

# **Aerodynamic flow deflector to increase large scale wind turbine power generation by 10%**

FINAL REPORT  
November 2015

Submitted by:

**Arturo Villegas, PhD**  
Postdoctoral Associate

**Anagha Ray, MS**  
Research/Technical Assistant

**Jubilee Prasad, PhD Student**  
Teaching Assistant

Department of Mechanical & Aerospace Engineering  
Rutgers, The State University of New Jersey  
98 Brett Road, Piscataway, NJ 08854

External Project Manager  
F. Javier Diez-Garias, Ph.D.  
Associate Professor  
Rutgers, The State University of New Jersey

In cooperation with  
Rutgers, The State University of New Jersey  
And  
U.S. Department of Transportation  
Federal Highway Administration

## **Disclaimer Statement**

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

The Center for Advanced Infrastructure and Transportation (CAIT) is a Tier I UTC Consortium led by Rutgers, The State University. Members of the consortium are the University of Delaware, Utah State University, Columbia University, New Jersey Institute of Technology, Princeton University, University of Texas at El Paso, University of Virginia and Virginia Polytechnic Institute. The Center is funded by the U.S. Department of Transportation.

1. Report No. <b>CAIT-UTC-058</b>		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle <b>Aerodynamic flow deflector to increase large scale wind turbine power generation by 10%</b>				5. Report Date <b>November 2015</b>	
				6. Performing Organization Code <b>CAIT/Rutgers University</b>	
7. Author(s) <b>Arturo Villegas, Anagha Ray and Jubilee Prasad</b>				8. Performing Organization Report No. <b>CAIT-UTC-058</b>	
9. Performing Organization Name and Address <b>Department of Mechanical &amp; Aerospace Engineering Rutgers, The State University of New Jersey 98 Brett Road, Piscataway, NJ 08854</b>				10. Work Unit No.	
				11. Contract or Grant No. <b>DTRT12-G-UTC16</b>	
12. Sponsoring Agency Name and Address <b>Center for Advanced Infrastructure and Transportation Rutgers, The State University of New Jersey 100 Brett Road Piscataway, NJ 08854</b>				13. Type of Report and Period Covered <b>Final Report 5/18/2015-11/30/2015</b>	
				14. Sponsoring Agency Code	
15. Supplementary Notes <b>U.S. Department of Transportation/Research and Innovative Technology Administration 1200 New Jersey Avenue, SE Washington, DC 20590-0001</b>					
16. Abstract <p>The innovation proposed in this paper has the potential to address both the efficiency demands of wind farm owners as well as to provide a disruptive design innovation to turbine manufacturers. The aerodynamic deflector technology was created to improve the efficiency of any current wind turbine around the world and to be included with new blade designs. To prove the feasibility of the deflectors, two tests have been done during this project for two different wind turbines.</p> <p>The first test was performed at the wind tunnel facility at Rutgers University. Two identical wind turbines were 3D printed, one with deflectors on its blades and the other one without deflectors. An average power coefficient <math>C_p</math> improvement of 10% was observed during this test.</p> <p>The second test was performed for the Whisper 100 turbine at the Wind Application Center at Appalachian State University. The turbine performance was measured without deflectors for 2 weeks. Then, the turbine was retrofitted with deflectors and its power performance was measured for another 2 weeks. An average <math>C_p</math> improvement of 7.7% was observed during this test. The estimated AEP increase was between 8.7 to 11.4 %, depending on the site annual average wind speed.</p> <p>All tests show important improvements in power performance and AEP. This technology could represent the biggest wind turbine aerodynamic improvement in the last decade and a game changer to the wind energy industry since even 2% AEP improvement allows wind farm profits to raise by 8%.</p>					
17. Key Words <b>Enhanced Wind Turbine Efficiency, Cost of Energy Reduction, Wind Turbine Infrastructure, Renewable Energy</b>				18. Distribution Statement	
19. Security Classification (of this report) <b>Unclassified</b>		20. Security Classification (of this page) <b>Unclassified</b>		21. No. of Pages <b>27</b>	22. Price

## **ACKNOWLEDGMENTS**

We would like to thank the Center for Advanced Infrastructure and Transportation (CAIT) for their support on this project. We would like to thank Dr. Patrick Szary, CAIT Associate Director, for believing in our technology and making this happen. We would like to thank Joey Sanchez, CAIT Research Program Coordinator, for his support as well. Finally, thanks to all kind staff members at CAIT that contributed and helped to this project, greatly appreciated.

We would like to thanks the Department of Mechanical and Aerospace Engineering at Rutgers University for providing 3D rapid prototyping services and the wind tunnel testing facility.

We would like to thank Brent Summerville, Appalachian State University Practitioner-in-Residence, and Dennis Scanlin, Appalachian State University Professor and Coordinator, for their help and support during this project and for allowing us to test on their Whisper 100 wind turbine.

We would like to thanks NITTO and 3M for providing double side tapes and adhesive promoter samples to test our technology.

# TABLE OF CONTENTS

<b>LIST OF FIGURES .....</b>	<b>1</b>
<b>LIST OF TABLES .....</b>	<b>2</b>
<b>DESCRIPTION OF THE PROBLEM.....</b>	<b>3</b>
<b>APPROACH.....</b>	<b>4</b>
<b>METHODOLOGY .....</b>	<b>5</b>
Literature Review .....	5
<i>Research background .....</i>	<i>5</i>
<i>Power performance .....</i>	<i>8</i>
<i>Cost of Energy and Return on Investment .....</i>	<i>10</i>
Wind tunnel test: Rutgers University .....	14
Field test: Appalachian State University .....	15
<i>Deflectors design, manufacture and adhesion .....</i>	<i>15</i>
<i>Field Test: Appalachian State University.....</i>	<i>17</i>
<b>FINDINGS.....</b>	<b>20</b>
<i>Wind Tunnel Test: Rutgers University.....</i>	<i>20</i>
<i>Whisper 100 field test: Appalachian State University.....</i>	<i>20</i>
<b>CONCLUSION .....</b>	<b>20</b>
<b>RECOMMENDATIONS.....</b>	<b>21</b>
<b>REFERENCES.....</b>	<b>22</b>

## LIST OF FIGURES

Fig. 1. Silk threads on turbine blade showing the radial component of the velocity.....	6
Fig. 2. a) Water channel setup sketch for the turbine – DC motor system and b) turbine mounted in the water channel for the turbine – load cell system.....	7
Fig. 3. Moving averaged power (P) obtained for both baseline turbine and turbine retrofitted with deflectors during 500 seconds.....	8
Fig. 4. Flow chart for field test data analysis.....	9
Fig. 5. Deflectors ROI for 3 different AEP increase scenarios for a single 1.5 MW turbine at 40% Capacity Factor and 7.5% Discount Rate .....	11
Fig. 6. Deflectors ROI for 3 different discount rates for a single 1.5 MW turbine at 40% Capacity Factor and 6% AEP increase.....	12
Fig. 7. Deflectors ROI for 3 different capacity factors for a single 1.5 MW turbine at 7.5% discount rate and 6% AEP increase.....	13
Fig. 8. Deflectors ROI after 10 years as a function of the capacity factor for 3 different turbine sizes at a 7.5% discount rate and 6% AEP increase .....	13
Fig. 9. Wind turbine mounted in the wind tunnel.....	14
Fig. 10. Power coefficient (CP) versus tip speed ratio ( $\lambda$ ) showing the power performance increase when installing flow deflectors on the blades.....	15
Fig. 11. Beech Mountain average wind speed at 30m (Courtesy of Appalachian State University) .....	17
Fig. 12. a) Beech Mountain test site top view and b) test setup (Courtesy of Appalachian State University) .....	17
Fig. 13. Whisper 100 wind turbine density corrected power coefficient at different wind speeds for both configurations with and without deflectors. ....	19
Fig. 14. Whisper 100 wind turbine AEP at different site average wind speeds for both configurations with and without deflectors.....	19
Fig. 15. Whisper 100 wind turbine AEP increase at different site average wind speeds with and without deflectors.....	20

## LIST OF TABLES

Table 1. LCOE reduction at different AEP increase scenarios for a 1.5MW turbine at 40% capacity factor and 7.5% discount rate.....	10
Table 2. Double side tapes peeling force and shear stresses resistances. Test result “Pass” stand for no detachment of deflector during the experiment .....	16

## DESCRIPTION OF THE PROBLEM

All wind farm owners face issues related to limited land space, high capital costs for installing new turbines and long-term delays in returns on investments (ROIs). To combat these limitations and maintain a competitive advantage, manufacturers are producing larger and more sophisticated turbine systems. One existing technology that improve wind turbines efficiency to reduce times until ROIs is vortex generators. A company selling these vortex generators (UpWind) has recently installed and tested the devices at full-scale turbines. They state that VGs provide a 2-3% power increase [1]. In fact, in November 2013, one of the biggest wind farm owner companies (AES) purchased those vortex generators for a 101 MW wind farm in the U.S. The proposed flow deflector technology increases power by 10% which is a tremendous advancement in wind/tidal energy generation. Although there are associated increases in operation efficacies by scaling up turbine sizes and incorporating additional powertrain and tilt technologies, the overall approach has created logistical challenges in terms of manufacturing, deploying and installing such massive structures. The innovation proposed in this application has the potential to address both the efficiency demands of wind farm owners (reducing the time until ROIs) as well as provide a disruptive design innovation to turbine manufacturers providing them a sustainable competitive edge. An important emphasis to make regarding this technology is that it can be retrofitted to existing turbines as well as incorporated into the design of newly manufactured blades.

