameters create dual helical wake structures that mix much more aggressively than for single-rotor configurations. This augmented wake mixing further reduces downstream array effect losses. Although this multistage approach with different shaft speeds seems complicated at first glance, it is standard practice in modern gas turbine engine designs. The German manufacturer Enercon has a relevant U.S. patent on this design from 2006 (Wobben 2006).

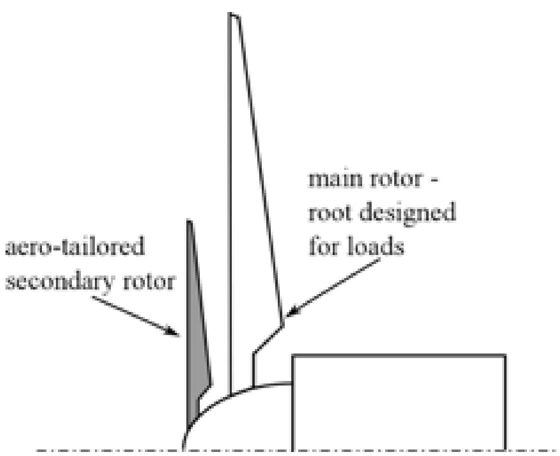

Figure 3. Visual depiction of a co-axial dual-stage rotor. ***Image from Rosenberg, Selvaraj, and Sharma (2014)***

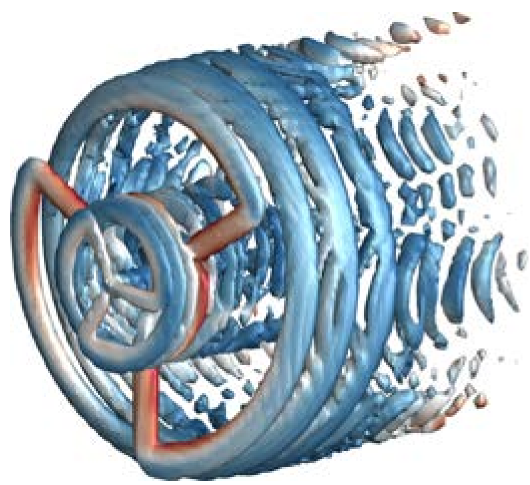

Figure 4. Enhanced wake mixing from interaction of inner and outer helical wakes. ***Image from Rosenberg and Sharma (2016)***

By using multiple "actuator disks," these designs can exceed the Betz limit of a single-stage turbine for the same stream tube area (Newman 1986). Numerical and experimental results from Iowa State show power production improvements from 4.5%–7% (Rosenberg, Selvaraj, and Sharma 2014). Augmented wake mixing can be exploited by increasing plant net power production for a given layout or further minimizing plant footprint while tolerating similar array losses.

The co-axial, dual-stage rotor concept would not only be beneficial for increased power production but could also enable larger rotor diameters and blade segmentation to eschew transportation constraints on the design. Because no attempt at power production near the hub for the larger rotor is necessary, the geometry could be configured almost solely for structural performance. The root of the blade could even be a long flange that connects to the hub and the new blade root located near 25% span or where the tip of the smaller rotor ends. This design approach for the larger blade would be well suited for segmentation without incurring a heavy mass penalty in the design. The segmentation approach would also alleviate transportation constraints on the design because no high-twist, wide-chord geometry is needed near the root of the long blade.

Although there are several attractive upsides to this concept, several downsides are also foreseen. First, the cost of the rotor would increase due to the need to manufacture six blade components instead of three. However, the total blade mass will likely only increase modestly under this approach. Second, the drivetrain complexity will increase significantly because there will be concentric low-speed and high-speed shafts separated with a high-quality bearing system, and both shafts must feed the same gear and generator system. Furthermore, the control system that adjusts the blade pitch and rotor speed will become more intricate as well.

2.3 Rotor Topology: Multirotor

One potential solution for circumventing the limitations of transport and logistics while allowing for larger power output is through a multirotor concept, such as the one that has been introduced by Vestas (Renewables Now 2017). The concept of a multirotor wind turbine has been around for a very long time. Herman Honnef in Germany conceptualized and patented multirotor designs in the 1930s (Honnef 1934). William Heronemus revisited the concept for large-scale offshore floating wind energy systems composed of multirotors in the 1980s and 1990s (Heronemus 2006). However, the actual demonstration of the technology is very recent. Vestas had demonstrated a prototype multirotor concept at the Technical University of Denmark Wind Energy test facility in Roskilde, Denmark from 2016–2018. The prototype has four rotors on two separate horizontal booms (see Figure 6). The concept is specifically designed to “explore a different approach to lower cost of energy by challenging scaling rules” (Vestas 2017).

Figure 5. Visual depiction of Vestas’s multirotor concept. *Image from Renewables Now (2017)*

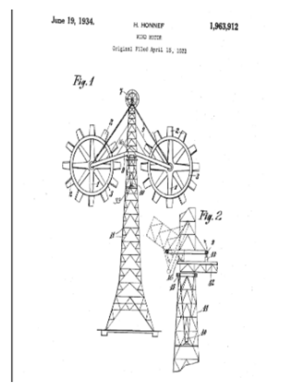

Figure 6. Multirotor concept by Honnef in 1934 patent. *Image from Honnef (1934)*

Given the challenges of transportation and logistics for large blades, multirotors may enable continued scaling of power rating and energy production from a given wind turbine pad using blade designs that are well below transportation limits. However, there may be additional benefits to multirotors beyond overcoming the transportation constraints. The overall size of the components and systems are for instance smaller, which may enable easier manufacture and servicing for lower capital expenditures (CapEx) and operational expenditures (OpEx).

Figure 7. Crane installation of the Vestas multirotor turbine. ***Image from de Vries (2016)***

Additionally, multirotors may provide new opportunities with respect to power plant control for reduced losses and increased plant energy production. The collective wake produced by the multirotor turbine compared to a conventional turbine of the same size may have more favorable characteristics for mixing and dissipation. This could reduce plant losses compared to conventional technology for a comparable power rating and turbine spacing. In addition, the fact that the rotors are placed on a horizontal boom (around a vertical tower) could potentially enable increased degrees of freedom of the collective yaw control of the overall wind turbine multirotor system as well as the tilt collectively and individually of the rotors themselves. Tilt control has recently seen promise for entrainment of higher energy winds from aloft down into and through the plant for additional reductions to wind plant losses and increased overall energy production (Annoni et al. 2017). Smaller rotor diameters finally allow for lower torque drivetrains.

Although there are several attractive upsides to this concept, there are several potential downsides as well. First, the complexity of the tower, control, and yaw systems is increased. Additionally, for a given rated power, multiple drivetrains are needed. This undoubtedly increases complexity and could also reduce reliability. There may also be complex loading on the turbine (and the support structure in particular) because of the independence of the individual rotor/drivetrain systems.

2.4 Orientation: Downwind

An important design driver of very long blades is the minimum clearance between tip and tower to prevent strikes. The design of large upwind rotors is typically highly driven by this design requirement (Bortolotti, Bottasso, and Croce 2016). To meet it, designers are increasingly adopting the combination of thick airfoils and high stiffness moduli composites to increase the out-of-plane stiffness of the blades. Together with an increase in rotor coning angle and shaft tilt angles, this helps satisfy the tower clearance constraint.

Figure 8. Hitachi Ltd. downwind wind turbines installed in Japan. ***Image from Kress, Chokani, and Abhari (2015b)***

Figure 9. Upwind, downwind, and prealigned configurations of the International Energy Agency Wind Task 37 land-based reference wind turbine. ***Image created by Pietro Bortolotti, NREL***

Cost reductions could be obtained from lighter and more flexible blades following a relaxed tower clearance constraint, while an increased annual energy production (AEP) could be generated thanks to reduced coning and uptilt angles as well as a favorable blockage effect generated by the nacelle. Sites characterized by upflow angles, such as hills and ridges, could especially favor downwind designs thanks to a more perpendicular orientation of the rotor plane in respect to the wind. In addition, downwind rotors could be designed with a simplified yawing system (Kress, Chokani, and Abhari 2015a).

An additional potential advantage of downwind rotors is the possibility to achieve load alignment along the blades, proposed and investigated in Ichter et al. (2016) and Loth et al. (2017). The load alignment may be bioinspired by palm trees, which sustain storms by bending downwind and aligning their leaves in the wind direction, in turn making the loads primarily tensile as opposed to bending loads. In Ichter et al. (2016) and Loth et al. (2017), the concept is investigated by designing a 13.2-MW two-bladed downwind rotor concept, and the authors report a decreased cost of energy in comparison to an equivalent upwind three-bladed configuration. The claim is supported by reduced out-of-plane fatigue and ultimate loads that lead to blade mass reduction.

Clearly, benefits would not come free, and downwind rotors struggle against a major disadvantage, namely an increased tower shadow effect (Reiso 2013). This results in three main negative effects compared to equivalent upwind designs. First, fatigue loads typically suffer an increase due to a higher one-per-revolution harmonic of the blade loading (Kress, Chokani, and Abhari 2015b). Second, a higher generation of aeroacoustic noise is experienced due to the blade interfering with the tower wake, especially in the low frequency range of the noise spectrum (Madsen et al. 2007). Third, the torque signal is more unsteady than in upwind rotors. These three aspects have been especially important for early land-based machines and, as a result, modern installations worldwide adopt the largest majority of upwind rotors. One notable exception sees downwind rotors developed by Hitachi Ltd. and installed in Japan (Kress, Chokani, and Abhari 2015b). Additionally, much of the blade mass decrease may be offset by added requirements of tower stiffness (Ning and Petch 2016) needed for downwind machines where the rotor mass and thrust loads introduce tower overturning moments in the same direction. For an upwind machine, this moment counteracts in a different direction. Some additional research may be required to optimize the placement of the rotor-nacelle-assembly center of gravity to offset this tendency.

2.5 Blade Configuration: Slender, High Tip-Speed-Ratio Blades

Increasing the aspect ratio of rotor blades (or increasing the slenderness of the blade) has several advantages. First, high aspect ratio wings are commonly used on high performance gliders that aim to maximize the lift-to-drag ratio through minimization of induced drag effects. Second, transportation is likely to benefit from slender blades because the maximum chord for the blade will be smaller and more likely to meet clearance requirements from overhead obstructions. Third, when considering buckling-related design issues, a high aspect ratio blade has the benefit of small unsupported shell sections toward the root of the blade, which helps to increase the buckling safety in these critical areas. Because the overall blade surface area is reduced, a slender blade design would also help reduce loads on the turbine for parked extreme load cases (Wendt 2013). Because the TSR and operational speed for slender blades is higher, drivetrain torque is lower and may enable cost savings for the gearbox and/or generator; however, blade loads may increase (Dykes et al. 2014; Ning and Dykes 2014). Additionally, with a higher TSR design, there is an opportunity to reduce the overall blade mass due to the lower solidity and thus lower blade cost, but this is only if the lower solidity blade does not require the use of expensive materials, such as carbon fiber, to create the stiffness properties necessary to meet deflection constraints/tower clearance requirements (Resor et al. 2014).

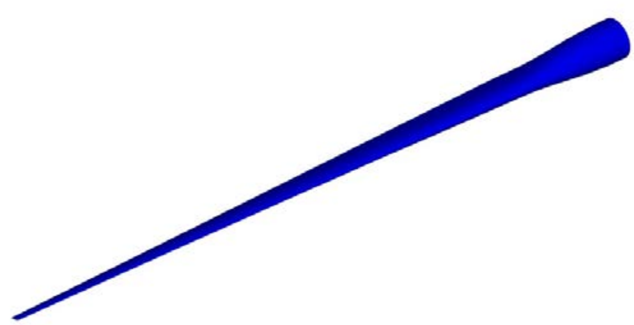

Figure 10. High tip-speed/TSR blade design results in a very slender/low-solidity blade. ***Image from Resor et al. (2014)***

Figure 11. EB 28 glide, aspect ratio: 47. ***Image from Les Grands Planeurs (2010)***

Several disadvantages are also present. From a structural perspective, more slender blade designs are likely to have a reduced absolute thickness, which means that the area moment of inertia is reduced. Consequently, the overall blade structure would be either characterized by a lower bending stiffness or, as previously mentioned, would require the use of high modulus composites (i.e., those that contain carbon fiber) in the spar cap regions, which may increase the blade cost. A solution to this problem could be to operate these blades on downwind turbines to remove tower-clearance-related design constraints, but there would still be potential tower clearance issues in certain loading conditions (e.g., in an emergency stop). In addition, operating at higher tip speeds may be challenging in terms of blade tip erosion, aeroacoustic noise generation, and fatigue damage (Resor et al. 2014; Dykes et al. 2014). A soft and fast rotating blade also may also have issues with unwanted aeroelastic effects (e.g., flutter) that would need to be addressed.

2.6 Blade Configuration: Highly Flexible Blades

Wind turbine manufacturers constantly balance the cost of blades through minimal use of blade materials against stiffness and strength requirements for performance and safe operation. Flexibility is introduced through the reduction of materials or use of less expensive materials in either the spanwise or chordwise direction. Flexibility in the spanwise direction is constrained by the tower strike limitation of upwind machines and can be reduced by allowing the rotor to be downwind of the tower. Flexible blades inherently have system-level benefits by reducing the number of bending loads at the hub and enabling further system cost benefits through the turbine loading path.

With a downwind machine and more spanwise flexible designs (Rasmussen and Petersen 1999; Loth et al. 2012; Steele et al. 2013), as much as 25% of the blade cost of traditional upwind designs could be eliminated. The detailed design of introducing this spanwise flexibility includes eliminating the traditional spar and using a shell beam construction (Rasmussen and Petersen 1999).

Allowing flexibility in the chordwise direction also has benefits. A related recent example of the technology is bend-twist coupling, where flexibility in the spanwise direction can be harnessed to reduce loading from the chordwise lift to decrease overall bending moments. Many research groups are advancing this concept through smart rotor design that use flaps or general torsional flexibility to reduce loads and increase power (Pechlivanoglou et al. 2010). Some groups (Cognet et al. 2017) have suggested that power can increase by 35% if torsional stiffness is greatly reduced, a finding that has yet to be reproduced in the field. Flexibility of blade trailing edges also has advantages for lowering noise levels.

The disadvantage of flexibility is loss of controllability and performance. Flexibility in the spanwise direction introduces power losses from a reduced swept area of the overall rotor. This can often be compensated by increasing the rotor diameter beyond the original with minimal increase in cost. Too much flexibility in either direction can introduce new dynamic modes including coupled modes that are not well understood. Controlling these modes will require distributed added sensors and actuators at considerable added complexity and cost. Further research into new materials to better enable and control additional flexibility at a reasonable cost is required.

