To justify the economic viability of a potential offshore wind energy project, an accurate assessment of the site-specific wind resource, thus expected energy yield, is required prior to wind farm construction. Unfortunately, uncertainties during this assessment exist, due in-part to limited offshore wind measurements throughout a turbine’s rotor-layer (~40-200m) and related uncertainties predicting a turbine’s available power. To better understand these uncertainties in the Mid-Atlantic USA, Doppler wind lidar and other met-ocean measurements were collected offshore within Maryland’s Wind Energy Area from July-August 2013. Given the diversity of vertical wind speed profile (VWP) observations, VWPs are classified based on the goodness-of-fit to several mathematical expressions. Results demonstrate VWP classification is dependent on the temporal and spatial resolution of analysis, however for 10-min VWP types (40-220m), low-level wind maximum are the most frequent (~37%), while only ~17% resemble industry-standard logarithmic-like, power law wind profiles. In addition, VWP variability is related to prevailing wind direction (i.e. offshore fetch), as more unexpected VWPs are found during wind regimes flowing from land to sea, while power-law profiles persist during northeasterly flow. In terms of potential impact on a wind turbine’s available power, unexpected VWP types are associated with greater variability in superimposed meteorological features demonstrated to impact turbine performance, therefore the importance of predicting such variability cannot be understated. Finally, the sensitivity of VWP type on several techniques used to estimate a turbine’s available power are demonstrated, elucidating how both an overestimate and underestimate of traditional hub-height available power may occur given distinct VWP type and power assessment technique employed; therefore, a possible concern for the offshore wind energy industry in the Mid-Atlantic USA.
Classifying Vertical Wind Speed Profiles for Offshore Wind Resource and Power Assessment

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Ph.D. Candidate
Geography & Environmental Systems
University of Maryland Baltimore County (UMBC)

Atmospheric Lidar Group:
Shelbi Tippett, Scott Rabenhorst, Ruben Delgado
Motivation: Wind Farm Underperformance Bias

- Operational energy yield $< \text{expected energy yield}$
- Early 2000s, wind farm underperformance gains spotlight
- "haircut" phenomenon
- Investors/lenders began correcting energy projections (AWS Truepower 2015)

Research Focus
Uncertainty: Turbine Power Curve

**Rotor Equivalent Wind (REW)** term introduced to account for wind characteristics throughout a turbine’s rotor layer.

- May reduce uncertainty in turbine’s power curve measurements

![Wind Speed vs Height Graph](image)

- Sumner and Masson 2006
- Choukulkar et al. 2015

**PowerEstimate** = 0.5 * \( \rho \) * \( A \) * \( \bar{U}^3 \) * \( C_p \)

- \( \rho \) = air density
- \( A \) = area of rotor layer
- \( \bar{U} \) = hub-height, wind-speed
- \( C_p \) = power coefficient

\[ \begin{align*}
&\bar{U}_1 = \text{Wind Speed (m/s)} \\
&\bar{U}_2 \\
&\bar{U}_3 \\
&\bar{U}_4 \\
&\bar{U}_5 \\
&\bar{U}_6 \\
&\bar{U}_7 \\
\end{align*} \]
Atmospheric stability can fluctuate between neutral to unstable to stable conditions, thereby changing the 'shape' of the wind profile.

- Severe lack of met-ocean measurements

Uncertainties:

Turbine Power Curve ↔ Wind Resource

Need to measure & predict unexpected VWP shapes to utilize REW power estimate tools

- Atmospheric stability can fluctuate between neutral to unstable to stable conditions, thereby changing the 'shape' of the wind profile.
Overview: Maryland Offshore Campaign

- 2013 July-August Offshore Measurements
  - During MEA sponsored Geophysical Survey
  - Leosphere Windcube V2 Offshore
    - Wind speed/direction 40m-220m

Research Questions:

1. How do measurements compare to traditional wind resource estimates?
2. What is the variability in the shape of vertical wind speed profiles (VWPs)?
3. Are there relationships between VWP shape and met conditions?
4. How do available power estimates vary by VWP shape?
Methodology