This aerodynamic flow deflector innovation will critically improve the power generation of any current and future wind/tidal turbine by 5-10% without the need of increasing their height or diameter. For a small additional investment, wind farm owners can have customized deflectors installed on to existing blades, leading to an increase in the Annual Energy Production (AEP) by 10% of each upgraded turbine. The retrofitting could be in the form of deployable (bold, adhesive or magnetic) sets of deflectors for placement along each blade. This translates into a shorter time period to recover sunken capital costs for the construction of farms (shorter ROI) and an increased profits over the lifetime of the farm. It is estimated that this innovation can lead to an overall decrease in the Levelized Cost of Energy (LCOE) by 8%. This technology offers a tremendous value to current owners of wind farms, since even a 2% LCOE reduction is an important advancement in this industry and raises profits considerably (8%). This large jump in efficiency will also be very attractive to turbine manufacturers who continuously compete to gain a larger market share. By delivering 5-10% extra power and reducing the price of this energy source, more households and companies would be willing to purchase this energy. In addition, the deflectors would also help to reduce greenhouse gas emissions by decreasing the consumption of other non-renewable energies. Reduction of imported energy would also be possible since more and cheaper energy would be obtained from wind/tidal turbines integrating this technology.

The goal of the proposed aerodynamic deflectors is the generation of an additional 5-10% power when installed in any new and current turbine compared to the same turbine without the deflectors. In turn, the price of this energy could be critically reduced. Just one single 1MW turbine comprising the deflectors could provide enough energy to power 30 additional houses per year. A worldwide implementation of this technology would exceed the billion dollar profit for turbine companies and wind farms. This technology would allow wind farms to be more profitable (up to 40%) and reduce the price of this energy. The technology focuses in reducing imported energy, reducing energy-related emissions, and improving energy efficiency. The implementation of this technology would help to improve the energy security of the U.S., create hundreds of jobs

nationally, make wind/tidal energy more competitive compared to other non-renewable energies, and enhance the US economy by applying this technology worldwide.

Our initial water channel experimental results showed 8-12% power increase for turbines tested at different channel speeds. This initial proof-of-concept supported our preliminary theoretical results and established a strong case for which we were certain that the proposed project was going to be successful. The final goal of the proposed project is to show a 5-10% power increase for a large wind turbine in both a wind tunnel facility and a field testing site. Successful performance of these experiments would lead to a commercially relevant and attractive product for wind and tidal energy companies and wind farms worldwide.

Wind and field tests would provide the proof-of-concept needed to convince manufacturers and wind farm owners of the benefit of the technology. A market approach was done at the AWEA 2015 Wind Power Conference to evaluate the acceptance of the technology in the wind turbine industry. A general agreement was that larger scale testing would be necessary. Further development of the product could be done by starting a company that retrofits the turbines or by partnering with wind turbine OEM companies.

## **APPROACH**

The proposed approach was to first test the deflectors on a small turbine (0.4m diameter) in a wind tunnel facility and then scale up the experiment to retrofit a 2 diameter turbine for field testing. This proof-of-concept required a wind tunnel test as well as a field test. Rutgers, The State University of New Jersey, owns a small wind tunnel facility that was selected to perform the small wind tunnel test. Appalachian State University owns a Wind Application Center at Beech Mountain (NC) that was selected to perform the first field test.

This 6-month project included the following steps:

1. Selection of base turbines for wind tunnel and field tests.
2. Study of loads and velocity fields acting on the deflectors.
3. Study of the cost of energy (COE).
4. Design of deflectors for selected turbines by using theory and dimensional analysis to produce the final CAD model.
5. Manufacture of deflectors by 3D rapid prototyping.
6. Assembly and pre-test to evaluate adhesion properties of deflectors to the blades.
7. Wind tunnel testing at Rutgers University.
8. Field testing at Appalachian State University.
9. Analysis of collected data to evaluate performance of turbines with and without deflectors.
10. Final report.

The main objective of this project is to demonstrate the substantial power increase when turbines are retrofitted with our technology while lowering the cost of energy. There are two questions to be answered to determine whether the proposed technology is feasible or not:

1. The first question is: Is the Annual Energy Production (AEP) increased substantially ( $>2\%$ ) when retrofitting the deflectors in an existing turbine? We are expecting an AEP increment of 5-10%; however, even a 2-3% AEP increment (as in VG's) has proven to increase profits considerably (8%) and can be considered a success.
2. The second question is: Is the Levelized Cost of Energy (LCOE) reduced substantially ( $>1\%$ ) when retrofitting the deflectors in an existing commercial turbine? We are expecting a LCOE reduction of 8%; however, even a 1-2% LCOE reduction (as in VG's) has proven to increase profits considerably.

If the two questions above are successfully addressed, then we will have a product incredibly attractive for commercialization. This will not just increase the interest of wind farm owners and turbine manufacturers but also private investors.

## **METHODOLOGY**

### Literature Review

#### *Research background*

Over the last 5 years, we have been designing and testing novel wind/water turbines to understand and improve their aerodynamics, efficiency and power production without increasing their size or Levelized Cost of Energy (LCOE). This process included both theoretical and experimental components.

The Blade Element Momentum Theory (BEMT) [2] was coded in-house to help with the design of the wind turbine blades. This theory is generally accepted for designing wind turbines in the industry. The code includes Galuert and Prandtl corrections to the 2-dimensional BEM Theory analysis to extend it to 3-dimensional flows. We have validated the code against one of the National Renewable Energy Laboratory's rotor geometry [3].

We have also manufactured and tested turbines in a water channel to visualize and analyze the flow around the blades and the wake of the turbine. We developed a new method to calculate unsteady forces produced by the blades. The method uses instantaneous velocity data and the Navier-Stokes equations to solve for the instantaneous forces [4-5]. During the design and analysis process, we made a significant discovery that represents a departure from current wind theory studies. It should be noted that the design of wind turbine blades originates on the development of airplane wings and propellers, among others. In short, the technology of wind turbines has really been ported from the aerospace industry and applied in a completely different industry (alternative energy). Our team discovered that optimization for maximum efficiency for wind turbine power production has unique differences not relevant in the aerospace industry. It was during this process that we had a novel conceptual idea to create more efficient wind turbines by adding a deflector that can take advantage of forces and moments that were previously not even considered.

The conceptual idea is based on the radial component of the flow velocity as it moves over the blade. It is well known on airplane applications that there is always a small radial component of

the velocity pointing from root towards the tip of the wing. That component is always there and it is considered a loss in airplanes due to three dimensionality of the wing. Even for an upstream wind perfectly aligned with the airplane wing, when the air flow reaches the airplane it will decelerate and generate a radial component of the velocity towards the tip of the wings. This produces a change in momentum due to the presence of the airplane as it advances through the air. The same phenomena appears in wind turbines.

Since the radial component of the velocity is more pronounced in wind turbines due to angular rotation, the losses due to three dimensionality effects are higher than in airplane wings. Using this as a hypothesis, we decided to investigate whether this third component can be used to reduce those losses in wind turbines. This led to the development of the aerodynamic deflectors to redirect the third component of the flow velocity on the blade and create an extra torque. Clearly, this torque is useless and even harmful in airplane wings, but for wind turbines is highly beneficial, as the power generated increases with torque.