2.7 Blade Configuration: Low-Induction Rotor

Low-induction rotors refer to wind turbine blades that are designed to operate with axial induction factors below a value of $\frac{1}{3}$. Rotor blades typically slow down the incoming wind by $\frac{1}{3}$ at the rotor disc because this maximizes the power coefficient of the rotor—that is, it extracts the most power for a constrained rotor area. However, reducing induction below $\frac{1}{3}$ more rapidly changes thrust coefficient than power coefficient. This means low-induction rotors are an opportunity to increase energy capture, CF, blade length, and swept area without increasing each blade's root bending moment. Energy capture can increase despite the power coefficient decreasing because the power curve in region 2 is defined by the product of the power coefficient and radius squared, $C_P R^2$.

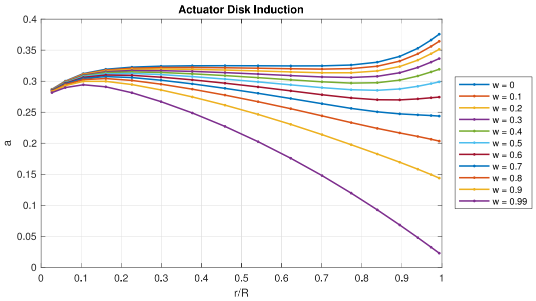

Figure 12. Optimum induction distributions across the rotor radius, w=0 for maximum power coefficient and w = 0.99 for maximum annual energy production, all with the same root bending moment. *Image from Kelley (2017)*

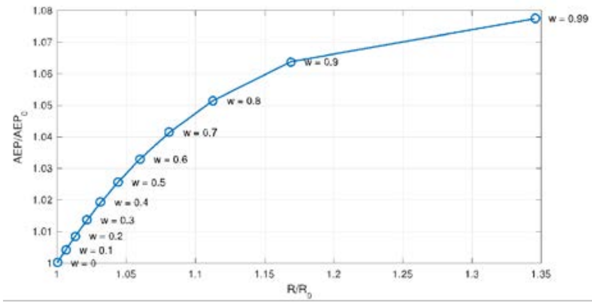

Figure 13. Annual energy production increase for various weightings of optimal low induction. *Image from Kelley (2017)*

This concept is initially attributed to Prandtl (1933) in the analysis of the optimal circulation distribution of an aircraft wing, which is elliptical for a maximum lift/drag ratio for a constrained wingspan, and a bell-shaped curve for a maximum lift/drag ratio for a constrained root bending moment (Prandtl 1933). This same concept has been applied to wind turbine blade design to maximize AEP. For a constrained root bending moment and a constant low-induction value across the blade, the optimum axial induction is 0.20 (Chaviaropolous 2013). This optimal solution was generalized and allowed to vary across the blade length, as shown in Kelley (2017). The set of optimal, low inductions across a blade for various weightings of highest power coefficient versus highest AEP is shown in Figure 13.

The benefit of low-induction rotors is the ability to produce more power (through increased swept area) for a given constraint on root bending moment so that the loads on the rest of the system are reduced (potentially resulting in lower drivetrain and tower costs). This in turn may allow for a lower cost of energy for low-induction turbines compared to power-optimized designs for a given power rating. In addition, the larger rotor relative to the power rating will drive down the specific power, which is a key metric of the overall BAR project. At the same time, however, the turbine is no longer optimized for maximum aerodynamic efficiency and thus will produce less power, resulting in a relative loss of energy production compared to a power-coefficient-optimized machine. The lower power coefficient will also shift the power curve toward higher wind speeds, potentially reducing the CF of the machine, compared to a power-coefficient-optimized machine.

2.8 Blade Configuration: Wake-Optimized Rotor

Larger rotors require more land for the same interturbine diameter spacing to prevent wake array losses in a wind farm and damaging fatigue loads due to wake turbulence. To prevent the increased costs associated with more land and higher balance of system (BOS) costs, one technology concept that tries to eliminate this problem is the wake-optimized rotor. The concept is to design a blade set for a rotor that produces a more unstable wake that mixes faster and recovers momentum sooner downstream. The mechanism for the wake-optimized rotor is to adjust the aerodynamic design of the blade to increase induction inboard and decrease induction outboard (preserving the overall thrust coefficient of the turbine). This results in a less stable wake that recovers faster and thus would reduce wake losses on a downstream turbine for a given interturbine spacing.

This idea was investigated with Sandia's free wake vortex lattice code CACTUS and showed that a rotor with the same thrust coefficient but different loading distribution had faster wake recovery (Kelley 2015). The momentum recovered to 90% of freestream 5.1 rotor diameters sooner. It remains an open question as to what blade load distribution is optimal.

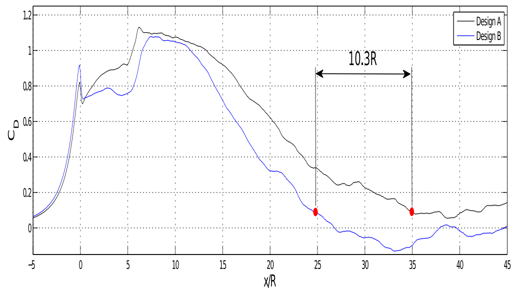

Figure 14. Two rotors with the same thrust coefficient (Design A is Cp optimized, Design B is adjusted for faster wake recovery) but different wake recovery rates, modeled in Sandia's CACTUS vortex code. ***Image from Kelley (2015)***

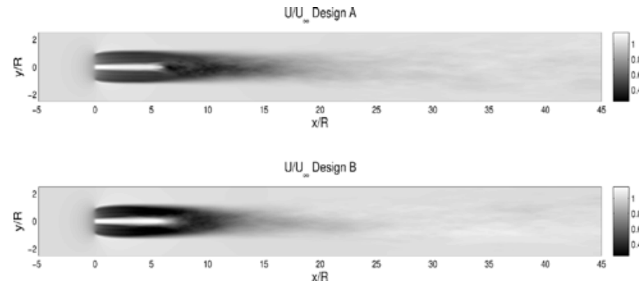

Figure 15. Time-averaged axial velocity contours for the two different designs. ***Image from Kelley (2015)***

As mentioned, the benefits of a wake-optimized turbine are that turbines may potentially be placed closer together in a wind power plant and still achieve the same (or better) AEP. This would decrease cost of energy through decreased BOS costs, such as the electrical infrastructure, roads, and land lease costs. In a land-constrained site, the closer turbine spacing would allow larger rotors where wake losses would otherwise limit their application. It may be possible to show that the induction distribution for an unstable wake also has the benefits associated with a low-induction rotor.

Challenges associated with this concept are potentially increasing the turbulence in the wake, which could lead to higher fatigue loads on downstream turbines. In addition, the wake-optimized turbine has the same thrust as a conventional turbine but a lower power coefficient and thus produces less power than a conventionally designed machine, creating a trade-off in the power produced from upstream and downstream turbines. An overall system optimization approach is needed to assess if the gains in energy production from reduced wake losses offset the energy production losses from less aerodynamically efficient machine design.

2.9 Blade Design Features: Multielement Airfoils

Thick inboard sections of wind turbine blades have undesirable aerodynamic characteristics and are prone to flow separation, causing high fatigue loading. As wind turbine blades become larger, the structural inboard section becomes thicker, thereby further reducing the aerodynamic efficiency of that section. Multielement airfoils allow designers to achieve the required structural performance by optimizing the placement of the spar caps without increasing the overall thickness of the airfoil. This approach possibly also reduces the overall weight of the blade and has positive loading impacts on the rest of the wind turbine system.

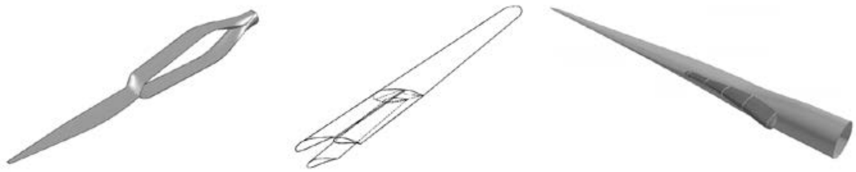

Figure 16. Visual depiction of multielement airfoil concepts. ***Image from Roth-Johnson (2014)***

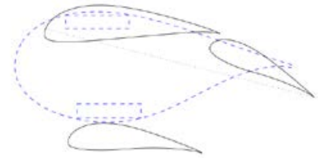

Figure 17. Two-dimensional depiction of a multielement airfoil concept. ***Image from Ragheb and Selig (2011)***

Improved efficiency of the inboard section would also enable cut-in and rated wind speed lower than in traditional designs. This would have the effect of increasing the AEP and CF for the turbine.

As wind turbine blades get longer, it becomes more difficult to transport them over land. Many different approaches have been proposed to address this issue, but one of the most promising is modular blades that can be shipped in smaller sections and then assembled on-site. Multielement airfoil designs lend themselves very well to this modular design approach because the transition from multielement sections to one airfoil in the outboard section can be optimized to alleviate the logistical transportation concerns associated with blade length. Having multielement airfoils inboard also offers the advantage of reducing maximum chord and large root diameters, which are chief concerns regarding transportation constraints (Ragheb and Selig 2011).

However, several disadvantages are present with this concept. First, multielement airfoils increase the overall complexity of the blade design and may present challenges in manufacturing for complex geometry and compound structures associated with struts, flaps, slats, and segments. The overall design of a blade with multielement airfoils is more complex. Finally, the complexity of the design has unknown reliability impacts on the blade.

2.10 Blade Design Features: Segmented Blades

The concept of segmenting a blade into smaller pieces to save on transportation costs has been around for several decades (Peeter et al. 2017). As land-based wind turbine blades have grown from a few to over 60 m in length, logistic suppliers have historically been able to offer transportation solutions that have outweighed the costs associated with segmentation. As the demand for larger and larger rotor diameters continues to grow, in the very near future, blade lengths could reach a point where transportation costs will rise significantly, making segmentation, on-site manufacturing, or alternative transportation methods, such as lighter-than-air transport, economically viable options.

Figure 18. Blade segmented. ***Image from CompositesWorld (2018)***

Figure 19. Blade segmented. ***Image from CompositesWorld (2016)***

Historically, the two most common approaches to blade segmentation have been to split the blade spanwise. It would, however, be conceivable to also split the blade in the chordwise direction if maximum chord is a limiting transportation constraint. The joint could be made with either mechanics (i.e., bolted connection) or adhesive.

Each method clearly has its challenges. Mechanical joints add mass, fastening hardware, structural hot spots, changes in stiffness, labor, tooling, on-site assembly, and reliability issues, which all translate into increased costs. Adhesive joints have minimal mass penalty but add a substantial risk when considering surface preparation, bond-line control, and environment control during field assembly. Advances in thermoplastic resins have enabled welding as a more recent segmentation option, which is showing promise. The benefits of thermo-welding include a fusion process that avoids the added mass of adhesives and fasteners as well as potentially lower on-site assembly process risks. However, unlike thermoset resins, which are well known and qualified, new thermoplastic resin systems with a viscosity that can be used with an infusion process as well as the required thermo-welding process are relatively new and require further qualification, especially in fatigue.

Regardless of the concept, the presence of a joint in the blade will increase the capital costs and may also increase the maintenance costs compared to an unsegmented blade. The added mass of the joint may also increase the loads for the blade and potentially impact the design of the rest of the system (from the pitch bearings to the drivetrain and tower). In addition, the requirement of on-site assembly of the blade would be an additional cost to the BOS. These overall costs must be compared to the cost increase of transportation for the unsegmented blade. Overall, segmentation concepts that minimize cost and risk while maximizing reliability could become competitive options when blade transportation costs escalate due to infrastructure constraints.

2.11 Blade Design Features: Inflatable Blades

One method to enable larger blades and circumvent transportation limits could be the use of unconventional blade topologies such as inflatable blades. Similar to segmented or multielement airfoil blades, these blade designs may be transported at very low-cost relative to conventional blade designs and could have additional benefits (e.g., reduced blade weight).

Inflatable blades can take many forms and geometries and could be constructed with many different materials. The common theme for inflatable blades is a blade skin made of a flexible material that is given its aerodynamic shape from either air or a rigid material such as foam. In many of the conceptual designs, the structure is no longer necessarily coupled with the aerodynamic shape of the blade as it is with conventional blade design. This enables a simpler structural design with reduced material usage and cost, while maintaining a desired aerodynamic performance. In one concept proposed by workshop participants, the structural portion of the blade would be a simple cylindrical tube shipped as one piece or in sections to the site. The aerodynamic shape would then be assembled on-site using a foam filler or multicompartment air-filled cavities. Inflatable blade concepts also have the potential to be designed with multielement airfoils or other distributed aerodynamic controls perhaps more readily than conventional blade designs. Depending on the design, inflatable blades could be designed for periodic replacement and maintenance at a much lower cost than the replacement of a conventional blade design. Some of the challenges with this design approach include a possibly reduced torsional stiffness of the blade, buckling performance, overall reliability, and aerodynamic performance. Generally, there has not been significant research or technology development effort around this concept to date. A large amount of uncertainty and risk associated with both the benefits and potential challenges of the concept is therefore present.

2.12 Blade Design Features: Variably Coned Rotor

As mentioned with previous concepts, the weight of wind turbine blades is largely driven by stiffness requirements, ensuring that the blades do not hit the tower on upwind machines. This leads to significant blade root bending moments that must be resisted by the blade structure. By removing this stiffness constraint, most often by allowing the blades to operate downwind of the tower, significant blade mass reductions are possible, as high as 25% in some studies (Loth et al. 2017). If the rotor is also allowed to hinge, additional cost and weight reductions are possible by lowering the blade root bending moment. Materials needed for additional stiffness and strength may be removed.