- Classifying **Vertical Wind Profiles**:

  - **Type I**: Power law Fit (+)
  - **Type II**: Linear Fit
  - **Type III**: Power law Fit (-)
  - **Type IV**: Fourier Fit (2 term)

**Based on goodness of fit:**

- Criteria: $\text{RSS} \leq 0.10$

\[
\text{RSS} = \sum_{i=1}^{10} (u_{fit}(z_i) - u_i)^2
\]

where $h$ is the number of measurement heights, $u_{fit}$ are the fit functions and $u_i$ is the lidar wind speed measurement at height $z_i$ ($i=1-h$).

**Type I**: Power law Fit (+)
**Type II**: Linear Fit
**Type III**: Power law Fit (-)
**Type VI**: Fourier Fit (2 term)

**Based on Max & Min Wind Speed Height:**

- **Type IV**: Low-Level Wind Min (LLWMin)
- **Type V**: Low-Level Wind Max (LLWMax)
Methodology

- Investigating VWP Type & Local Meteorological Conditions:
  - Buoy 44009
  - Buoy BTHD1
  - Air Temperature
  - SST
  - MSLP
  - Wind Speed

July-Aug 2013: Buoy 44009 Analysis

July-Aug 2013: Mesoscale Analysis

STAY TUNED
Methodology

VWP Type & Turbine Available Power Assessment:

-NREL 5 MW Offshore Wind Reference Turbine

\[ P_W = 0.5\rho A \overline{U}^3 C_p \]

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \overline{U}_{100m} )</td>
<td>Lidar hub-height measurements</td>
</tr>
<tr>
<td>( \overline{U}_{Disk} )</td>
<td>Area averaged wind speed across entire rotor-layer</td>
</tr>
<tr>
<td>( \overline{U}_{TI} )</td>
<td>Modified ( U_{EQ} ) to account for weighted speed shear &amp; turbulence (TI)</td>
</tr>
<tr>
<td>( \overline{U}_{TID} )</td>
<td>Modified ( U_{EQ, TI} ) to account for direction shear &amp; fluctuations</td>
</tr>
</tbody>
</table>

\[ \overline{U}_{Disk} = \frac{2}{A_t} \int_{H-r}^{H+r} U(z)(r^2 - H^2 + 2Hz - z^2)^{1/2} \delta z \]

where

- \( A_t = \) total rotor area
- \( H = 100m \) hub height,
- \( r = \) rotor radius,
- \( z = \) height, \( \delta z = 20 \)

\[ \overline{U}_{TI} = \sqrt[3]{ \frac{1}{A} \sum_i U_i^3 \cdot A_i } \]

where \( U_i(z) = \overline{U}_i \left( 1 + 3 \left( \frac{\sigma_{ui}}{U_i} \right)^2 \right)^{1/3} \)

Modified \( U_{EQ} \) to account for weighted speed shear & turbulence (TI)

\[ \overline{U}_{TID} = \sqrt[3]{ \frac{1}{A} \sum_{i=1}^{N} U_i^3 \left[ 1 + 3 \left( \frac{\sigma_{ui}}{U_i} \right)^2 \right] \left[ 1 - \frac{\hat{\theta}_i^2}{2} - \frac{\sigma_{\theta i}^2}{2} \right]^3 A_i } \]

where \( \hat{\theta}_i \) is the difference of wind direction at a specific height (i) (compared to 100m direction)
Results: 100m Lidar WS vs. Buoy 44009

- Buoy 44009 **underestimates** wind speed

Power Law Equation:

\[
\frac{\bar{U}_{100m}}{\bar{U}_{5m}} = \left( \frac{100m}{5m} \right)^{0.11}
\]

<table>
<thead>
<tr>
<th>July17-August 30 Average</th>
<th>Median Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{U}_{100m} )</td>
<td>7.40 (+/- 3.29)</td>
</tr>
<tr>
<td>( \bar{U}_{Ext.Buoy} )</td>
<td>4.73 (+/-3.34)</td>
</tr>
</tbody>
</table>
Results: 100m Lidar WS vs. Model/Reanalysis