An experimental visualization of the radial component was performed on a Primus AIR 40 wind turbine. Silk threads of 0.2mm diameter were glued to the blades to observe the direction of the wind over the blades. A PowerView HS2000 High Speed camera was used to capture the movement of silk threads on the blades while the turbine was operating. Fig. 1 shows an example of the radial component of the velocity with angles changing from about 5 to 20 degrees. This validated our hypothesis of radial component over the blades and will help with the deflectors' design.

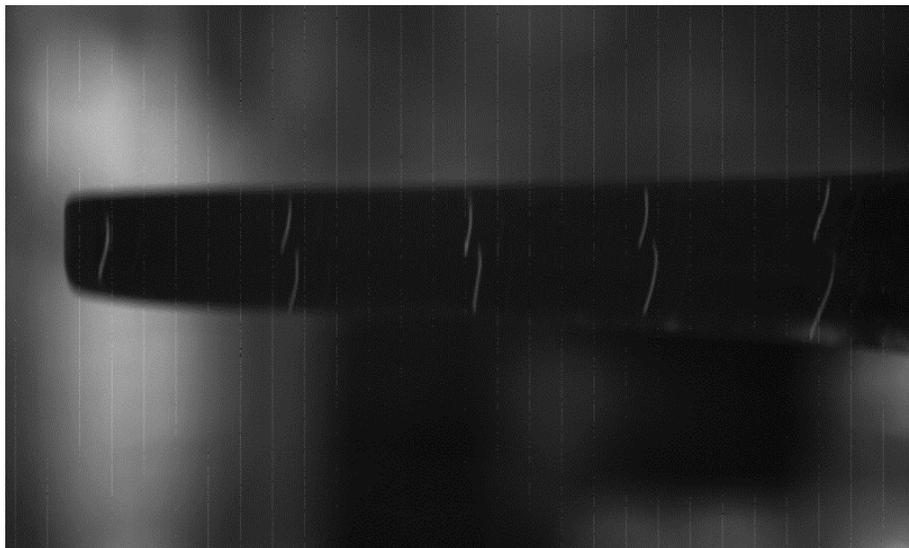


Fig. 1. Silk threads on turbine blade showing the radial component of the velocity

Briefly, when obtaining the ideal performance of a wind turbine blade, the assumption is that it behaves as a large number of 2D infinitesimal airfoil elements. In reality this is not accurate. The air flow around each blade element does not show a 2D behavior where the velocity component of the incoming air flow is contained in the same plane. There are two effects caused by the deflectors:

- Redirect the flow at different radial stations on the turbine blade. In turn, this allows each blade element to show a nearly 2D behavior. Furthermore, it brings the total performance of the wind turbine to near ideal performance conditions.
- Considering that the wind deflector is shaped as an aerodynamic airfoil, the ratio between lift and drag produced by these elements creates a resultant force that increases the torque.

These two effects increase the output power for the same wind speed by smoothly redirecting the air flow through the blades. In short, the deflectors extract the maximum amount of power from the wind kinetic energy by redirecting the wind and reducing 3D effect losses.

To better understand if the idea could be feasible, we first developed a non-dimensional analysis in terms of Levelized Cost of Energy and BEM theory. The results showed a 12% power increase from the use of deflectors. We then manufactured and tested in our small scale water channel a few possible configuration of the deflectors in one of our turbine models. We then recorded the electric power at different water channel speeds when attaching the turbine shaft to a DC motor and an electric resistance (Fig. 2a). We later measured power, torque and rpm by using a load cell and an rpm sensor at different water channel speeds to validate the previous results (Fig. 2b). Fig. 3 shows one of our earliest experiments using the DC motor, where the moving averaged power ( $P$ ) was obtained of both baseline turbine and turbine retrofitted with deflectors for 500 measurements. We quickly realized about the potential of the technology since an average 10.5% power increase was obtained from the water channel measurements. Similar results were obtained for different sets and channel speeds.

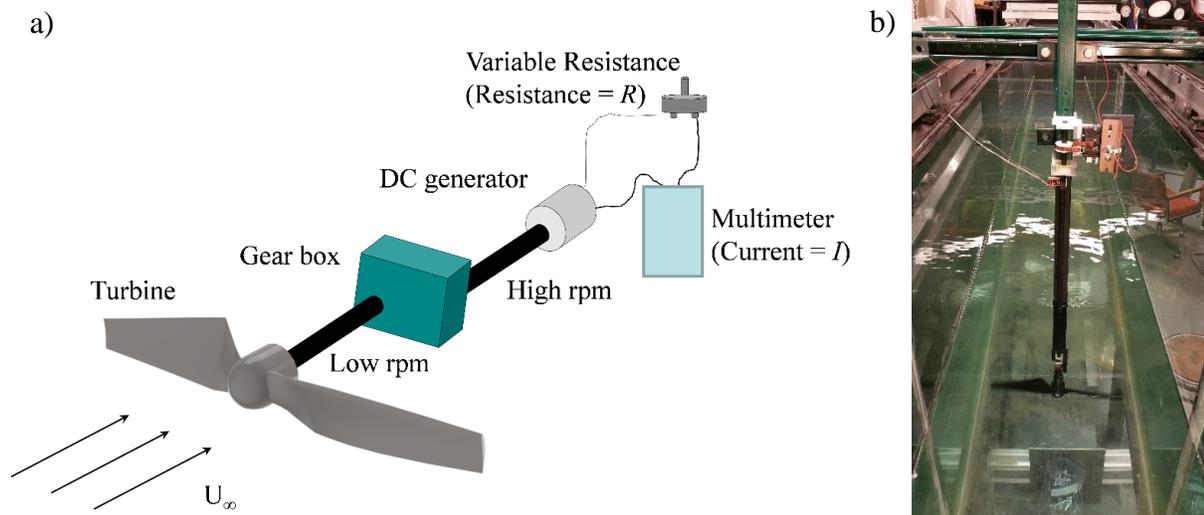


Fig. 2. a) Water channel setup sketch for the turbine – DC motor system and b) turbine mounted in the water channel for the turbine – load cell system

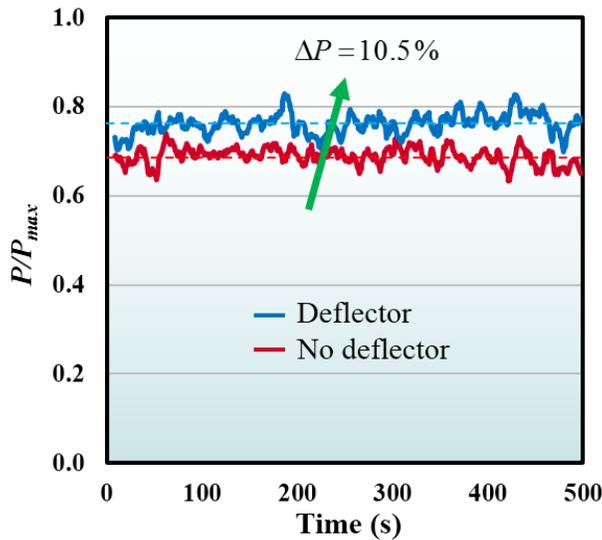


Fig. 3. Moving averaged power ( $P$ ) obtained for both baseline turbine and turbine retrofitted with deflectors during 500 seconds

### *Power performance*

All data is collected and processed using IEC 61400-12-1 [9] power performance standards for small wind turbines and here we just show a summary of the methodology utilized for our experiments. The net electric power of the wind turbine shall be measured using a power measurement device (e.g. power transducer) and be based on measurements of current and voltage on each phase. The wind speed measurements shall be made with a cup anemometer. The wind direction should be measured with a wind vane. The combined calibration, operation, and orientation uncertainty of the wind direction measurement should be less than 5%. The air density shall be derived from the measurement of air temperature and air pressure. A digital data acquisition system should have a sampling rate per channel of at least 1 Hz to collect measurements and store pre-processed data.

The data acquisition system shall store either sampled data or statistics of data sets as follows:

- mean value;
- standard deviation;
- maximum value;
- minimum value.