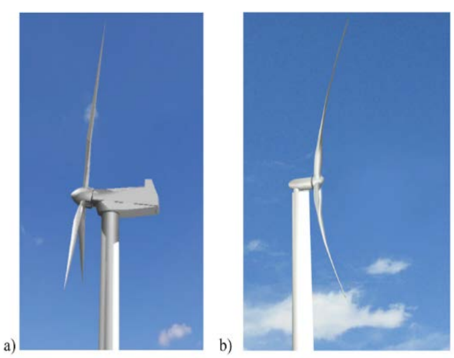

Figure 20. Comparison of traditional versus downwind coned design. ***Image from Loth et al. (2017)***

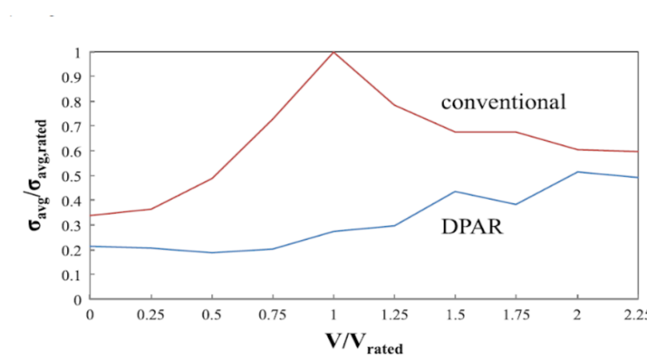

Figure 21. Comparison of blade root stresses for conventional versus downwind coned design. ***Image from Loth et al. (2017)***

This downwind hinged system requires a complicated blade hinge mechanism that will either be actively or passively controlled. The hinged blades can act as a control on normal unsteady thrust loads in a similar manner to teetered rotors or those with individual pitch control. In a downwind configuration, variable coning also allows for more of a passive control of the yaw direction because the rotor would be able to track the wind direction much in the same way as a wind vane. Lighter blades on the tower top may also enable further system benefits from reduced tower top mass and loads to the drivetrain and tower.

Because traditional blades have been optimized for upwind configurations without a significant amount of coning, new aerodynamic understanding (Crawford 2007) and blade design optimization may introduce further cost savings in the system. It is not well understood how well greater coning can be modeled with current engineering design approaches. The major disadvantage of this concept is the added cost, complexity, and weight of the hinge. The reliability of the hinge and associated actuators and bearings present a risk to the design concept.

2.13 Blade Design Features: Variable Diameter Rotor

One potential solution for circumventing the limitations of transport and logistics while allowing for larger-rotor turbines is through a variable diameter rotor. Variable diameter rotors have been investigated in the past because of their potential to increase power capture at lower wind speeds and decrease loading at higher wind speeds (Dawson 2005; Dawson and Wallace 2005; Jamieson et al. 2005). By increasing the size of the rotor (through actively controlled tip extensions), the wind turbine can capture more energy at lower wind speeds. The wind turbine can retract the extensions at higher wind speeds so that the rated power production stays the same or is even increased if the contraction is smaller than the baseline design. This allows for greater overall energy capture compared to a given fixed diameter baseline system that will reduce the overall system LCOE.

In addition, by contracting the rotor size at higher wind speeds, the system may experience reduced fatigue loads for improved reliability of the major load-bearing components for lower operations and maintenance (O&M) costs and even potentially longer turbine lifetime. It may also be possible to control the shape of the blade (e.g., sweep, bend, tip shapes).

There have been past attempts to demonstrate the technology. In 2002, Energy Unlimited combined portions of blade design from two separate blades and demonstrated the ability to dynamically control the rotor diameter in a test over a period of 34 months (Dawson 2005). They subsequently received a DOE grant, executed a second test in 2004–2005, and filed a patent for the technology (Dawson and Wallace 2005). Independently, a consortium led by GE filed a patent on a similar variable rotor diameter technology that was also awarded in 2005 (Jamieson et al. 2005). However, past attempts for moving the technology toward commercialization were not successful. Part of the lack of success was attributed to the lack of availability of control systems (sensing technology and controller design) that ensure robust operation of the system. Advances in technologies relating to sensing and control since the initial concept development may enable feasibility of variable diameter rotors.

Another consideration for the technology moving from a turbine to a plant perspective is that the reduced size of the rotor at higher wind speeds may be favorable from a wake generation and losses perspective. Through contracting the rotor at higher speeds, there is a smaller rotor area and wake that might be more easily steered away from downstream turbines. The combination of sizing may enable novel wind plant controls that take advantage of the ability to dynamically size turbines in a farm for maximum energy production and minimal losses.

The key challenge of the variable-diameter rotor is the added complexity, control, and reliability issues associated with the blade-extension device. Any additional active control device in the system suffers challenges related to wear and maintenance requirements on the control actuators and any bearings that can be a significant problem, especially as component sizes reach extreme scales. In addition, the overall packaging of the blade-extension device inside of the inboard blade section may pose challenges in manufacturing, and accrue additional costs in the design and material usage.

2.14 Blade Design Features: Winglets

Winglets are devices attached to the end of a wing or blade that improve performance by reducing the lift-induced drag from tip vortices (Figure 23). There is, however, a resulting increase in profile drag. Thus, the winglet must be designed such that the reduction in lift-induced drag is larger than the increase in profile drag (Johansen and Sørensen 2006).

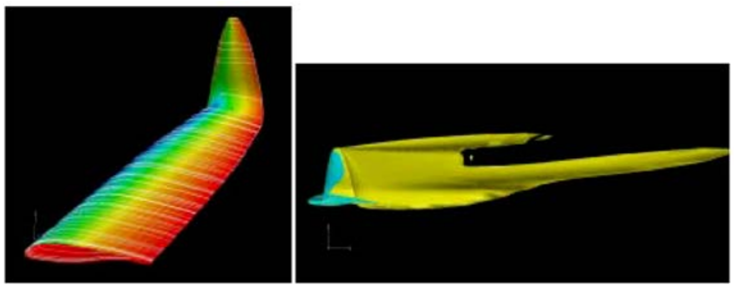

Figure 22. Computational fluid dynamics model of flow over and vorticity behind a wind blade winglet. ***Image from Gaunaa and Johansen (2007)***

For airplane wings, winglets optimally extend in the direction of the suction side, thus producing an inward force. In the case of wind blades, while slightly less optimal in terms of performance, it is preferred to extend winglets from the pressure side of wind blades to maintain tip-tower clearance (Figure 24). This results in the winglet producing a radially outward force. Winglets and blade-tip extensions both result in performance increases. However, winglets have been shown to increase energy capture with a smaller increase in blade bending moment and less tip-tower clearance impacts, which may allow for lower weight growth, depending on the driving design loads (Zahle et al. 2018). Overall performance gains of 2% have been predicted (Gaunaa and Johansen 2007). Recent studies have examined aerostructural-optimized winglet shapes and dimensions. Potential future research opportunities remain including: more complex winglet shapes; the effect of winglets in all design conditions; the potential for noise reduction; and integration with lightning protection systems.

Figure 23. Winglet on Enercon e-101 turbine. ***Image from Marc-André Aßbrock***[2]

[2] https://commons.wikimedia.org/wiki/File:E-101,_Saerbeck_2.jpg

Winglets present a manufacturing challenge given current methods commonly in use and may require the use of a joint. There may also be negative impacts on transportation, especially for blades with large precurve. Finally, a trend toward lightly loaded blade tips runs counter to the adoption of winglets, which effectively increase loading.

2.15 Blade Design Features: Distributed Aerodynamic Controls

Loads on modern wind blades are controlled through both rotational speed and blade pitch. Speed is controlled through torque demand from the generator in low to moderate wind conditions and is relatively slow compared to pitch control, which is employed in higher winds. Additionally, very slow-acting yaw control is used to maintain alignment with wind direction. As blades grow in length and weight, there are increased root moment loads and increased demand on pitch systems, resulting in lower pitch rates. Control of extreme loads on the blade, tower, and drivetrain is dependent on sensing of loads and the combined actuation of these control systems. The ability to adapt to extreme loading conditions typically drives the weight of turbine components. Distributed aerodynamic controls, or controls placed on the blades themselves, have the potential to offer much faster response to extreme loads, reducing the resulting mass increase in longer blades (Barlas et al. 2016). Ultimate load reductions of 20% have been shown through analysis. Active controls have also been shown to reduce fatigue loads. Various actuators have been proposed and studied, including tabs, ailerons, morphing trailing edges, jets, and plasma actuators (Berg, Johnson, and van Dam 2008). All the methods allow for control of lift in the local region of the controller, either through modifying flow attachment (Figure 25) or effective camber.

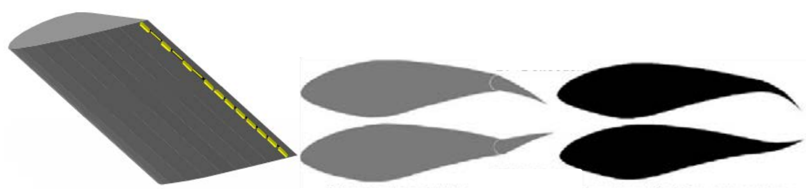

Figure 24. Microtabs, flaps, and morphing trailing edges. ***Image from Berg, Johnson, and van Dam (2008)***

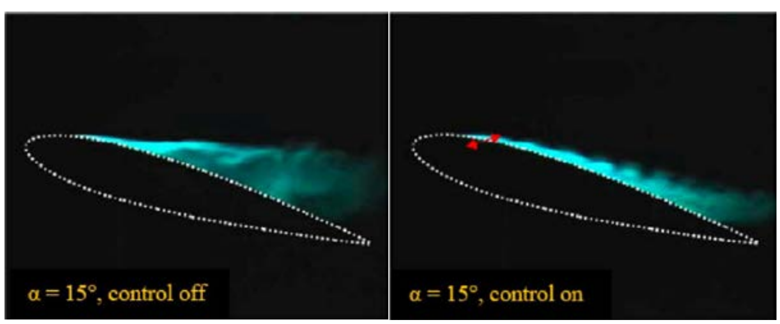

Figure 25. Effect of flow attachment from use of a synthetic jet. ***Image from Berg, Johnson, and van Dam (2008)***

There are several challenges associated with implementing active controls into wind blades. The reliability of the devices has not been proven in wind blades, although flaps or ailerons are widespread in aviation. Concerns about actuator reliability is associated both with maintaining the device itself and the impact of device failure on the ability of the turbine to survive extreme loads. To address the latter, the turbine may be able to operate in an alternative safe mode. Additionally, integration into the manufacturing process may be difficult depending on how large the device is and how much of the chord and any associated mechanisms it would occupy. Sensing for these devices has not been demonstrated and optimized. Several methods have been proposed, including aerodynamic, strain, and acceleration sensors, while tip displacement was identified (Berg, Johnson, and van Dam 2008) as the ideal input into a controller-actuator system. Finally, the ability of the device to maintain control authority under unsteady aerodynamic loading could be problematic.

2.16 Hub Configuration: Large Hub Radius

The inner portion of a rotor does not substantially contribute to energy capture but adds to blade design constraints. As blades continue to grow in length to benefit from the larger swept area, one solution is to remove the inner portion where the same length of blade sweeps a much smaller area than at the tip. To accomplish this, there can be segmented blades with or without partial pitch designs, or there can simply be a large hub radius where the inner portion is fixed.

The inner rotor section often results in overall drag losses for the rotor due to manufacturing limitations on aerodynamic twist, so an additional option to having a large hub radius would be to force the air that would travel through this inner section outboard on the rotor where it can contribute more substantially to machine torque. This mechanism is not required for large hub radius designs but would be complementary by reducing the aerodynamic losses in this region.

These concepts have been explored by turbine original equipment manufacturers in the past, including the partial-pitch Envision EN128/3.6 wind turbine and the GE ecoROTR designs.

Figure 26. Envision's partial pitch blade of the EN128/3.6 turbine. *Image from WindPower Offshore (2014)*

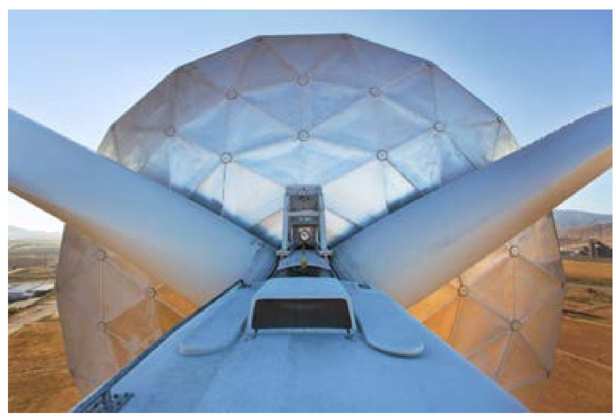

Figure 27. GE's ecoROTR. *Image from Lord (2015)*

The main benefit of this technology is that it reduces the effective blade length (because the aerodynamically active portion of the blade is shorter and bolted to the hub at a significant distance outboard of the hub center) while maintaining rotor diameter, which eases transportation constraints. It can also be used to increase rotor swept area for the same blade length in a repowering application. Additionally, pitch systems that are only active for the blade (at the hub-blade interface) would carry a lower pitching moment for the same rotor diameter, which would improve the responsiveness of these systems and likely reduce their costs. The hub and the blade portion could have lower maximum chord, which would reduce the costs of transportation for very large rotor-diameter wind turbines. With the addition of the aerodynamic nose cone, the overall energy production of the machine for a given rotor diameter would be increased.

Challenges include increased drag on the rotor for the longer hub section that provides purely structural support and increased rotor thrust for the large nose cone that could increase demands on the tower. In addition, the placement of the pitch system outboard would add complexity, which could increase O&M costs and introduce reliability issues.

2.17 Additional Concepts

The BAR concepts identified and articulated above are by no means an exhaustive set of concepts that might be considered. At the workshop, several other ideas were presented for inclusion, but there was not strong enough support for the concepts or they were deemed to already be handled (at least to some degree) by the preceding list of concepts. Concepts that were deemed to already be included with the preceding concepts were:

- Midspan or outboard pitch blades: Moving the pitch system outboard would reduce loads on the pitch system. These systems are a reliability issue for current turbines and will presumably have additional reliability issues with the next generation of longer blades. Moving the pitch and bearing systems outboard would require moving non-structural mass outboard as well. This concept is treated, to some degree, in the large hub radius concept.
- Counter-rotating dual rotors: This concept is an extension of the dual-rotor concept where the two rotors are rotating in opposing directions to mitigate the interference of flow between the two rotors and realize improved wake-mixing properties. This concept was seen as already being a part of the dual-rotor concept.
- Highly instrumented and controllable blades: This concept is an extension of the distributed aerodynamic controls concept. However, there are some unique features that should be considered when looking into other concepts that use control features on the blade—namely, the need for additional sensors and actuators.

Other concepts that were introduced but did not have enough support to be included for more detailed evaluation included:

- Passive load control techniques (through structural design, materials, or aerostructurally coupled design): This concept was considered to already be part of current technology configurations because there are commercial wind turbine blades that actively employ one or more of these technologies.
- Frangible blades: This is a concept for the introduction of a mechanical fuse in the blade or rotor system that would “trip” in the presence of excess loads, thereby protecting the rest of the turbine system from damage. The fuse could then either be reset, repaired, or replaced, depending on the design.
- Seasonally dependent blade designs: Operating conditions can vary significantly depending on the season. The wind speed, prominent wind direction, frequency of different stability conditions, and turbulence intensity change from month to month. Like snow tires for automobiles, this concept argued for modifications to the blade (from full blade replacement to sub-component retrofits to controls adaptations) that would adapt to the season for reducing loads and increasing reliability.