Selected data sets shall be based on 1-min periods derived from contiguous measured data. Data sets shall be excluded from the database under the following circumstances:

- external conditions other than wind speed are out of the operating range of the wind turbine;
- turbine cannot operate because of a turbine fault condition;
- turbine is manually shut down or in a test or maintenance operating mode;
- failure or degradation (e.g. due to icing) of test equipment;

- wind direction outside the measurement sector(s);
- wind directions outside valid (complete) site calibration sectors.

The selected data sets, after normalization, shall be sorted using the “method of bins”. The selected data sets shall at least cover a wind speed range extending from 1 m/s below cut-in to 1.5 times the wind speed at 85 % of the rated power of the wind turbine. The database shall be considered complete when:

- each wind speed bin between 1 m/s below cut-in and 14 m/s contains a minimum of 10 min of sampled data,
- the total database contains at least 60 hours of data with the small wind turbine within the wind speed range,
- in the case of furling turbines, the database should include completed wind speed bins characterizing performance when the turbine is furling.

The selected data sets shall be normalized to two reference air densities. One shall be the sea level air density, referring to ISO standard atmosphere (1.225 kg/m<sup>3</sup>). The other shall be the average of the measured air density data at the test site during periods of valid data collection, rounded to the nearest 0.05 kg/m<sup>3</sup>.

The measured power curve is determined by applying the "method of bins" for the normalized data sets, using 0.5 m/s bins and by calculation of the mean values of the normalized wind speed and normalized power output for each wind speed bin. The

The AEP is estimated by applying the measured power curve to different reference wind speed frequency distributions. A Rayleigh distribution, which is identical to a Weibull distribution with a shape factor of 2, shall be used as the reference wind speed frequency distribution. AEP estimations shall be made for hub height annual average wind speeds of 4, 5, 6, 7, 8, 9, 10 and 11 m/s according to the equation:

$$AEP = N_h \sum_{i=1}^N [F(V_i) - F(V_{i-1})] \left( \frac{P_{i-1} + P_i}{2} \right) \quad (1)$$

$$F(V) = 1 - \exp\left(-\frac{\pi}{4} \left(\frac{V}{V_{ave}}\right)^2\right)$$

The next chart (Fig. 4) shows the steps taken when processing and presenting data

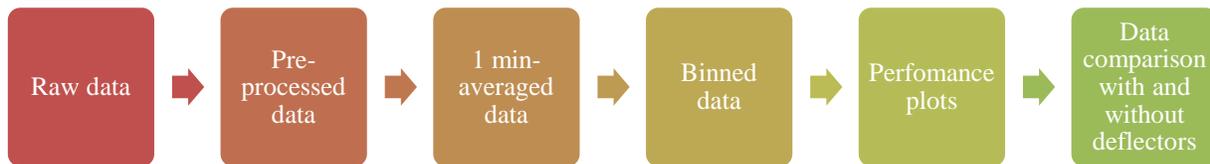


Fig. 4. Flow chart for field test data analysis

### Cost of Energy and Return on Investment

One of the main challenges for wind development is the reduction of the levelized cost of energy (LCOE). When devolving new technologies and innovations this parameter should be estimated to prove the feasibility of the new product. The LCOE is the price of electricity required for a project where revenues would equal costs including return in the invested capital [10]:

$$LCOE = \frac{\sum_t^n \frac{I_t + M_t}{(1+r)^t}}{\sum_t^n \frac{AEP_t}{(1+r)^t}} \quad (2)$$

LCOE = the average lifetime levelized cost of electricity

$I_t$  = investment expenditures in the year t

$M_t$  = operations and maintenance expenditures in the year t

$AEP_t$  = electricity generation in the year t

r = discount rate

n = economic life of the system

The cost of wind turbines vary as a function of project size, region and turbine. Taking a closer look at data from 2013-2014 [11], the regional weighted average of installed costs for onshore wind ranges from \$1280/kW - \$2290/kW. This includes the price of the wind turbine, civil works, grid connection costs, planning and project cost, other capital costs and technology improvement. We estimate the average cost of installed onshore wind as 1700/ kW. Once the wind turbine is installed, the additional costs come in the form of operation and maintenance. The O&M expenditure for both fixed and variable costs can be 20%-25% of the LCOE [11].

By using the formula above for 3 different AEP increase scenarios (3%, 6% and 10%) we are able to estimate the LCOE reduction for a 1.5MW turbine at 40% capacity factor and 7.5% discount rate (Table 1). Both capacity factor and discount rate average values are taken from the 2015 IRENA report [11].

<b>% AEP Increase</b>	3	6	10
<b>% LCOE Reduction</b>	2.2	4.9	8.4

Table 1. LCOE reduction at different AEP increase scenarios for a 1.5MW turbine at 40% capacity factor and 7.5% discount rate

The values shown in the table above will be compared to those values obtained from our wind tunnel and field testing in the next section. However, by using the vortex generators study [1] for a 2.2% AEP increase, the LCOE reduction is about 1.19%. The test results presented in this report shows 3-10% AEP increase, which shows that deflectors benefits are superior to its competitors.

By estimating the dimensions and cost of deflectors for a 1.5MW turbine and using an injection molding method, we find that the cost of producing 1000 deflectors using Polyether Sulfone

Thermoplastic will be about \$80/unit. Using 10 deflectors per turbine blade, the manufacturing cost for a single turbine would be  $30 \times \$80 = \$2,400$ . Using the case study done for vortex generators [1], we can estimate a total cost of \$10,000 for the manufacture and installation of deflectors on each turbine.

To predict the benefits of this technology for different wind farms with different capacity factors, turbine size and discount rates, we have also estimated the deflectors return on investment (ROI) for several cases (Figs. 5-8). The average price for wind energy and LCOE are taken from IRENA 2015 [11] report as \$0.07/kWh and \$0.04/kWh. Fig. 5 show 3 AEP increase cases for a single 1.5 MW turbine at 40% Capacity Factor and 7.5% Discount Rate. An O&M cost of 20% the total cost of the deflectors was estimated over 10 years. The larger the AEP increase, the sooner positives ROIs are generated and the greater the total amount after 10 years. Positive ROIs occur in less than a year for the small 3% AEP increase and just about 5 months for a 10% AEP increase. It is encouraging that for a very small initial investment, the return on investment could multiply by 6 to 25 times the initial invested amount after 10 years.

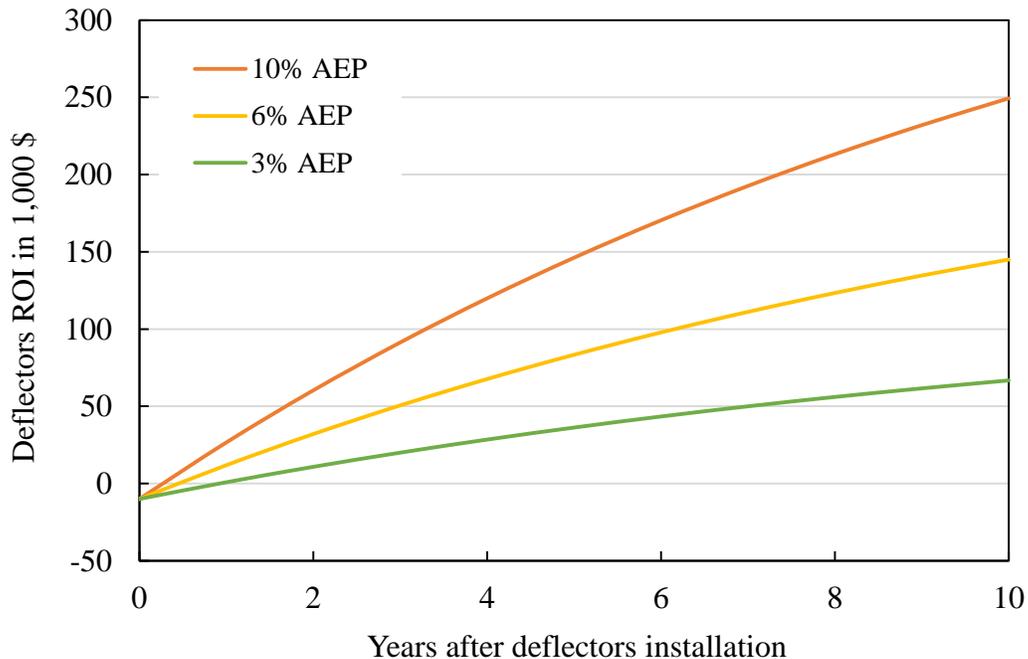


Fig. 5. Deflectors ROI for 3 different AEP increase scenarios for a single 1.5 MW turbine at 40% Capacity Factor and 7.5% Discount Rate

By looking at the change of the discount rate from 5% to 10% (Fig. 6) for a single 1.5 MW turbine at 40% Capacity Factor and 6% AEP increase, ROIs remains similar in the short term, but can add up quickly on time. Differences of more than 10% on cumulative ROIs after 10 years are observed for different discount rates. The smaller the discount rate the bigger returns will be generated on time.

By looking at the capacity factor change from 30% to 50% (Fig. 7) for a single 1.5 MW turbine at 7.5% Discount Rate and 6% AEP increase, bigger ROIs are estimated for larger capacity factors. In addition, shorter times to positive ROIs are expected for larger capacity factors.

By looking at the cumulative ROI as a function of the capacity factor after 10 years for different turbine sizes (Fig. 8) at 7.5% Discount Rate and 6% AEP increase, bigger ROIs are estimated for larger capacity factors and larger turbines.

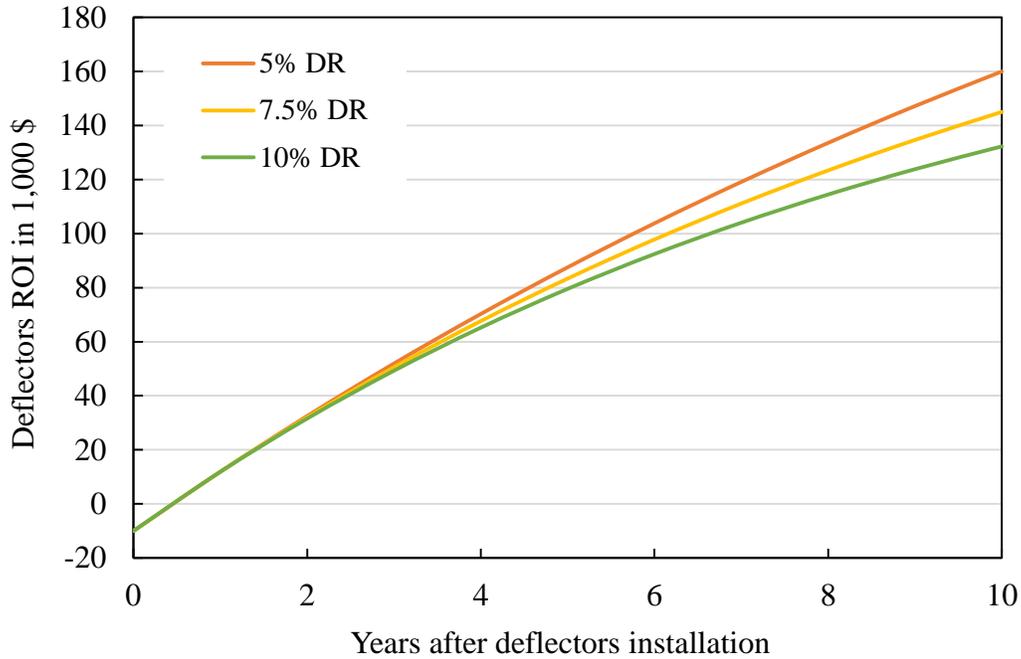


Fig. 6. Deflectors ROI for 3 different discount rates for a single 1.5 MW turbine at 40% Capacity Factor and 6% AEP increase

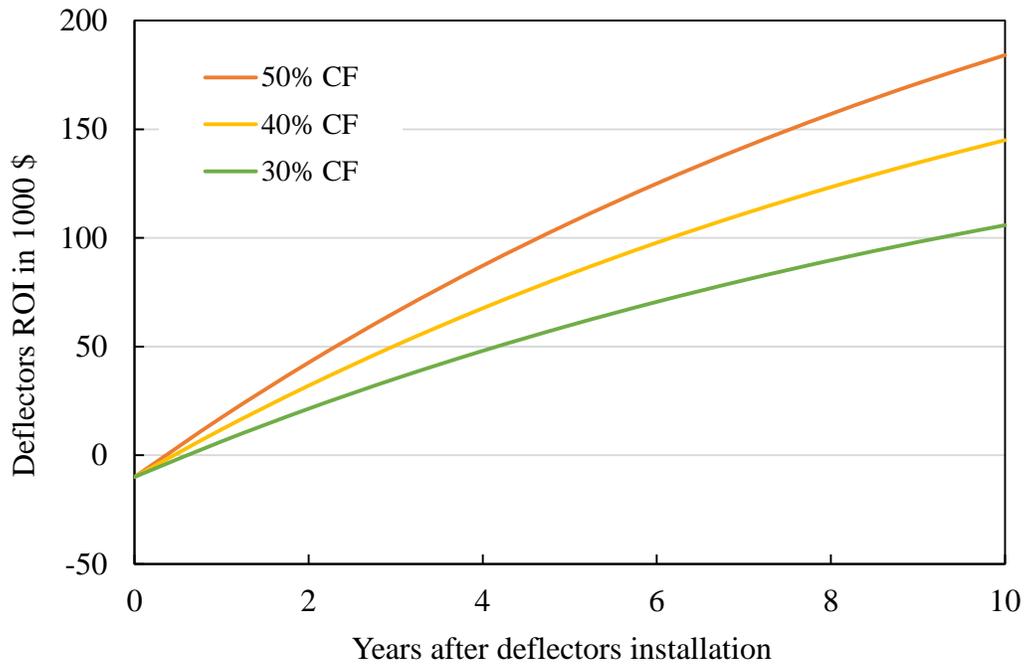


Fig. 7. Deflectors ROI for 3 different capacity factors for a single 1.5 MW turbine at 7.5% discount rate and 6% AEP increase

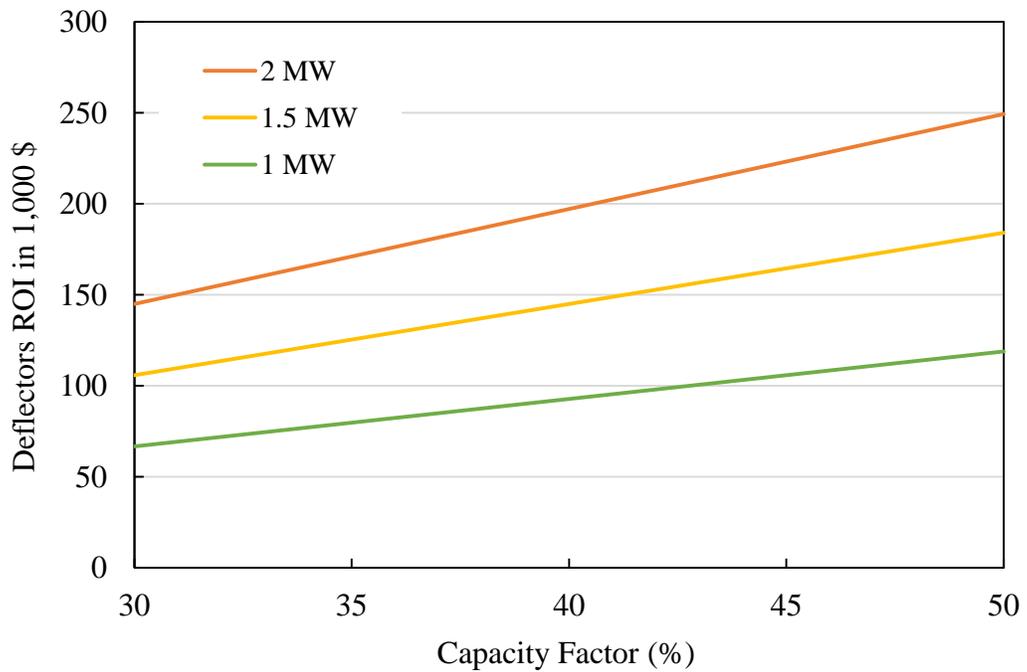


Fig. 8. Deflectors ROI after 10 years as a function of the capacity factor for 3 different turbine sizes at a 7.5% discount rate and 6% AEP increase

When applied to wind farms, the study above gives an estimate of the profitability and ROIs of the wind farm with time thanks to the deflectors. For instance, if 100 turbines of 1.5MW were retrofitted with our technology to gain a 6% AEP increase, an extra 10 to 18 million dollars would be generated by the wind farm thanks to the deflectors (an initial investment of 1 million dollars would be paid for the retrofitting service). This could represent a great opportunity to acquire more customers by reducing the price of the wind farm energy.