All these additional concepts have their own associated potential benefits, challenges, and risks. To ensure reasonable scope for the project, these additional concepts are excluded from the subsequent detailed evaluation and analysis.

3 BAR Evaluation Workshop

The national laboratory team held a workshop in Lubbock, Texas, on August 30, 2018, to evaluate the performance impacts and science and engineering challenges associated with the BAR concepts. In all, 65 wind energy experts from the national laboratories, DOE, academia, and the wind industry reviewed and evaluated concepts at the workshop. There was also a brainstorming session where concepts not in the catalog were considered for evaluation. The inflatable blade and two-bladed concepts were introduced during the brainstorming session.

Participants were split into seven breakout groups. Each group evaluated the potential benefits and challenges of about eight concepts. Not all groups evaluated the same concepts, but at least three groups evaluated each of the concepts in order to reduce the uncertainty in the results. Numerical scores were assigned to each metric category, comments on the relative strengths and weaknesses were collected, and the data were aggregated by the national laboratory team. A similar exercise was conducted internally by experts at NREL and Sandia.

3.1 Evaluation Approach

During the workshop, participants were asked to first evaluate the BAR concepts according to their potential to impact various metrics associated with system cost and performance. Then, for the same concepts, the participants were asked to consider the science and engineering challenges that might limit the ability to realize the BAR concepts.

Through this evaluation process, the goal was to produce a qualitative understanding of the research and development (R&D) pathways to the realization of the various technologies and the expected impact to system performance and costs if the concepts were successfully commercialized.

Participants were first asked to assess the potential of different BAR concepts to influence key wind plant (not just turbine) performance and cost metrics. The classic metric for evaluating an innovation from a full wind power plant perspective is in terms of the LCOE, which aggregates CapEx (that include both turbine capital costs [TCC] and BOS costs) and OpEx (that include O&M costs, financing [F] terms, and AEP) into a single equation.

$$LCOE = \frac{F * CAPEX + OPEX}{AEP}$$

While still critical to the competitiveness of wind energy compared to other electricity generation technologies, there is increasing emphasis on metrics of system performance other than LCOE. As the share of wind energy in the overall electricity generation portfolio in many regions grows, there is growing interest in the *value* that wind energy has to the overall electricity system in terms of:

- Energy value: the correlation of wind energy production with energy demand as well as its predictability and dispatchability to apply downward pressure on time-varying electricity prices
- Capacity value: the correlation of wind energy production with demand profiles over the course of the year so that there is less need to back up wind energy with alternative electricity generation sources
- Ancillary services value: the ability to support grid reliability and stability at various timescales.

Although different systems have different needs for wind energy depending on the generation mix of a specific electric grid system, in an increasing renewable-energy-dominated electricity system there will be increasing pressure on wind power plants to not only provide competitive LCOE but also increasing value in the above categories to the electric grid. However, for the purposes of BAR concept development, critical evaluation of these system value metrics is very difficult such that the value to the system was simplified to the potential of the concepts to increase CF, which would in turn support all the above system value metrics.

Beyond LCOE and system value, additional metrics that could be considered are the ability of the concept to minimize negative societal and environmental impacts as well as maximize workforce and economic development. These were not directly included in the evaluation process but may be part of the BAR concept evaluation later in the project.

The final metrics for evaluation of the technologies are provided in Table 2.

Table 2. Cost and Performance Metrics for BAR Concept Evaluation

Levelized Cost of Energy					Economic Value
Turbine Capital Costs	Turbine Spacing	Foundations/ Transportation/Erection	Annual Energy Production	Operational Expenditures	Capacity Factor

Having considered all the concepts in terms of their potential impact to the above metrics, participants were then asked to consider the science and engineering challenges that would limit the ability to realize a given BAR concept and thus would need R&D support. First, participants were asked to consider fundamental science research challenges associated with the concepts (i.e., gaps in understanding in wind energy physics that would impact the concept). Participants were specifically asked to consider (1) What is new/novel about the concept that may challenge the current state-of-the-art in understanding wind turbine and plant physics? and (2) What about the operating environment of these machines is not well understood? Table 3 provides the categories of fundamental science that were considered for each BAR concept.

Table 3. Science Challenges

Science Challenges				
Turbine and Plant Physics				Atmospheric Physics
Blade Aerodynamics	Wake Generation/Growth/ Interaction/Recovery	Aeroelasticity	Noise	Atmosphere (Normal/ Extreme Operation)

For each subcategory, reviewers were asked to evaluate whether the state-of-the-art physical models were appropriate to analyze the new concept. For blade aerodynamics, the capability of the state-of-the-art model to characterize unsteady aerodynamics for the new concept was assessed. For wakes, the capability of the state-of-the-art model to characterize wake merging or reenergization was assessed. For aeroelasticity, the capability of the state-of-the-art model to characterize things like flutter was assessed. For noise, the capability of the state-of-the-art model to characterize noise generation was assessed. For atmosphere, the capability of the state-of-the-art model to characterize inflow conditions at heights above 200 m was assessed.

While Table 3 focuses on gaps in understanding, it is necessary to characterize the engineering challenges associated with the various BAR concepts. Participants were asked to consider how BAR concept technology development would face various engineering challenges that may require R&D investment to overcome. Table 4 summarizes these categories.

Table 4. Engineering Challenges

Engineering Challenges							
Blade Design			Controls	Manufacturing	Logistics	Reliability	System Impacts
Materials	Aerodynamics	Structures	Controls/ Sensors	Integration/ Manufacturing	Transport/ Logistics/ Installation	Reliability	Rest of System Design

Again, in Table 4, many subcategories were considered. For each subcategory, reviewers were asked to evaluate whether the new concept presented any technology development challenges. For blade materials, reviewers considered the ability to make the necessary materials needed for the concept. Reviewers considered the ability to design airfoils and structures needed for the concept. Reviewers considered the ability to design unique controller and sensor requirements needed for the concept. They also considered any challenges with integration of the technology and/or manufacturing of the concept. Transportation logistics and installation were considered for each concept, understanding that there are physical size limits to transportation. Many of the novel concepts may impact reliability either positively or negatively. Reviewers also considered impacts to the rest of the system (e.g., tower, foundation, yaw system).

4 Results of the Performance Metrics Evaluation

Each concept was evaluated against the performance metrics described in Section 3.1. The following sections provide a summary table for each concept and a summary of the comments collected from the reviewers during the workshop. Each of the concepts is given a stop sign indication, either positive (green), neutral (yellow), or negative (red).

4.1 Rotor Topology: Two Bladed

Table 5 summarizes the impact to the various LCOE elements as determined by the workshop participants for the two-bladed concept.

Table 5. Evaluation of LCOE Impacts for Two-Bladed Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
●	●	●	●	●	●

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: Participants acknowledged that two-bladed rotors would lead to savings in rotor mass and rotor cost. Such savings have been shown in the Segmented Ultralight Morphing Rotor project (Ichter et al. 2012). However, a trade-off would need to be found in terms of rotor solidity and corresponding rotor speed. If combined with higher rotational speeds, a two-bladed rotor could help reduce drivetrain and generator costs but increase aeroacoustic noise. Alternatively, rotor solidity could be preserved by enlarging the blade chord. In this case, blades would benefit in terms of structural efficiency, but transport would be negatively affected. The overall score is neutral.
- Turbine spacing: Two-bladed rotors are not expected to help reduce turbine spacing compared to an equivalent three-bladed configuration. Wakes of two-bladed rotors may even feature less turbulent structures and cause higher wake losses.
- Foundation and construction costs: Compared to three-bladed configurations, two-bladed rotors may simplify and speed up the erection process thanks to the lower rotor mass. Nonetheless, the costs are not expected to decrease significantly because these are typically driven by the nacelle mass. Assuming higher chords, transport costs may instead increase. The overall expectation is neutral.
- Annual energy production: The survey returns the expectation of slightly lower AEP due to slightly lower efficiencies, possibly increased downtime because of noise-related constraints, and possibly higher wake losses in a farm.

- Operation and maintenance costs: Two-bladed rotors have historically been proven worse in terms of reliability compared to three-bladed designs. Although one blade less means one less pitch system, gyroscopic loads in yaw, higher torsional moments in pitch, and rotor imbalances may result in larger wear on the actuation system. The final score is neutral.
- Capacity factor: Overall, this concept has a neutral impact on CF.

Overall, the technology of two-bladed rotors is seen to have no large potential for cost reductions. In addition, the technology readiness level (TRL) is estimated to be quite high. This is not considered promising and probably not worth dedicating further research efforts.

4.2 Rotor Topology: Dual Rotor

Table 6 summarizes the impact to the various LCOE elements as determined by the workshop participants for the dual-rotor concept.

Table 6. Evaluation of LCOE Impacts for Dual Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
🔴	🟡	🟡	🟢	🔴	🟢

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: TCC is expected to suffer a very large increase because of the more sophisticated and complex drivetrain system. In addition, the system may be subjected to a more complex set of frequencies, possibly impacting the dynamics of the whole turbine. The only benefit of dual-rotor configurations is found in the possibility to adopt thicker sections inboard in the larger rotor.
- Turbine spacing: Dual rotors would increase energy extraction and possibly cause a detrimental effect on the required spacing of the turbines. On the opposite, wakes could experience higher mixing and a faster dissipation. The overall score is neutral.
- Foundation and installation costs: No consensus was found among participants. Differences compared to standard configurations could come from a more complex assembly and erection process. At the same time, blades could be characterized by smaller chords, and this could simplify transport. A neutral final score was obtained.
- Annual energy production: The dual rotor has the potential to increase AEP. Nonetheless, savings could be fairly limited, namely a few percent, and possibly lower at the plant level.
- Operations and maintenance costs: Severe concerns were expressed during the survey about the reliability of such a system due to the increased number of parts and increased fatigue.

- Capacity factor: Several comments were made about the increase swept rotor area, likely leading to improvements to the CF.

Overall, the technology is received negatively. The largest challenge is found in the increased complexity of the drivetrain. This would lead to higher capital costs and likely higher O&M costs. AEP improvements do not seem to justify the increase in complexity to the system.

4.3 Rotor Topology: Multirotor

Table 7 summarizes the impact to the various LCOE elements as determined by the workshop participants for the multirotor concept.

Table 7. Evaluation of LCOE Impacts for Multirotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
🟡	🟢	🟢	🟡	🔴	🟡

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: When comparing a traditional single-rotor configuration with the multirotor, it appears that it is harder to build the same swept area due to many more parts. On one side, the technology may offer lower blade mass per swept area but higher tower mass due to the increased support structure. The multiple drivetrain systems would also be smaller, but more electronics and more cabling would be needed. Consumables for blade manufacturing would also be increasing. Transport would therefore benefit greatly, but it is only a one-time cost, and four 1-MW rotors may be more expensive than one 4-MW rotor. Overall, more sophisticated design analysis is needed to quantify any benefit, and a neutral overall score is so far returned.
- Turbine spacing: Research is likely needed to model the wakes of a multirotor, and the participants of the survey did not fully agree on this topic. Nonetheless, the majority of the comments stated that there might be a possibility for a reduction in the spacing thanks to increased wake mixing and better wake steering.
- Foundation and installation costs: Benefits are expected in this area. Easier transportation is for instance a source of cost savings as well as smaller cranes. Foundations are expected to be similar to normal wind turbines because of the similar thrust. The part count will still reduce the possible savings.
- Annual energy production: No agreement among participants. When comparing technologies at equal power, there might be a slight increase in availability thanks to system redundancy. At the same time, downtime might increase during service because all rotors would need to be shut

down. At the plant level, the wake steering opportunities and better wake properties may help increase AEP. Research is needed to quantify these benefits, and a neutral overall score is returned.

- Operation and maintenance costs: These costs are expected to increase following the higher number of parts. At the same time, advanced controls could help in handling veer and shear, while cheaper cranes could reduce down times. An expected slight increase in costs is foreseen.
- Capacity factor: The potential for a larger total swept area is there with this concept because transportation logistics do not limit the size of the blade as much as conventional blades.

Overall, the technology is found to be controversial. On one side, it is expected to be characterized by a higher complexity of the tower structure and power electronics compared to an equivalent standard configuration. At the same time, transportation logistics would be alleviated, and BOS costs could be somewhat less than standard. The machine may also be able to operate when one rotor is down, therefore increasing the CF. Research is instead needed to characterize the wake behavior.

4.4 Orientation: Downwind

Table 8 summarizes the impact to the various LCOE elements as determined by the workshop participants for the downwind concept.

Table 8. Evaluation of LCOE Impacts for Downwind Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
🟡	🟢	🟡	🟢	🟡	🟢

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: Downwind rotors free design space for lighter blades. This mass savings may result in savings in the rotor and system costs. Examples include possibly cheaper bearings and drivetrain system. Towers may instead become slightly more expensive as a result of possibly increased fatigue damage. The overall effect is nonetheless expected to be neutral.
- Turbine spacing: There are no major changes compared to an equivalent upwind configuration. However, downwind rotors may enable wake redirection through rotor tilting.
- Foundation and installation costs: Similar loads would most likely result in comparable costs in this area.
- Annual energy production: Effects such as nacelle blockage effect, wake control, and inclined flow in presence of ridges would positively impact AEP.
- Operation and maintenance costs: The costs are similar.

- Capacity factor: The downwind configuration may enable blades that are lighter weight, and therefore, a larger swept area is more feasible.

Overall, the technology is evaluated positively by the workshop participants, and it is worth further research explorations. A downwind configuration may offer a platform advantageous in many aspects. The relaxed tip-tower clearance constraints and the possibly beneficial nacelle blockage effect may push LCOE down.

4.5 Blade Configuration: Slender, High TSR Blades

Table 9 summarizes the impact to the various LCOE elements as determined by the workshop participants for the slender, high TSR blade concept.