#### Wind tunnel test: Rutgers University

The wind tunnel experiments were conducted at the wind tunnel facility inside the Mechanical and Aerospace Engineering department at Rutgers University. Fig. 9 shows the wind turbine mounted in the wind tunnel. Wind tunnel speeds from 3 to 6 m/s were tested. A load cell was used to measure the torque and an rpm hall sensor was used to measure the rpm. The power is then calculated by multiplying both torque and rpm.

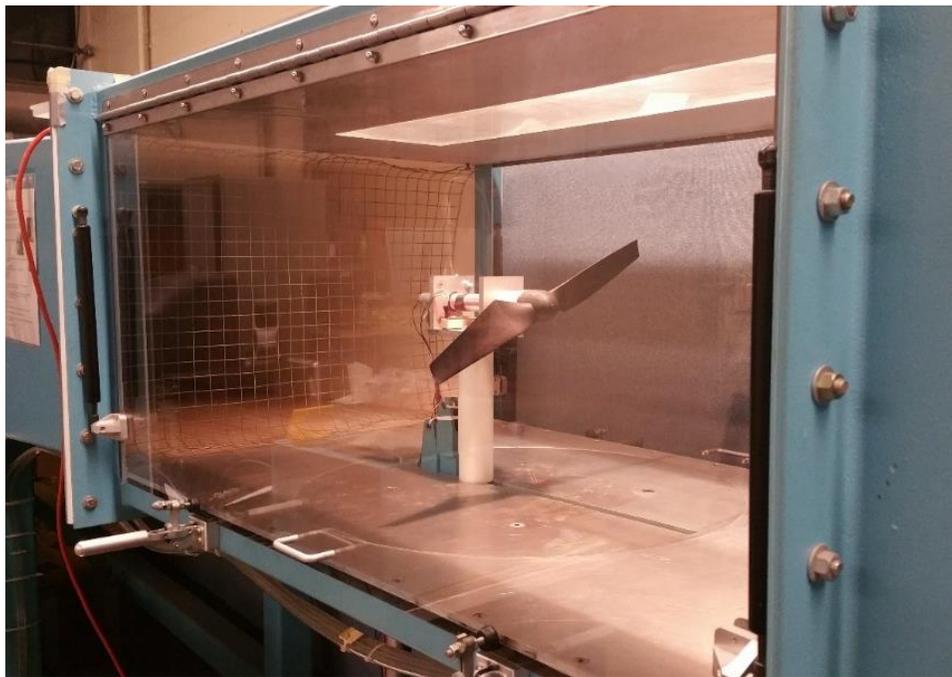


Fig. 9. Wind turbine mounted in the wind tunnel

The experiments produced an average 10% power increase as shown in Fig. 10. This figure shows the power performance of the turbine with and without deflectors. An average 10% power coefficient ( $C_p = 2P / (\rho V^3 A)$ ) increase is shown for different tip speed ratios ( $\lambda = \Omega R / V$ ) and wind tunnel velocities ( $V$ ). This wind tunnel test supports our preliminary results and establishes a strong case from which we are certain that the proposed technology will be successful.

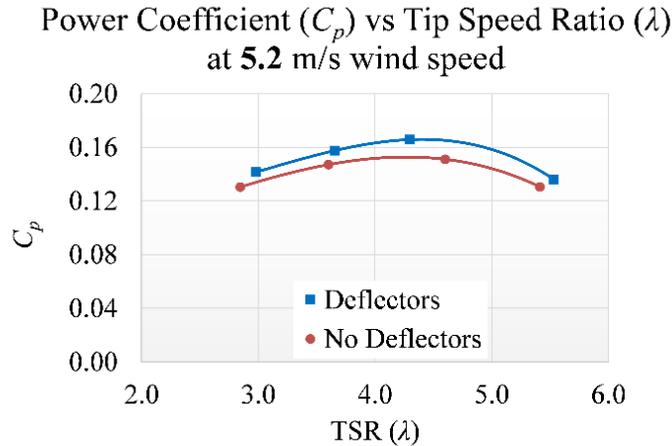


Fig. 10. Power coefficient ( $C_p$ ) versus tip speed ratio ( $\lambda$ ) showing the power performance increase when installing flow deflectors on the blades

### Field test: Appalachian State University

#### *Deflectors design, manufacture and adhesion*

The deflectors were designed based on the blade airfoil shape of the turbine. This ensures maximum adhesion to the blade. The wind turbine selected was the Whisper 100 which had an unknown blade shape. Two methods were used to quantify its shape. A contour gauge was first used to determine the shape of the suction and pressure sides. The shape was determined at several radial locations where deflectors are to be placed and an average non-dimensional airfoil shape was used for the design. An online digitizing application, 'web plot digitizer' [12] was used to generate the shape outline.

To verify the accuracy of the contour gauge we gain access to robotic arm laser scanner CMM available at the Rutgers MAE measurements laboratory. The laser scanner when triggered shoots a laser line segment which contains several laser beams and based on the reflection of the laser beams and the position and orientation of the robotic arms, it calculates and records where solid surface reflects the beam. The locations on the blades were marked where the deflectors were to be attached and the blade was firmly fixed to a table on which the robot arm was also fixed. The laser was triggered around the markers and each file for each marker location was saved individually. The file generated using this method contained the x, y and z co-ordinates of thousands of points and other data identifying those coordinates. Those points were post-processed to eliminate outliers and reflections from surfaces other than the blade. To do this, a python code was programmed to delete outliers and averaged the values of all other points so that a clean and precise airfoil surface curve was obtained. This program was run for all deflector's locations. The result was that each airfoil curve was transformed into 100 equidistant chord-wise locations which were copied into an excel file where they were compared to curves obtained using the contour gauge technique. Both methods agreed within 5-10% for all cases. For its simplicity, the contour gauge gives enough accuracy while extremely reducing the measurement time.

A SolidWorks CAD model was then developed with the carefully designed shape of the deflectors for the Whisper 100. Finally, the 3D printing service at Rutgers University was used to manufacture the deflectors.

Calculation of the maximum forces expected on the deflectors is necessary to select a method of adhesion that would be strong enough to hold the deflectors in place under the action of all the forces. Several double side tapes and adhesive promoters were selected and tested from NITTO and 3M to evaluate the bonding properties between deflector and blade. Adhesion strength of double sided tapes varies depending on the material of the substrates to be bonded and the double side tape material. All selected tapes for testing had a much greater stress resistance than the expected maximum stresses on the deflectors (see Table 2). The tests were done by attaching deflectors onto a turbine blade and rotating them using a motor to simulate the forces in real working situations. Results showed that all selected double side tapes worked at all rpms and did not detached during the experiments. In fact it was hard to detach most of them. Moreover, much stronger bonding was found when using adhesive promoter on the surfaces before attaching the double side tape. In this case, the deflectors was extremely hard to remove, requiring a knife tool to remove them.

Tape Name	Test result	Peel force (N/cm)	Shear stress (kPa)	Tensile stress (kPa)	Thickness (mm)
3M Solar Acrylic Foam Tape 4063	Pass	30 at 90 <sup>0</sup>	620	620	0.64
3M 4110	Pass	35 at 90 <sup>0</sup>	550	620	1.1
3M VHB 4941F	Pass	39 at 90 <sup>0</sup>	480	590	1.14
Nitto H 7012	Pass	18 at 90 <sup>0</sup>	131	–	1.2
Nitto 541	Pass	6.2 at 180 <sup>0</sup>	625	–	0.75
Nitto 5300 VR	Pass	15 at 180 <sup>0</sup>	2312 850	–	0.14
Nitto 5000 NS	Pass	8 at 180 <sup>0</sup>	1125	–	0.16

Table 2. Double side tapes peeling force and shear stresses resistances. Test result “Pass” stand for no detachment of deflector during the experiment

*Field Test: Appalachian State University*

The deflectors were tested at the Appalachian State University Small Wind Research and Demonstration Site on Beech Mountain, NC. As shown on the NC wind map below in Fig. 11, the site is 1556 m above sea level with an annual average wind speed of approximately 7 m/s at 30 m.