Table 9. Evaluation of LCOE Impacts for Slender, High TSR Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
					

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: Participants agreed that drivetrain costs are reduced for turbines with higher rotational speeds. On the opposite, blades with lower solidity tend to have higher mass and cost.
- Turbine spacing: A high TSR rotor meets rated speed quicker. This likely increases noise issues and might impose an increase of turbine spacing in land-based wind plants.
- Foundation and installation costs: A neutral impact is foreseen.
- Annual energy production: Slender blades may be more flexible and cause a small decrease in the overall AEP. However, high TSR rotors are characterized by a higher aerodynamic efficiency thanks to slightly better nominal coefficient of power values and higher Reynolds numbers.
- Operation and maintenance costs: Reviewers identified that slender blades may be more susceptible to flutter. If the relative tip speed is higher, this may lead to both increased soiling and leading-edge erosion.
- Capacity factor: Similar to the downwind configuration, the lighter weight should enable a larger blade with increased swept area.

Overall, the capital costs may be reduced thanks to a cheaper drivetrain system. Blade mass and cost could, however, be negatively impacted. The AEP is expected to increase. The rotor solidity and TSR should, in conclusion, be the topic of any well-posed rotor optimization.

4.6 Blade Configuration: Highly Flexible Blades

Table 10 summarizes the impact to the various LCOE elements as determined by the workshop participants for the highly flexible blade concept.

Table 10. Evaluation of LCOE Impacts for Highly Flexible Blade Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
🟢	🟡	🟡	🟡	🔴	🟡

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: When blades can be made more flexible, cost savings can be generated at both the rotor and system levels. Blades with a degree of bend-twist coupling are also able to shed extreme loads, further reducing mass and costs.
- Turbine spacing: This innovation is unlikely to have a large impact on turbine spacing, and a neutral score is returned.
- Foundation and installation costs: Tower and foundation costs are estimated to be possibly slightly lower thanks to a reduced rotor mass. Workshop participants commented positively about the ability of a flexible blade to be transported on railcars by allowing for controlled blade bending around curves. Nonetheless, advantages are to be proven, and a neutral impact is estimated.
- Annual energy production: The impact to the AEP is expected to be neutral. Care should nonetheless be paid to extreme blade flexibility, which might reduce the rotor swept area and possibly negatively impact AEP.
- Operation and maintenance costs: Reviewers expect that fatigue loads may be higher. High material strains might also increase failure issues. Overall, a negative impact is estimated.
- Capacity factor: As with other configurations, the lighter weight should enable a larger blade with increased swept area.

Overall, the technology is well received and the grade of flexibility of modern blades is higher than in the past. Blade design should aim at further increasing this flexibility without incurring excessive material strains, fatigue damages, and AEP losses.

4.7 Blade Configuration: Low-Induction Rotor

Table 11 summarizes the impact to the various LCOE elements as determined by the workshop participants for the low-induction rotor concept.

Table 11. Evaluation of LCOE Impacts for Low-Induction Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
● (yellow)	● (green)	● (yellow)	● (green)	● (yellow)	● (green)

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: By changing the induction profile of the blade, it would be possible to design a longer blade with no increase to blade root moments for a given turbine rating. However, this reduction in loads is offset by lower blade performance. Additionally, more material is needed when adopting longer blades for the same turbine rating.
- Turbine spacing: Low-induction rotors have shown some of the same benefits as wake-optimized rotors for faster mixing and wake recovery. This effect allows for a relative reduction in turbine spacing.
- Foundation and installation costs: Low-induction rotors have a neutral impact on BOS.
- Annual energy production: The CF of the turbine would increase, and from a wind farm perspective, the AEP may increase slightly.
- Operation and maintenance costs: A neutral impact is foreseen for tip deflections and damage equivalent loads. A larger blade could have reduced tip clearance, but the low induction and reduced rated wind speed keep the thrust load constrained. Additionally, the larger blade will have a reduced solidity, keeping damage equivalent loads constrained.
- Capacity factor: The CF is expected to increase with this concept.

Overall, slightly positive effects are estimated in turbine spacing and AEP, while neutral scores characterize the other three fields.

4.8 Blade Configuration: Wake-Optimized Rotor

Table 12 summarizes the impact to the various LCOE elements as determined by the workshop participants for the wake-optimized rotor concept.

Table 12. Evaluation of LCOE Impacts for Wake-Optimized Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
🟡	🟢	🟡	🟢	🟡	🟡

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: Blades would operate at slightly lower Cp and would need to be slightly longer. Downstream turbines may also experience higher wake energy and may therefore require additional reinforcement. Nonetheless, changes in the overall costs are estimated to be negligible, and a neutral score is recorded.
- Turbine spacing: The turbines would be allowed to be spaced more closely with a wake-optimized rotor. This would lead to positive effects.
- Foundation and installation costs: Blades would be somewhat larger, while land use may decrease. Overall, small changes are expected.
- Annual energy production: AEP may be slightly lower at the turbine level but net positive for the wind plant.
- Operation and maintenance costs: No major changes are estimated.
- Capacity factor: This concept is expected to have the largest positive impacts on the CF of the entire wind plant.

Overall, the technology results in lower AEP at the turbine level and higher AEP at the plant level. The TRL level of this concept is, however, relatively high, and R&D efforts to meet the BAR objectives are expected to be limited.

4.9 Blade Design Features: Multielement Airfoils

Table 13 summarizes the impact to the various LCOE elements as determined by the workshop participants for the multielement airfoil concept.

Table 13. Evaluation of LCOE Impacts for Multielement Airfoil Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
🔴	🟡	🟡	🟢	🔴	🟡

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: This concept has the potential to save mass on the inboard section of the blade by removing material, while simultaneously increasing the aerodynamic efficiency of that section of the blade. Blade manufacturing is, however, likely to be much more complex and costlier. The overall torsional stiffness may suffer, and this would have negative impacts on the blade and possibly system design.
- Turbine spacing: The wake characteristics may be improved due to thinner airfoils and multiple wakes. However, a neutral score is returned.
- Foundation and installation costs: The potential for reducing the maximum chord may lead to a reduction in the transportation costs. The concept may also favor blade segmentation. In this case, on-site assembly costs may be higher. Overall, a neutral score is recorded.
- Annual energy production: Although not much energy is produced by the inner portion of the blade, blades equipped with multielement airfoils would have improved aerodynamic performance compared to standard configurations. Smaller wake losses from the root section could also translate into higher AEP for the wind plant.
- Operation and maintenance costs: Workshop participants reported concerns on the impact of this concept on the reliability of the blade, especially in the presence of a segmented configuration.
- Capacity factor: Overall, the impact on CF is neutral.

Overall, some structural robustness may be lost by going to a bi-wing configuration at root. This concept could help with transportation logistics if it were segmented at the joint. The blades would also be more complex and may reduce reliability issues. At the same time, it may be possible to design lighter structures, which would benefit the overall LCOE of the turbine. The higher blade aerodynamic performance and the possibly improved wake properties could also lead to increased AEP.

4.10 Blade Design Features: Segmented Blades

Table 14 summarizes the impact to the various LCOE elements as determined by the workshop participants for the segmented blade concept.

Table 14. Evaluation of LCOE Impacts for Segmented Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
🔴	🟡	🟢	🟡	🔴	🟡

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: The segments in the blade increase the capital cost of the rotor.
- Turbine spacing: The concept has no effect on turbine spacing.
- Foundation and installation costs: Segmentation has a major contribution to transportation costs, possibly drastically reducing them.
- Annual energy production: No marked effect on AEP is foreseen by workshop participants.
- Operation and maintenance costs: Reliability can be negatively affected by segmentation due to mechanical or adhesive joints.
- Capacity factor: This concept directly enables larger blades, so there is a net positive effect on CF; however, the reviewers of this technology did not consider this to be a major advantage over conventional, unsegmented blades.

Overall, costs go up because of joints. The only benefit from segmented blades is to alleviate transportation constraints, which likely would be extremely severe for very large blades.

4.11 Blade Design Features: Inflatable Blades

Table 15 summarizes the impact to the various LCOE elements as determined by the workshop participants for the inflatable blade concept.

Table 15. Evaluation of LCOE Impacts for Inflatable Blades

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
🟢	🟡	🟢	🟡	🔴	🟢

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: The decoupled aerodynamic and structure design may allow for a design that is less costly. There is also an opportunity to design the pitch system further outboard with this design. This approach allows for a design that could enable aerostructural optimization.
- Turbine spacing: This concept has little impact on turbine spacing.
- Foundation and installation costs: There is a great opportunity to reduce transportation costs and constraints with this concept. This concept lends itself very well to segmentation, and it is likely that the transportation costs associated with this concept will be reduced. There is also an opportunity to reduce the mass of the blade, thereby reducing the loading and material requirements of the entire system. This is likely to bring LCOE down.
- Annual energy production: It may be difficult to maintain the airfoil shape, and this will likely lead to some losses in AEP; however, it may be possible to design thinner airfoils with higher Cp, so it could be a neutral result for AEP.
- Operation and maintenance costs: Depending on the material used for the outer skin, maintenance may need to be performed more regularly than conventional blades. The outer skin may also be more susceptible to icing and soiling.
- Capacity factor: This concept can alleviate issues with transportation logistics by segmenting and on-site assembly, thus enabling larger rotors.

The reviewers found many nice features in the inflatable blade concept. First, the decoupled structural/aero could open space for optimization and result in a blade that is easier to transport and is less expensive than conventional blades. Additionally, it could reduce pitch system, possibly lead to much lighter and longer blades, and alleviate transportation constraints.

4.12 Blade Design Features: Variably Coned Rotor

Table 16 summarizes the impact to the various LCOE elements as determined by the workshop participants for the variably coned rotor concept.

Table 16. Evaluation of LCOE Impacts for Variably Coned Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
●	●	●	●	●	●

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: The capital costs associated with this concept are increased due to the added complexity of the hub system required to achieve a variably coned rotor. Reviewers thought that this configuration may be good to partner with advanced control systems that could control the loads and therefore allow for lighter blades.
- Turbine spacing: This technology has the potential to achieve higher wind plant AEP through the additional degree of freedom and may allow turbines to be spaced more closely. However, reviewers thought that this impact would be relatively small.
- Foundation and installation costs: A neutral impact is estimated. Operational loads could be reduced, but foundation costs may be somewhat increased following higher rotor mass due to the presence of the actuators at blade root.
- Annual energy production: There is likely to be no impact on AEP. For a given rotor diameter, AEP is reduced, but thanks to the load alignments, blades can be made longer.
- Operation and maintenance costs: O&M costs are expected to greatly increase due to the complexity of the system and the higher number of mechanical parts.
- Capacity factor: This concept has a neutral impact on CF.

Overall, workshop participants evaluated this concept very negatively. The technology overall system costs are expected to increase due to more complex mechanisms. Increases overhanging moment, tower, and foundation costs may also increase. O&M costs are likely to increase greatly.

4.13 Blade Design Features: Variable Diameter Rotor

Table 17 summarizes the impact to the various LCOE elements as determined by workshop participants for the variable diameter rotor concept.

Table 17. Evaluation of LCOE Impacts for Variable Diameter Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
🔴	🟡	🟡	🟢	🔴	🟢

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: Participants acknowledged that variable diameter rotors can reduce loads at higher wind speeds and enable design of turbine components with less overall material usage and cost. However, there was a very strong consensus that any reductions in TCCs from the rest of the system would be more than offset by the increased costs of the blades and the extension mechanism itself. There was also significant concern over the packaging of the extension mechanism and the implications for blade manufacturing.
- Turbine spacing: If the ability to reduce the rotor size was used to reduce the impact of wakes on downstream turbines substantially, then turbines could be placed closer together, which would reduce infrastructure costs for roads and the collection system. However, the effects of this were expected to be minor with negligible impacts to overall costs.
- Foundation and installation costs: Transport costs would potentially be lower because the length of the blade would be reduced (although the blade itself with the internal extension mechanism would be heavier). There may be some reductions in foundation costs through reducing loads at high wind speeds, but overall, the impacts to BOS costs for transport, foundations, and construction were found to be negligible.
- Annual energy production: The main benefit to LCOE was expected to come from improved AEP through the ability to reduce wake losses at higher wind speeds for overall improved plant performance.
- Operation and maintenance costs: The extension mechanism was expected to result in significant increases to O&M costs as with most mechanical components in the system.
- Capacity factor: The CF may benefit because this concept enables larger blades.

Overall, the impact of the technology application was projected to increase LCOE, likely substantially. The collective result of significantly increasing TCC and OpEx while only slightly increasing AEP is expected to increase LCOE. While the variable diameter may be a solution to shipping very long blades (through the ability to ship the extension portion of the blade inside of the inboard portion), the LCOE compared to other technology solutions is not favorable.

On the other hand, the additional control mechanism for being able to vary the rotor diameter and control the wakes produced by the turbine were expected to allow a significant increase in the overall wind power plant CF. The additional control mechanism might allow the ability to have more predictive control over the project energy production to improve its performance from a grid integration perspective.

Finally, the TRL for the technology is somewhat low (estimated to be between TRL 3 and TRL 4 by workshop participants), which indicates that there is a lot of opportunity for further development of the technology. Such development could potentially address many of the uncertainties and concerns about the negative cost impacts of the technology in terms of both upfront capital costs of the extension mechanism and blade manufacturing as well as the downstream costs of maintenance of the mechanism over the lifetime of a project.

4.14 Blade Design Features: Winglets

Table 18 summarizes the impact to the various LCOE elements as determined by workshop participants for the winglets concept.

Table 18. Evaluation of LCOE Impacts for Rotors Adopting Winglets

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
🔴	🟡	🟡	🟡	🟡	🟡

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: This concept has a negligible effect on capital costs. The addition of the winglet would make the blade slightly more expensive.
- Turbine spacing: This concept has a negligible effect on turbine spacing.
- Foundation and installation costs: This concept has a negligible effect on foundation and installation costs.
- Annual energy production: This concept is expected to increase AEP slightly due to the longer apparent length of the blade. Nonetheless, benefits are expected to be marginal.
- Operation and maintenance costs: This concept has a negligible effect on O&M.
- Capacity factor: The CF impact of this concept is neutral.

Overall, the technology is rather mature and would have a limited impact on the LCOE of the system. The impact on wakes is quite unknown. Some slight improvements to AEP and CF are likely.

4.15 Blade Design Features: Distributed Aerodynamic Controls

Table 19 summarizes the impact to the various LCOE elements as determined by workshop participants for the distributed aerodynamic controls concept.