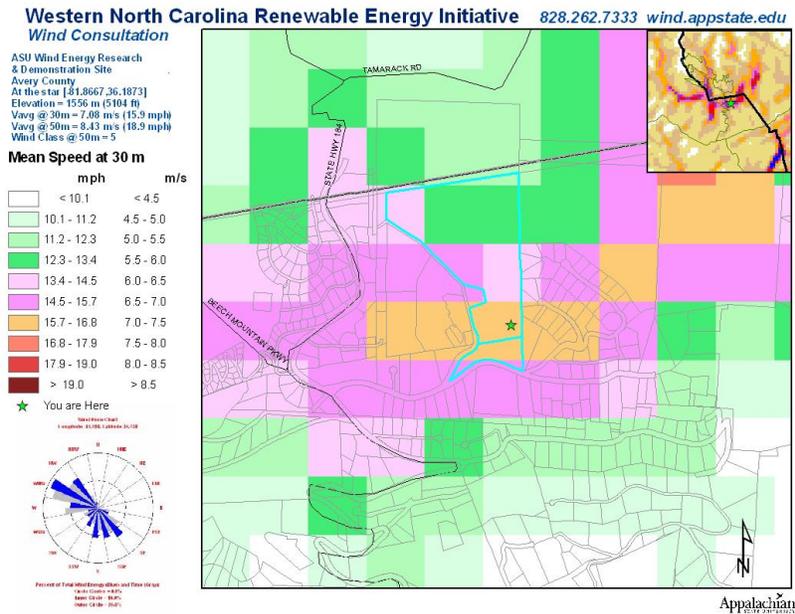


Fig. 11. Beech Mountain average wind speed at 30m (Courtesy of Appalachian State University)

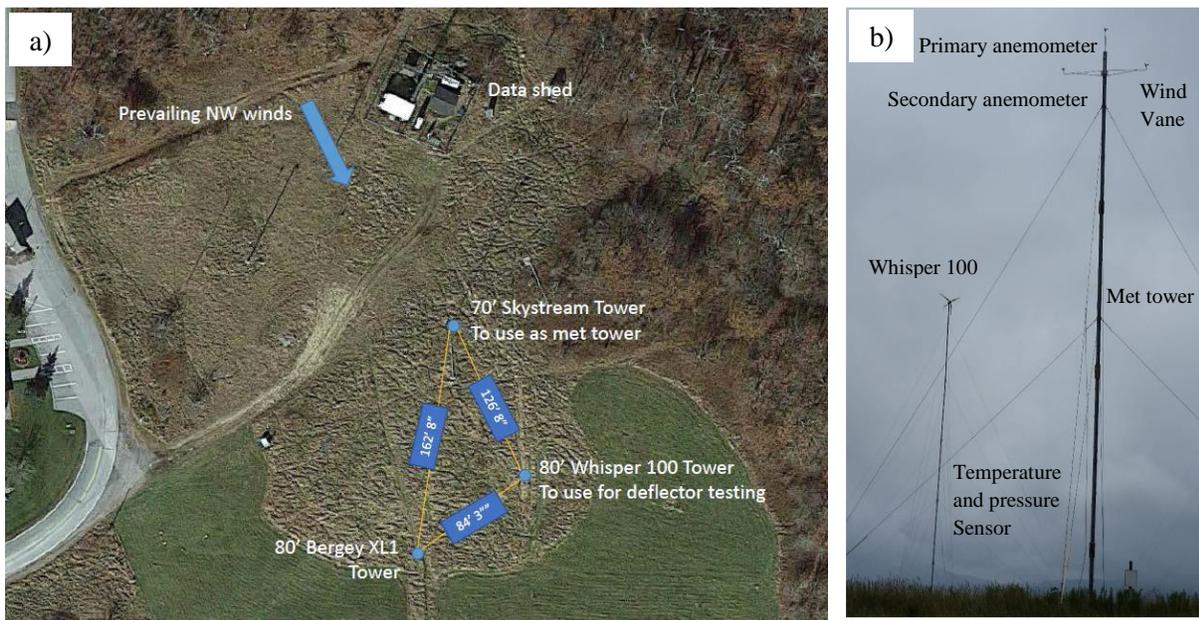


Fig. 12. a) Beech Mountain test site top view and b) test setup (Courtesy of Appalachian State University)

A 70' tilting tower was used to raise the meteorological sensors used for in this test. The Whisper 100 tower was located at 35m from the meteorological tower. Fig. 12 shows the top view of the site layout (a) and the test instrumentation setup (b).

The primary anemometer used for the test was an NRG #40C mounted at 73' above grade. A reference NRG #40C was installed 5' feet below the primary at 68' above grade. An NRG 200P vane was also installed at the 68' height. IEC 61400-12-1 Annex G was used for the layout.

During the full measurement period, the mean wind speed of the primary was 4.48 m/s and the mean of the reference anemometer was 4.24 m/s. After the deflectors were installed, a second reference NRG #40C was installed on the Whisper 100 tower at a height of 72' above grade with a hypothesis that the readings would be slightly lower than the primary wind speed. During the post-deflector measurement period, the mean wind speed of the primary was 5.38 m/s and the mean of the Whisper reference anemometer was 5.21 m/s. Temperature was measured by a 110S with radiation shield, mounted at the base of the Whisper tower at a height of 2 m. RPM was measured using a low voltage wind turbine speed sensor (WTSS-LV) from APRS World. Power was measured using an Ohio Semitronics power transducer. Reference power was measured by measuring DC amps and volts using CR Magnetics transducers, calculating power in the logger program. Data was logged on a Campbell Scientific CR3000, sampled at 1 Hz with 1-minute averages.

The test consisted in measuring power performance for the Whisper 100 turbine with and without deflectors for about 1 month to compare and analyze efficiency improvements. Data was collected for 2 weeks before deflectors were installed. This represented the baseline of the Whisper 100 performance at Beech Mountain. Then, the turbine tower was lowered to install the custom designed deflectors on the turbine blades. After that, the turbine tower was raised and data was collected for another 2 weeks.

The primary wind speed 1-min average ranged from 0 to 14.7 m/s during the whole test. The max wind speed was 20.2 m/s. The primary wind speed appeared to correlate with the reference anemometers with some minor divergence at high wind speeds. According to IEC 61400-12-1 Annex H, the usable data should include voltages of 50.4 VDC +/- 5% or 47.9 to 52.9 VDC. The load voltage data was confirmed to lay within that range and few outliers were excluded. Winds from 150° (130° -170°) were excluded from the data set for wind that passed through the turbine before reaching the primary anemometer. Power was normalized to standard sea-level conditions to eliminate the effect of temperature and pressure on air density and thus power.

Fig. 13 shows the measured power coefficient curve corrected by density for the Whisper 100 turbine with and without deflectors at different wind speeds. The blue line (blade with retrofitted deflectors) is always above the red line indicating power improvements for a broad range of operational wind speeds. The maximum  $C_p$  improvement occurs at 8 m/s with a 20% power increase (from 0.25 to 0.30). The average  $C_p$  improvement is 7.7% over the whole curve.

To measure the effect of the power increase on the potential increase in energy to be produced in a year, the AEP was calculated for both cases with and without deflectors as explained in the *Power Performance* section above. Fig. 14 shows the calculated AEP for both cases at different site average wind speeds. The maximum AEP improvement occurs at 4 m/s with an 11.4% AEP increase (see Fig. 15). The minimum AEP improvement is 8.7% at 11 m/s.

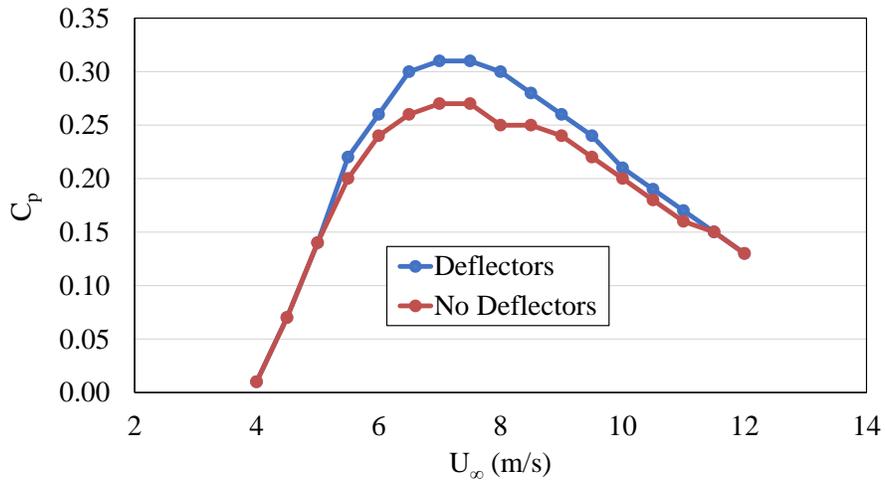


Fig. 13. Whisper 100 wind turbine density corrected power coefficient at different wind speeds for both configurations with and without deflectors.

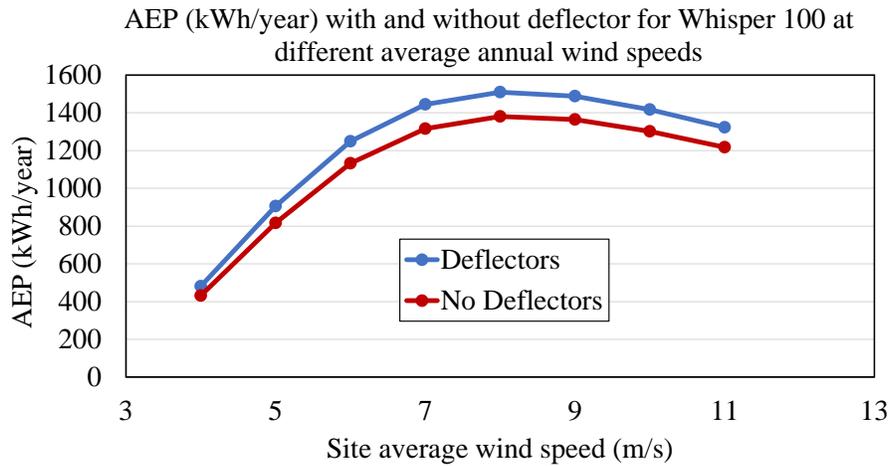


Fig. 14. Whisper 100 wind turbine AEP at different site average wind speeds for both configurations with and without deflectors.

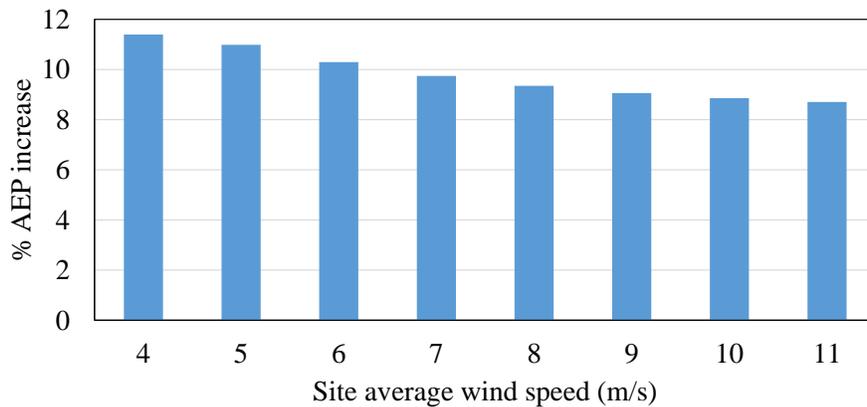


Fig. 15. Whisper 100 wind turbine AEP increase at different site average wind speeds with and without deflectors

## FINDINGS

### *Wind Tunnel Test: Rutgers University*

- An average 10% power increase was observed when using aerodynamic deflectors
- Power improvement depends on the operational wind speed and tip speed ratio

### *Whisper 100 field test: Appalachian State University*

- Maximum  $C_p$  improvement was observed at 8 m/s from 0.25 to 0.30 (20%). The average  $C_p$  improvement was 7.7%
- A maximum 11.4% AEP improvement is estimated for a site with annual average wind speed of 4 m/s. A minimum 8.7% AEP improvement is estimated at a site with average winds of 11 m/s

## CONCLUSION

The innovation proposed in this paper has the potential to address both the efficiency demands of wind farm owners as well as to provide a disruptive design innovation to turbine manufacturers. The aerodynamic deflector technology was created to improve the efficiency of any current wind turbine around the world and to be included with new blade designs. To prove the feasibility of the deflectors, two tests have been done during this project for two different wind turbines.

The first test was performed at the wind tunnel facility at Rutgers University. Two identical wind turbines were 3D printed, one with deflectors on its blades and the other one without deflectors. Power coefficient curves were calculated to show the performance improvement when using deflectors. An average  $C_p$  improvement of 10% was observed during this test.

The second test was performed on the Whisper 100 turbine at the Wind Application Center at Appalachian State University. The turbine performance was measured without deflectors for 2 weeks. Then, the turbine was retrofitted with deflectors and its power performance was measured for another 2 weeks. Power coefficient curves were calculated to show the performance improvement when using deflectors. An average  $C_p$  improvement of 7.7% was observed during this test. The estimated AEP increase was between 8.7 to 11.4 %.

All test show important improvements in power performance and AEP. This technology could represent the biggest wind turbine aerodynamic improvement in the last decade and a game changer to the wind energy industry since even 2% AEP improvement allows wind farm profits to raise by 8%.

## **RECOMMENDATIONS**

Only two experiments have been performed at the Rutgers University Wind Tunnel Facility and Appalachian State University to measure power improvements for this novel technology. Several tests and simulations need to be done to further proof-the-concept before entering the market due to the technical challenges as weather conditions and times needed to obtain reliable power curves. The suitable aerodynamic shape and location of the deflectors can have a broad impact. An erroneous shape or location of the deflectors can have a negative impact to power generation. Therefore, full-scale CFD simulations should be done simultaneously with future experiments to find optimal shapes and locations of the deflectors to generate maximum power output. CFD simulations are also needed to avoid higher costs associated with the trial-error nature of the experiments.

Briefly, long periods of larger scale testing should be done together with CFD simulations to quantify the deflector's performance and evaluate its commercial viability in larger scale turbines (>10m diameter). Typically, 2-3 months field turbine operation would be needed to certify this type of turbine. Next, a full scale test (>100 meter diameter) should be done. In addition, CFD simulations will be performed to evaluate and validate the deflector's performance in full scale turbines (10-100m diameter). Typically more than 6 months of turbine operation would be needed to certify the power performance of this type of turbine.

## REFERENCES

- [1] UpWind Solutions, “Proving the Value of Vortex Generators,” 2015.
- [2] T. Burton, *Wind energy handbook*. Chichester; New York: Wiley, 2011.
- [3] A. Villegas, Y. Cheng, V. del Campo, and F. J. Diez, “Characterization of Low Reynolds Number Wind Turbine Aerodynamics by BEM Theory and PIV Measurements,” in *ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting*, 2010.
- [4] A. Villegas and F. J. Diez, “Evaluation of unsteady pressure fields and forces in rotating airfoils from time-resolved PIV,” *Exp. Fluids*, vol. 55, no. 4, pp. 1–17, 2014.
- [5] A. Villegas and F. J. Diez, “On the quasi-instantaneous aerodynamic load and pressure field measurements on turbines by non-intrusive PIV,” *Renew. Energy*, vol. 63, pp. 181–193, 2014.
- [6] M. O. . Hansen, *Aerodynamics of wind turbines*. Earthscan/James & James, 2008.
- [7] H. Hirahara, M. Z. Hossain, M. Kawahashi, and Y. Nonomura, “Testing basic performance of a very small wind turbine designed for multi-purposes,” *Renew. Energy*, vol. 30, no. 8, pp. 1279–1297, 2005.
- [8] D. Micallef, G. van Bussel, C. S. Ferreira, and T. Sant, “An investigation of radial velocities for a horizontal axis wind turbine in axial and yawed flows: An investigation of spanwise velocities for a HAWT,” *Wind Energy*, vol. 16, no. 4, pp. 529–544, May 2013.
- [9] W. Turbines, “Part 12-1: Power performance measurements of electricity producing wind turbines; IEC TC/SC 88,” IEC 61400-12-1, 2005.
- [10] IRENA, “RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES (Wind Power),” Jun. 2012.
- [11] IRENA, “RENEWABLE POWER GENERATION COSTS IN 2014,” Jan. 2015.
- [12] “Web plot digitalizer.” [Online]. Available: <http://arohatgi.info/WebPlotDigitizer/>.