Table 19. Evaluation of LCOE Impacts for Rotors Adopting Distributed Aerodynamic Controls

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
●	●	●	●	●	●

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: Aerodynamic control can enable larger rotors at lower costs by controlling the amount of loading on the blade without sacrificing energy production. The comments from the reviewers state that the overall cost of the control system would outweigh any weight reductions enabled by the load-reduction devices.
- Turbine spacing: No substantial changes to turbine spacing are expected.
- Foundation and installation costs: The overall weight of the blade may be reduced because of the active load mitigation devices on the blades. This would result in a net positive effect for drivetrain, tower, and foundation costs. However, this benefit could be somewhat small.
- Annual energy production: The impact on AEP is expected to be positive.
- Operation and maintenance costs: O&M costs are most likely to increase due to the complexity that the actuators and sensors add to the system.
- Capacity factor: This is another enabling technology for longer blades because less loads will allow for blades with less structure. It is likely that blades with these devices will weigh less than conventional blades on a per-megawatt basis.

Overall, this concept adds costs but may enable lighter blades thanks to better load control. There is also some opportunity to manipulate the wake for wind plant applications, which may increase the overall AEP. Reliability remains the largest challenge, while the concept could help enable larger rotors by controlling loads.

4.16 Hub Configuration: Large Hub Radius Rotors

Table 20 summarizes the impact to the various LCOE elements as determined by workshop participants for the large hub radius concept.

Table 20. Evaluation of LCOE Impacts for Large Hub Radius Rotors

Turbine Capital Costs	Turbine Spacing	Foundations / Transportation / Erection	Annual Energy Production	Operational Expenditures	Capacity Factor
●	●	●	●	●	●

Detailed assessment of the impacts to the different LCOE elements included:

- Turbine capital costs: The larger hub or nose cone adds weight to the system. However, it may also provide some cost savings by reducing the pitch system requirements. Overall, the reviewers saw this as a net negative and predicted an increase in the cost of the turbine.
- Turbine spacing: This technology is not expected to have a major impact on turbine spacing.
- Foundation and installation costs: This technology is not expected to have a major impact on the foundation or installation.
- Annual energy production: This technology aims at improving AEP, but workshop participants expected AEP benefits to be very limited.
- Operation and maintenance costs: This technology is not expected to have a major impact on O&M.
- Capacity factor: This concept may slightly improve the CF by enabling larger blades due to reduced root diameter.

Overall, the technology has the possibility to reduce the costs of some components, namely pitch actuators and blade root, at the expense of a more expensive hub structure, larger overhanging moments, and a more expensive tower and foundation. Maximum chord could be potentially reduced, facilitating transport, but this might offset the already limited AEP advantages generated by this concept.

5 Evaluation of Science and Engineering Challenges

This section reports the evaluation of the science and engineering challenges. Science challenges are defined as those that pertain to a fundamental understanding in physical response. Engineering challenges are defined as the need for technology development to overcome a certain challenge. For each concept, a table reports relative ranking that is denoted with a stoplight convention. Green means that a concept has few weaknesses in the given category; yellow means that a concept has a moderate number of weaknesses in the given category; and red means that a concept has many weaknesses in the given category. In other words, an area marked with green is well characterized, and an area with a red light requires significant R&D efforts. For each concept, a short summary reports the most important considerations that can be drawn.

5.1 Rotor Topology: Two-Bladed Rotor

Overall, reviewers found that there are few open science and engineering challenges for the two-bladed rotor concept. Table 21 shows the relative ranking of the science challenges, and Table 22 shows the relative ranking of the engineering challenges.

Table 21. Ranking of Science Challenges for the Two-Bladed Rotor Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
● (green)	● (green)	● (green)	● (green)	● (green)

There are relatively few open science challenges that apply to this concept. From a physics perspective, this concept is similar to a conventional three-bladed upwind horizontal-axis wind turbine, which is rather well characterized. There may be some issues with characterizing the airfoil behavior for high Reynolds numbers because of the higher chord lengths compared to the ones of a conventional blade, but this effect is expected to be relatively small. Finally, flutter may be an issue because two-bladed rotors tend to rotate faster than conventional rotors.

Table 22. Ranking of Engineering Challenges for the Two-Bladed Rotor Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
● (green)	● (green)	● (green)	● (yellow)	● (green)	● (green)	● (yellow)	● (green)

Reviewers agreed that there are not many engineering challenges preventing this concept from achieving commercialization. There are a few items around control (e.g., individual pitch control [IPC], yawing, control for mitigation of wind shear/veer effects, tower shadow mitigation) and reliability (e.g., teeter join, erosion, IPC actuators) that the reviewers were concerned about.

5.2 Rotor Topology: Dual Rotor

Overall, reviewers found many science and engineering challenges for the dual-rotor concept. Table 23 shows the relative ranking of the science challenges, and Table 24 shows the relative ranking of the engineering challenges.

Table 23. Ranking of Science Challenges for the Dual-Rotor Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🟡	🟡	🟡	🔴	🟢

The reviewers had concern about the ability to model the wake interactions between the two rotors and the ability to use traditional solvers based on blade element momentum theory (BEMT) to model the complex interactions occurring between the two rotors. The airflow mixing may complicate the modeling of noise within the available toolsets. It would likely require large R&D efforts to address these issues.

Table 24. Ranking of Engineering Challenges for the Dual-Rotor Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🟢	🟡	🟡	🔴	🟡	🟢	🔴	🔴

Reviewers thought that airfoil design might be different than for conventional blades with the inboard part of the larger rotor likely to be less efficient than conventional blades, while the inner rotor blades would be expected to capture more energy in that region. There are also concerns over the constraints required for the inner rotor to avoid a strike with the outer rotor. This would likely result in stiffer blades for the inner rotor. Pitching in this configuration would present more difficulties over conventional technology, and torque control would likely be more difficult depending on how the two shafts of the rotors interface. The reliability of and complexity of the drivetrain is seen as an overwhelming challenge, and solutions are likely to push the LCOE into an untenable position. The rest of the system would suffer because of the additional overhanging mass of the inner rotor, and the hub and pitching systems would be more complex. Overall, the reviewers viewed this concept unfavorably and thought that continued development would not result in lower LCOE.

5.3 Rotor Topology: Multirotor

Overall, reviewers were mostly concerned about the tip interactions between rotors and the overall complexity of the system. Table 25 shows the relative ranking of the science challenges for the multirotor concept, and Table 26 shows the relative ranking of the engineering challenges.

Table 25. Ranking of Science Challenges for the Multirotor Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🟢	🟡	🟢	🟢	🟢

Some reviewers expressed concerns about tip interference between the rotors, and there may be issues with modeling this type of behavior accurately with current aeroelastic models. The wakes from multiple rotors have not been sufficiently studied; however, reviewers thought that this area presented some exciting opportunities for research because wake losses are an important phenomenon for wind plant analysis.

Table 26. Ranking of Engineering Challenges for the Multirotor Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🟢	🟢	🟢	🟡	🟡	🟢	🟡	🟡

Reviewers were not concerned about the difficulty of blade designs for this concept because this concept has been demonstrated by Vestas with V29 rotors. There are concerns about the control and actuator system, which have many more moving parts, making pitching and yawing more difficult. These considerations also have a direct impact on reliability, which is another area the reviewers were concerned about.

5.4 Orientation: Downwind

Overall, reviewers thought that the most pressing science challenge was to characterize the low frequency noise from the tower shadow effect. Table 27 shows the relative ranking of the science challenges for the downwind concept, and Table 28 shows the relative ranking of the engineering challenges.

Table 27. Ranking of Science Challenges for the Downwind Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🟡	🟡	🟡	🔴	🟡

Reviewers were most concerned about the tower shadow and the impact it has on blade aerodynamics. There needs to be some model development and validation in this area for modern rotors and towers. There is an assumption that this is a critical issue because of many of the tests conducted in the early years of wind turbine technology development. However, these assumptions need to be revisited with modern technology. Tilted rotors were considered for this configuration to steer the wake toward the ground and capture more energy at the plant level. This requires some additional research on wake behaviors. Improved tower shadow models are necessary for aeroelastic tools. A better understanding of the low frequency noise is required in order for it to fully gain acceptance as a viable technology.

Table 28. Ranking of Engineering Challenges for the Downwind Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🟢	🟢	🟡	🟡	🟢	🟢	🟡	🟡

Overall, reviewers saw little change in the engineering approach to designing a downwind rotor. If the blades are designed to be very flexible, then special attention must be made in order to prevent tower strikes during emergency shutdowns. Fatigue loads may also increase slightly due to tower shadow effect, so designs must take this into consideration. There may be some benefits from the nacelle blockage effect. Additionally, the yaw system might be able to be simplified. Nacelle-mounted anemometers and wind vanes will benefit from being outside of the rotor wake. Overall, the science and engineering challenges are seen as achievable.

5.5 Blade Configuration: Slender, High TSR Blades

Overall, reviewers were mostly concerned about the effect of higher tip speeds and the difficulties around noise and erosion. However, this concept is for high TSRs, and this does not necessarily result in high tip speeds. Table 29 shows the relative ranking of the science challenges for the slender, high TSR blades concept, and Table 30 shows the relative ranking of the engineering challenges.

Table 29. Ranking of Science Challenges for the Slender, High TSR Blades Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
Yellow	Yellow	Yellow	Yellow	Green

Reviewers found few issues with the scientific understanding in blade aerodynamics and wake aerodynamics but pointed out that stability analysis on blades that are much more flexible may cause issues with current modeling techniques.

Table 30. Ranking of Engineering Challenges for the Slender, High TSR Blades Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
Yellow	Yellow	Yellow	Green	Yellow	Green	Yellow	Green

Reviewers were concerned with the materials for slender blades because stiffer materials may be needed for increased tip deflections. The airfoil design would not be as much of an issue because of the use of thinner airfoils. This will reduce the effective length for Reynolds number calculations. The structure of the blade presents some of the most pressing issues because there is less area and therefore less structural robustness. The impacts on the rest of the system are favorable but somewhat unknown and present an area for research.

5.6 Blade Configuration: Highly Flexible Blades

Overall, reviewers thought that the most challenging problems characterizing the highly flexible blades concept were the unknown dynamics involved with the loss of structural stiffness and the difficulties of modeling the aerodynamic response with large out-of-plane deflections. Table 31 shows the relative ranking of the science challenges for the highly flexible blades concept, and Table 32 shows the relative ranking of the engineering challenges.

Table 31. Ranking of Science Challenges for the Highly Flexible Blades Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🔴	🔴	🔴	🟡	🟡

It is unknown if the current modeling approaches using BEMT will be valid because highly flexible blades will result in large out-of-plane deflections. These phenomena may be able to be accounted for in model tuning, but this is unknown at the current time. The aerodynamic and aeroelastic responses of the wake are also unknown for blades with very large deflections. Models would need to be validated before being fully incorporated within design processes. There are some concerns over flutter and unsteady aerodynamics and their impacts on noise generation.

Table 32. Ranking of Engineering Challenges for the Highly Flexible Blades Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🟡	🟢	🔴	🟡	🟡	🟢	🔴	🟡

Reviewers were concerned about the ability to use materials that have been used for wind turbine applications in the past due to high strain requirements. Additionally, it may be necessary to adopt new materials for these applications, in which case they might not be as characterized. Airfoil selection may present some challenges due to the different dynamic performances caused by large out-of-plane deflections. The structural design of the blade will likely be more complicated, and controlling fatigue will be difficult. Controlling emergency stops will present a challenge for downwind configurations, and controlling tower strikes in normal operation for upwind configurations will be a major challenge. Reviewers were concerned about the reliability of highly flexible blades due to the high strains. One nice feature of this design is that it could enable transport of very long blades via rail by bending them around curves.

5.7 Blade Configuration: Low-Induction Rotor

Overall, the consensus among reviewers was that there are very few science and/or engineering challenges associated with lowering the induction along the blade. Table 33 shows the relative ranking of the science challenges for the downwind concept, and Table 34 shows the relative ranking of the engineering challenges.

Table 33. Ranking of Science Challenges for the Low-Induction Rotor Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🟢	🟢	🟢	🟢	🟢

Table 34. Ranking of Engineering Challenges for the Low-Induction Rotor Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢

5.8 Blade Configuration: Wake-Optimized Rotor

Overall, the consensus among reviewers was that there are very few science and/or engineering challenges associated with optimizing the induction along the blade to optimize the performance for wind plant applications. Table 35 shows the relative ranking of the science challenges for the wake-optimized rotor concept, and Table 36 shows the relative ranking of the engineering challenges.

Table 35. Ranking of Science Challenges for the Wake-Optimized Rotor Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🟢	🟡	🟢	🟢	🟢

The reviewers only raised questions about how the wake behavior would change and how this change could be quantified.

Table 36. Ranking of Engineering Challenges for the Wake-Optimized Rotor Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢

Reviewers expressed some concern over the increase in wake energy and fatigue that these types of rotors may induce.

5.9 Blade Design Features: Multielement Airfoils

Reviewers saw a number of science and engineering challenges associated with the multielement airfoil concept and were mostly concerned with the impacts to the structure, ability to manufacture, and reliability of the blade. Table 37 shows the relative ranking of the science challenges, and Table 38 shows the relative ranking of the engineering challenges.

Table 37. Ranking of Science Challenges for the Multielement Airfoil Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🟡	🟡	🟡	🟡	🟢

Reviewers pointed out that there may be challenges with using BEMT for multielement airfoils and that CFD analysis may be necessary. The aerodynamics of the system will be more complicated to model and will affect wake and aeroelastic analysis. For certain configurations, there may also be changes to the structure, which will affect the aeroelastic response in unknown ways. Noise from these devices may be greater due to the increased number of trailing edges and potentially at attachment points.

Table 38. Ranking of Engineering Challenges for the Multielement Airfoil Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
Green	Yellow	Red	Yellow	Red	Green	Red	Green

This concept presents the opportunity to incorporate thin airfoils near the root and along the blade. There are concerns about optimizing these types of configurations. The torsional stiffness may be reduced for the bi-wing configuration. There are major concerns regarding the manufacturing and installation of some of these devices. For example, leading edge slats must be fixed to the blade in some robust and reliable fashion. The bi-wing type configuration could lend itself to segmentation, thereby alleviating some transportation constraints.

5.10 Blade Design Features: Segmented Blades

Workshop participants saw no science challenges but a moderate number of engineering challenges associated with the segmented blades concept. The impacts to the structure, ability to manufacture, and reliability of the blade raised the biggest concerns. Table 39 shows the relative ranking of the science challenges, and Table 40 shows the relative ranking of the engineering challenges.

Table 39. Ranking of Science Challenges for the Segmented Blades Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
Green	Green	Green	Green	Green

Overall, workshop participants did not see any science challenges for the segmented blade concept.

Table 40. Ranking of Engineering Challenges for the Segmented Blades Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🟡	🟡	🔴	🟢	🔴	🟡	🔴	🟢

Reviewers had some concerns regarding the materials used in joining the segments together because some of the options considered included thermoplastics. More research is needed to determine if these materials can be used for wind turbine blade applications. The structure of the blade is also a major concern because a joint will likely add complexity to the structural design of the blade. Jointed blades will require on-site assembly, which is a risk for the technology, and reliability of the joint is a question.

5.11 Blade Design Features: Inflatable Blades

The inflatable blades concept has a large number of science and engineering challenges. Table 41 shows the relative ranking of the science challenges for the inflatable blades concept, and Table 42 shows the relative ranking of the engineering challenges.

Table 41. Ranking of Science Challenges for the Inflatable Blades Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🟡	🟡	🔴	🟡	🟢

Reviewers commented that it will be difficult to make and maintain an airfoil shape with an inflatable blade. This would lead to what some called "nondeterministic aerodynamics." This difficulty predicting the airfoil shape extends to difficulties with wake and aeroelastic modeling. Airfoils that are not rigid could also lead to additional aeroacoustic noise generation.

Table 42. Ranking of Engineering Challenges for the Inflatable Blades Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🔴	🟡	🔴	🟡	🔴	🟡	🔴	🟡

The material selection for the shell is likely very important to the success of the inflatable blade concept. There are concerns about the shell holding its shape and its overall reliability in harsh conditions. The materials for the main load-carrying structure and filler material must be optimized to find a balance between strength and weight. Additionally, the ability to transfer the loads from the shell to the load-carrying member is unknown and will likely require some engineering ingenuity. The controls for this concept could be complicated if the blade has a midspan pitch mechanism. Using this approach would likely simplify the pitch system and could enable this scale of blade. Integration and manufacturing are likely complicated by completing some of these tasks on-site. Finally, reviewers were very concerned about the reliability of the blade, mostly where it concerned the blade shell.

5.12 Blade Design Features: Variably Coned Rotor

The variably coned rotor concept has several science and engineering challenges. Overall, the complexity of the concept was cause for concern for the reviewers. Additional actuators and controls will be required to realize this concept. Table 43 shows the relative ranking of the science challenges for the variably coned rotor concept, and Table 44 shows the relative ranking of the engineering challenges.

Table 43. Ranking of Science Challenges for the Variably Coned Rotor Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🟡	🟡	🟡	🟡	🟡

Reviewers thought that the largest scientific challenge would be understanding and modeling the aerodynamics and aeroelasticity if the coning angles were very high. This would likely cause some issues with completing analysis with BEMT because the rotor disk would be out of plane. These difficulties analyzing the blade aerodynamics would likely extend to analysis of the wake and aeroelasticity.

Table 44. Ranking of Engineering Challenges for the Variably Coned Rotor Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🟢	🟢	🟡	🔴	🟡	🟢	🔴	🟡

Reviewers were mostly concerned about the system required for actuation and the controls and reliability complications associated with the additional complexity in the system. The hinge system was concerning for the same reason. The TRL and relative understanding of this system was considered to be low. The controller design will be much more complicated, and the additional actuation required will cause a reliability impact. The rest of the turbine might actually benefit from lower loads when the rotor is able to shed loads, perhaps mostly impacting the amplitude for fatigue loads.

5.13 Blade Design Features: Variable Diameter Rotor

Generally, workshop participants determined that the scientific challenges associated with the concept were minimal, but the engineering challenges would be substantial—particularly those associated with the mechanical aspects of extension or shape adaption. Table 45 shows the relative ranking of the science challenges associated with the variable diameter rotor concept, and Table 46 shows the relative ranking of the engineering challenges.

Table 45. Current Level of Scientific Understanding Relevant to the Variable Diameter Rotor Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🟢	🟢	🟡	🟡	🟢

Generally, participants agreed that the blade aerodynamics and wakes for rotors, even those that may adapt their shape—especially through extension of their diameter—are well understood. While there are general research challenges associated with these topic areas, the concept of the variable diameter rotor does not bring in any new phenomena to be studied. On the other hand, the aeroelasticity of the complex machine, especially during extension and retraction while operating, was something that would require some additional research. Similarly, there may be additional issues to address and understand related to the interface and discontinuity impacts on aeroacoustic noise generation. Research into the development of novel materials specific to the bearing and joint was considered to be important to the concept development. Similarly, airfoil research would be needed to develop novel thick airfoils with sufficient performance but also that could accept sliding and internal packaging of the outboard section when retracted.

Table 46. Ranking of Engineering Challenges for the Variable Diameter Rotor Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🟡	🟡	🔴	🟡	🟡	🟢	🔴	🟡

In contrast to the science challenges, a large hesitation about the viability of the concept stemmed from engineering challenges related to the mechanical system for extension in terms of design and packaging as well as reliability. The structural aspects of the design were thought to be very complex and would require substantial dedicated technology development effort. Reliability of the overall system was expected to be low (due to difficulty to design a robust control, actuation, joint, and bearing system) and difficult to maintain. For instance, in-field repair of the mechanical extension system would be difficult and costly. Other engineering challenges that were seen as relatively difficult included the control system design for retraction/extension during operation, the impact to the rest of the system design (e.g., additional sensors, a specialized hub system), and the overall system integration and manufacturing of the more complex blade elements. On the other hand, it was felt that there would be little additional effort required for transportation, logistics, and installation (assuming that the blade could be transported in its fully retracted state). Power electronics similarly were not felt to be more complex with the caveat that there would be a larger range of operating conditions in the various retracted and extended states.

In summary, while the variable diameter concept does not pose fundamental science challenges, the complexity of the mechanical system to extend the rotor blade or adapt its shape was seen as an area for significant engineering and technology development and likely would prove to be a limitation toward the successful development and commercialization of the concept.

5.14 Blade Design Features: Winglets

There are very few open science and engineering challenges associated with the winglet concept. Table 47 shows the relative ranking of the science challenges, and Table 48 shows the relative ranking of the engineering challenges.

Table 47. Ranking of Science Challenges for the Winglets Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
●	●	●	●	●

Overall, reviewers did not consider this concept to have many open science challenges, but they did mention that the aerodynamic modeling of the blade tip is often somewhat of a challenge. The winglet may also have an unknown impact on flutter analysis and noise generation.

Table 48. Ranking of Engineering Challenges for the Winglets Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
●	●	●	●	●	●	●	●

Overall, there were very few engineering challenges identified for winglets, except for the areas of manufacturing and transportation that could become more complicated and require innovative solutions.

5.15 Blade Design Features: Distributed Aerodynamic Controls

Reviewers identified a number of science and engineering challenges associated with distributed aerodynamic controls. Table 49 shows the relative ranking of the science challenges, and Table 50 shows the relative ranking of the engineering challenges.

Table 49. Ranking of Science Challenges for the Distributed Aerodynamics Controls Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
●	●	●	●	●

Depending on where the aerodynamic control actuators are, there may be some research needed to characterize the aerodynamics. The behavior of the wakes may be somewhat different depending on the actuators and controller. The aeroelasticity is certainly augmented by the aerodynamic controls and will need to be modeled properly to yield robust designs. Some research will be required to characterize the performance of the fluctuating airfoil shapes and the aeroelastic response of the blade. Some devices may increase the aeroacoustic noise, whereas others may reduce it.

Table 50. Ranking of Engineering Challenges for the Distributed Aerodynamic Controls Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
🟡	🟡	🟡	🔴	🔴	🟢	🔴	🟡

There is some opportunity to research and study new materials used for actuation, such as shape memory materials. Airfoil selection can be co-optimized with actuation technologies to develop the most efficient system possible. Controls is one of the largest risk areas and an area that requires the most engineering work. Integration of the actuators and their reliability is an area that has impeded the commercialization of distributed aerodynamic controls in the past and will be a necessary focus area to enable this technology going forward. The positive impacts to the rest of the system are reduced loads.

5.16 Hub Configuration: Large Hub Radius

The science and engineering challenges are seen to be quite low for the large hub radius concept. Table 51 shows the relative ranking of the science challenges, and Table 52 shows the relative ranking of the engineering challenges.

Table 51. Ranking of Science Challenges for the Large Hub Radius Concept

Blade Aero	Wake	Aeroelasticity	Noise	Mesoscale
🟢	🟡	🟢	🟢	🟢

Reviewers noted that there would be the need to quantify the wake of the hub and also the effect of the hub on the aerodynamics of the turbine.

Table 52. Ranking of Engineering Challenges for the Large Hub Radius Concept

Materials	Airfoils	Structures	Controls	Integration / Manufacturing	Transport / Logistics / Installation	Reliability	Rest of Turbine Design
●	●	●	●	●	●	●	●

Overall, the concept did not present any major science or engineering issues. In fact, it creates some system benefits by allowing the root of the blade to be further from the hub center, thereby reducing the pitch system requirements. There may be some issues with anemometer placement as the larger hub would likely block the flow around the nacelle. It also may be more difficult to transport the larger hub. Loads are likely to increase for this concept.

6 Concept Comparison

The objective of the workshop was to understand the potential of different technologies to enable large and low-specific-power wind turbines. As previously described, the workshop participants evaluated the impacts on performance and cost metrics and the associated challenges for each concept. The impacts and challenges were assessed relative to existing commercial technology. The feedback from the workshop is used in this section to perform a qualitative analysis that examines the relative performance across the concepts.

Some high-level trends emerged while examining the workshop feedback. For example, AEP and TCC were tightly coupled because an improvement in one dimension was often offset by a loss in the other dimension. This result might be predicted because the AEP increases considered for BAR concepts generally targeted longer blades that consisted of more materials and were therefore more costly. From an LCOE perspective, these types of blades may still be advantageous, but detailed analysis is needed to determine where these breakeven design points exist.

Reviewers were very sensitive to concepts that had a perceived negative impact on reliability and O&M cost, which lowered the overall performance metric of the concepts. This result is reasonable because a concept that causes more operational expenses is likely to increase the overall LCOE. However, there were some concepts that scored relatively low for operational expenses, but the total performance impact was high. Reviewers were less sensitive to BOS costs associated with the concepts, and most concepts were scored relatively equally unless they had very obvious deficiencies.

The concepts that were considered to have more science challenges generally scored low for blade aerodynamics and impacts on noise. The remaining categories were relatively consistent across the different concepts, especially for mesoscale impacts. This is likely because larger rotors will all experience the same relative environmental conditions, but the unknown impacts of the mesoscale effects were recognized by the reviewers as a general concern for all concepts. The concepts that were considered to have more engineering challenges generally scored low in the following areas: blade structural design, control and sensors, integration and manufacturing, and reliability. The results showed that reviewers did not give very much consideration to transportation logistics for the concepts in general. This could be because the industry has managed to innovate around transportation constraints, but the BAR project will continue to consider these as important constraints when analyzing future designs.

A scatter plot showing the relative rankings of the concepts is shown in Figure 28. Concepts that scored well in the performance metrics are higher in the plot on the y-axis, and concepts with fewer science and engineering challenges are plotted higher on the x-axis.

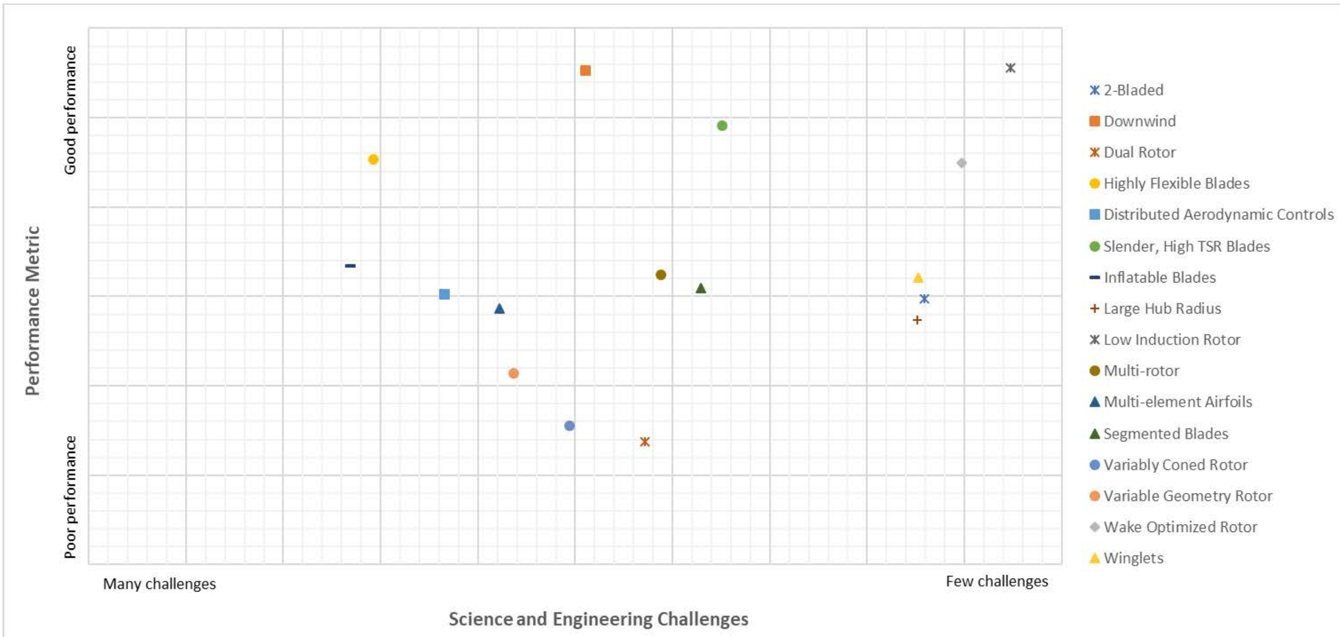

Figure 28. Scatter plot of performance metrics versus science and engineering challenges

Analysis shows that technologies at higher TRLs, such as downwind rotors, slender and high TSR blades, low-induction blades, and wake-optimized blades, scored higher in performance (lowering overall LCOE) and had comparatively fewer science and engineering challenges. From a Pareto front perspective, these technologies would be at the upper boundary in terms of identifying concepts with both high impact potential and those that would face few challenges in their development and commercialization. It was noted during the workshop, and in pre- and post-analysis, that many of these concepts have already been developed and deployed commercially (particularly downwind and low-induction technologies). However, the scale of BAR technologies pushing to extremely large blades would require significant additional R&D efforts.

The concepts that scored lower in terms of potential impact and had more science and engineering challenges included concepts that had significant additional mechanical complexity compared to conventional technology. Generally, concepts that included additional “moving parts” were evaluated more critically than others, including variable diameter rotors, variably coned rotors, and dual rotors. This was largely due to the potential negative impacts on TCCs, O&M costs, and the associated science and engineering challenges for their development. It is worth noting, however, that these devices were judged more favorably from a BOS perspective because many of them have the potential to alleviate transportation issues associated with very large blades.

One concept that was identified as having more science and engineering challenges but having high potential impact on performance was highly flexible blades. Whereas the other concepts that hold high potential impact were seen as having higher TRL and few development challenges, highly flexible blades were seen as having a number of challenges in materials and manufacturing, structural design and reliability, controls, and the rest of the system design. As judged by workshop participants, commercial realization of the technology would require significant investment in R&D. However, the potential reduction in LCOE compared to the conventional technology was perceived as relatively high because such blades could overcome some of the transportation challenges and high associated costs, as well as reduce the overall BOS for the turbine due to reduced rotor weight.

Several concepts had moderate potential impact for LCOE reduction with a large range of perceived associated science and engineering challenges. On one extreme, workshop participants found fewer science and engineering challenges associated with winglets, two-bladed rotors, and large-hub radius likely because variations of these technologies have been demonstrated and commercialized in wind energy or related applications in aerospace. Winglets may be a design feature worth R&D but not particularly specific to BAR application due to its relatively low amount of open research questions.

Workshop participants scored segmented blades and multirotors in the middle relative to other concepts on potential impacts and perceived challenges. Like two-bladed rotors, these technologies have been demonstrated (in both cases) and commercialized (in the case of segmented blades), but technology challenges persist related to their overall cost and reliability. For segmented blades, the reliability and cost of the joint was judged to be an ongoing challenge. For multirotors, the complexity of the additional dynamics, controls requirements, and reliability challenges were all judged to be significant—more significant than for the other two concepts.

The last group of concepts scored average on potential impact and were perceived to have significant science and engineering challenges. These included inflatable blades, multielement airfoils, and distributed aerodynamic controls. This group of concepts may represent a target for further investigation under the BAR project because solving some of the science and engineering challenges could enable impactful rotor design choices in the future.

The initial overall BAR project objective seeks to enable very large-scale wind turbines of over 5-MW capacity and specific power of 150 W/m^2, resulting in CF increases of 10% or more over conventional technology. At these parameters, blade sizes of 100 m will be necessary (or novel configurations such as dual- or multirotors). Scaling of conventional technology and blade sizes will be challenged by the cost and feasibility of manufacturing, transportation, and logistics (MTL). The BAR project seeks to identify concepts that can circumvent these challenges through novel solutions around MTL of conventional blades, or, as presented in this document, development of technology concepts that would seek to overcome the constraints presented by current MTL technologies and practice. While all the evaluated concepts have potential MTL reductions relative to current technologies, some show much more promise than others when evaluated relative to each other on potential LCOE impacts and the ability to overcome the remaining science and engineering challenges.

Future work for the BAR project will focus on concepts with higher potential for performance improvements and those that require significant technology development. This includes the following concepts: downwind rotors, slender and high TSR blades, highly flexible blades, inflatable blades, multielement airfoils, and distributed aerodynamic controls. On the other hand, there is less support for detailed R&D of concepts that have lower perceived impacts for reducing LCOE and higher perceived technology development challenges (particularly due to many moving parts), including variable diameter rotors, variably coned rotors, dual rotors, and multirotors. The results of this qualitative analysis will be used to inform additional BAR research that seeks to advance rotor technologies for the high capacity, high CF, and low-cost wind turbines of the future.

References

Annoni, Jennifer, Andrew Scholbrock, Matthew Churchfield, and Paul Fleming. 2017. "Evaluating Tilt for Wind Farms." Presented at the American Control Conference, Seattle, Washington. May 2017.

Barlas, T., V. Pettas, D. Gertz, and H. Madsen. 2016. "Extreme Load Alleviation Using Industrial Implementation of Active Trailing Edge Flaps in a Full Design Load Basis." *Journal of Physics: Conference Series* 753, 042001. https://iopscience.iop.org/article/10.1088/1742-6596/753/4/042001/pdf

Berg, D., S. Johnson, and C. van Dam. 2008. *Active Load Control Techniques for Wind Turbines*. SAND2008-4809. Albuquerque, NM: Sandia National Laboratories.

Bortolotti, P., C.L. Bottasso, and A. Croce. 2016. "Combined Preliminary-Detailed Design of Wind Turbines." *Wind Energy Science* 1(1):71–88. doi: 10.5194/wes-1-71-2016

Cognet, V., S.C. du Pont, I. Dobrev, F. Massouh, and B. Thiria. 2017. "Bioinspired Turbine Blades Offer New Perspectives for Wind Energy." *Proceedings of the Royal Society A* 473(2198): 20160726.

Chaviaropoulos, C., Beurskens, H.J.M., Voutsinas, S.G., 2013. "Moving towards Large(r) Rotors – Is that a good idea?" *European Wind Energy Conference and Exhibition, EWEC 2013*

CompositesWorld, 2016, "Automated filament winding aids segmented blade production", https://www.compositesworld.com/blog/post/automated-filament-winding-aids-segmented-blade-production

CompositesWorld, 2018, "The markets: Renewable energy (2019)", https://www.compositesworld.com/articles/the-markets-renewable-energy

Cotrell, J., T. Stehly, J. Johnson, J. Roberts, Z. Parker, G. Scott, and D. Heimiller. 2014. "Analysis of Transportation and Logistics Challenges Affecting the Deployment of Larger Wind Turbines: Summary of Results." NREL/TP-5000-61063. Golden, CO: National Renewable Energy Laboratory.

Crawford, C.A. 2007. "Advanced Engineering Models for Wind Turbines with Application to the Design of a Coning Rotor Concept." PhD diss., University of Cambridge.

Dawson, M. 2005. "Variable Length Wind Turbine Blade." Washington, D.C.: U.S. Department of Energy. http://www.osti.gov/scitech/servlets/purl/841190-OF8Frc. .

Dawson, M.H., and J.A. Wallace. 2005. "Telescoping wind turbine blade." *US 6,902,370 B2*.

de Vries, E. 2014. "Close-up: Envision's EN128/3.6MW direct drive turbine" *WindPower Ofshore*. https://www.windpoweroffshore.com/article/1227512/close-up-envisions-en128-36mw-direct-drive-turbine

de Vries, E. 2016. "Exclusive: Vestas Tests Four-Rotor Concept Turbine." *WindPower Monthly*. https://www.windpowermonthly.com/article/1391775/exclusive-vestas-tests-four-rotor-concept-turbine

Dykes, K., Platt, A., Guo, Y., Ning, A., King, R., Parsons, T., Petch, D., Veers, P., and Resor, B., 2014. "Effect of Tip-Speed Constraints on the Optimized Design of a Wind Turbine." NREL/TP-5000-61726. Golden, CO: National Renewable Energy Laboratory.

Dykes, K. 2016. "Dynamics of Technology Innovation and Diffusion with Emphasis on Wind Energy." PhD diss., MIT.

Gaunaa, M., and J. Johansen. 2007. "Determination of the Maximum Aerodynamic Efficiency of Wind Turbine Rotors with Winglets." *Journal of Physics* Conference Series 75 012006

Heronemus, W. 2006. Offshore Wind Turbine with Multiple Wind Rotors and Floating System. U.S. Patent. US7075189B2.

Honnef, H. 1934. Wind Motor. US1963912A.

Ichter, B., A. Steele, E. Loth, and P. Moriarty. 2012. "Structural Design and Analysis of a Segmented Ultralight Morphing Rotor (SUMR) for Extreme-Scale Wind Turbines." In *42nd AIAA Fluid Dynamics Conference and Exhibit* 3270.

Ichter, B., A. Steele, E. Loth, P. Moriarty, and M. Selig. 2016. "A Morphing Downwind-Aligned Rotor Concept Based on a 13-MW Wind Turbine." *Wind Energy* 19(4): 625–37. doi: 10.1002/we.1855

Johansen, J., and N. Sørensen. 2006. *Aerodynamic Investigation of Winglets on Wind Turbine Blades Using CFD*. Riso Report, Riso-R-1543.

Kelley, C. 2017. "Optimal Low-Induction Rotor Design." *Wind Energy Science Conference 2017.*

Kelley, C., Maniaci, D., and Resor, B., 2015. "Horizontal-Axis Wind Turbine Wake Sensitivity to Different Blade Load Distributions." *33rd Wind Energy Symposium, AIAA.*

Kress, C., N. Chokani, and R.S. Abhari. 2015a. "Downwind Wind Turbine Yaw Stability and Performance." *Renewable Energy* 83:1157–65. doi: 10.1016/j.renene.2015.05.040

Kress, C., N. Chokani, and R.S. Abhari. 2015b. "Design Considerations of Rotor Cone Angle for Downwind Wind Turbines." *Journal of Engineering for Gas Turbines and Power* 138(5): 052602–052602-10. doi: 10.1115/1.4031604

Loth, E., Steele, A., Ichter, B., Selig, M., and Moriarty, P., 2012. "Segmented Ultralight Pre-Aligned Rotor for Extreme-Scale Wind Turbines." In 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition (p. 1290).

Loth, E., A. Steele, C. Qin, B. Ichter, M.S. Selig, and P. Moriarty. 2017. "Downwind Pre-Aligned Rotors for Extreme-Scale Wind Turbines." *Wind Energy* 20(7): 1241–59. doi: 10.1002/we.2092

Les Grands Planeurs, 2010, http://lesgpr.free.fr/construire/eb-28/eb28.htm

Lysen, E. 1983. *Introduction to Wind Energy*. Amersfoort, Netherlands: CWD.

Jamieson, P.M., Hornzee-Jones, C., Moroz, E.M., and Blakemore, R.W. 2005. "Variable diameter wind turbine rotor blades." U.S. Patent. US6972498B2.

Lord, Z. 2015. "The Road to ecoROTR: How Building a Better Wind Turbine Began With an Online Shopping Spree for Styrofoam Balls." GE Reports. https://www.ge.com/reports/post/126500095500/the-road-to-ecorotr-how-building-a-better-wind-2/.

Madsen, H.A., J. Johansen, N.N. Sørensen, G.C. Larsen, and M.H. Hansen. 2007. "Simulation of Low Frequency Noise from a Downwind Wind Turbine Rotor." *45th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada. doi: 10.2514/6.2007-623

Newman, B.G. 1986. "Multiple Actuator-Disc Theory for Wind Turbines." *Journal of Wind Engineering and Industrial Aerodynamics* 24(3): 215–25.

Ning, A., and K. Dykes. 2014. "Understanding the Benefits and Limitations of Increasing Maximum Rotor Tip Speed for Utility-Scale Wind Turbines." Article No. 012087. *Journal of Physics: Conference Series* 524 (2014): 10 pp. https://dx.doi.org/10.1088/1742-6596/524/1/012087.

Ning, A., and D. Petch. 2016. "Integrated Design of Downwind Land-Based Wind Turbines Using Analytic Gradients." *Wind Energy* 19(12): 2137–52.

Pechlivanoglou, G., J. Wagner, C. Nayeri, and C. Paschereit. 2010. "Active Aerodynamic Control of Wind Turbine Blades with High Deflection Flexible Flaps." In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition,* p. 644.

Peeter, M., G. Santo, J. Degroote, and W. Van Paepegem. 2017. "The Concept of Segmented Wind Turbine Blades: A Review." *Energies* 10(8): 1112. http://www.mdpi.com/1996-1073/10/8/1112

Prandtl L (1933) Über tragflügel kleinsten induzierten widerstandes. Zeitschrift für Flugtecknik und Motorluftschiffahrt, 1 VI 1933 (München, Deustchland)

Ragheb, A., and M. Selig. 2011. "Multi-Element Airfoil Configurations for Wind Turbines." In *29th AIAA Applied Aerodynamics Conference,* p. 3971.

Rasmussen, F., and J.T. Petersen. 1999. "A Soft Rotor Concept-Design, Verification and Potentials." *Contributions from the Department of Wind Energy and Atmospheric Physics to EWEC'99,* Nice, France, 31.

Reiso, M. 2013. "Tower Shadow Effect in Downwind Wind Turbines." PhD diss., NTNU Norwegian University of Science and Technology.

Renewables Now. 2017. "Vestas to Test Multi-Rotor Wind Turbine Concept." https://renewablesnow.com/news/vestas-to-test-multi-rotor-wind-turbine-concept-521764/

Resor, B., D. Maniaci, J. Berg, and P. Richards. 2014. *Effects of Increasing Tip Velocity on Wind Turbine Rotor Design*. SAND2014-3136. Albuquerque, NM: Sandia National Laboratories.

Rosenberg, A., S. Selvaraj, and A. Sharma. 2014. "A Novel Dual-Rotor Turbine for Increased Wind Energy Capture." *Journal of Physics: Conference Series* 524(1), 1–10.

Rosenberg, A., and A. Sharma. 2016. "A Prescribed-Wake Vortex Lattice Method for Preliminary Design of Co-Axial, Dual-Rotor Wind Turbines." *Journal of Solar Energy Engineering* 138(6) 061002–061002-9.

Roth-Johnson, P. 2014. "Aero-Structural Design Investigations for Biplane Wind Turbine Blades." PhD diss., UCLA.

Schorbach, V., R. Haines, and P. Dalhoff. 2016. "Teeter End Impacts: Analysis and Classification of Most Unfavourable Events." *Wind Energy* 19: 115–31. doi: 10.1002/we.1823.

Steele, A., B. Ichter, C. Qin, E. Loth, M. Selig, and P. Moriarty. 2013. "Aerodynamics of an Ultra Light Load-Aligned Rotor for Extreme-Scale Wind Turbines." *AIAA* 914.

Segmented Ultralight Pre-Aligned Rotor for Extreme-Scale Wind Turbines

Vestas. 2017. "Facts: Vestas Multi Rotor Concept Demonstrator at Riso." https://www.vestas.com/~/media/files/multirotor%20fact%20sheet.pdf .

Wendt, F. 2013. "A Multi-MW Offshore Rotor Blade Design for Galveston, TX Wind Conditions." Master's thesis, University of Stuttgart.

Wiser, R., and M. Bolinger. 2017. *2016 Wind Technologies Market Report*. LBNL-2001042. Berkeley, CA: LBNL. http://eta-publications.lbl.gov/sites/default/files/ 2016_wind_technologies_market_report_-_corrected_back_cover.pdf.

Wobben, A. 2006. Wind Power Installation with Two Rotors in Tandem. U.S. Patent. US7074011B1.

Zahle, F., N. Sørensen, M. McWilliam, and A. Barlas. 2018. "Computational Fluid Dynamics-Based Surrogate Optimization of a Wind Turbine Blade Tip Extension for Maximising Energy Production." *Journal of Physics: Conference Series* 1037 042013.