- Models’ **underestimate** wind speed resource
- Moderate model error in wind direction
Results: VWP Classification

- 40-160m VWP Types (10-min & hourly) → mostly Type I (power law)
- 40-220m VWP Types (10-min & hourly) → mostly Type V & VI

<table>
<thead>
<tr>
<th>VWP Class</th>
<th>10-Minute Average</th>
<th>Hourly Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Total (40-160m)</td>
<td>% Total (40-220m)</td>
</tr>
<tr>
<td>unclassified</td>
<td>0.2%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Type I</td>
<td>31.7%</td>
<td>17.0%</td>
</tr>
<tr>
<td>Type II</td>
<td>14.8%</td>
<td>13.7%</td>
</tr>
<tr>
<td>Type III</td>
<td>6.1%</td>
<td>2.6%</td>
</tr>
<tr>
<td>Type IV</td>
<td>5.8%</td>
<td>8.5%</td>
</tr>
<tr>
<td>Type V</td>
<td>26.8%</td>
<td>36.9%</td>
</tr>
<tr>
<td>Type VI</td>
<td>14.7%</td>
<td>19.0%</td>
</tr>
</tbody>
</table>
Results: VWP Types & 100m Wind Stats

10-Min VWP Type I (100m) 10-Min VWP Type II (100m) 10-Min VWP Type III (100m)

10-Min VWP Type IV (100m) 10-Min VWP Type V (100m) 10-Min VWP Type VI (100m)
### Results: VWP Classification & 100m Wind

<table>
<thead>
<tr>
<th>VWP Type (hourly)</th>
<th>Offshore Windcube V2 100m (Median)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wind Speed (m/s)</td>
</tr>
<tr>
<td>I, II, III</td>
<td>6.03 m/s (+/- 3.10)</td>
</tr>
<tr>
<td>IV, V, VI</td>
<td>6.98 m/s (+/- 3.36)</td>
</tr>
</tbody>
</table>

- **Unexpected VWP Types IV-VI (compared to Types I-III):**
  - higher wind speed
  - stronger SW wind component
## Results: VWP Classification & Buoy 44009

<table>
<thead>
<tr>
<th>VWP Type (40/60mins)</th>
<th>Hourly Buoy 44009 (Median)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SST (C)</td>
</tr>
<tr>
<td>I, II, II</td>
<td>22.95 (+/- 1.32)</td>
</tr>
<tr>
<td>IV, V, VI</td>
<td>23.20 (+/- 1.31)</td>
</tr>
</tbody>
</table>

- Unexpected VWP Types IV-VI (compared to Types I-III):
  - warmer SST
  - warmer air mass
  - higher (stable) Air T- SST values
Results: Turbine Available Power Assessment

- On average, hub-height available power higher than other techniques
- Suggests traditional $\bar{U}_{100m}$ estimate may overestimate wind resource

<table>
<thead>
<tr>
<th>24hr Median $\Delta \bar{U}_{100m}$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{U}_{\text{Ext.Buoy100m}}$</td>
</tr>
<tr>
<td>$\bar{U}_{\text{Disk}}$</td>
</tr>
<tr>
<td>$\bar{U}_{TI}$</td>
</tr>
<tr>
<td>$\bar{U}_{TID}$</td>
</tr>
</tbody>
</table>
Results: VWP Type & Turbine Available Power

- Unexpected Types IV-VI  $\rightarrow$ greatest $\Delta$ from $\overline{U}_{100m}$
- Unexpected Types IV-VI  $\rightarrow$ highest $\sigma$ between power assessment
Summary/Next Steps

- Unexpected Types IV-VI related to higher hub-height wind speed, SW flow, warmer air mass & stable conditions (sfc)

- Buoy extrapolated wind estimates underestimates wind resource; however hub-height wind power assessment overestimates available power (compared to REW)

- $\Delta$ between power assessment techniques higher for unexpected VWP Type IV-VI

- Classifying VWPs useful tool for understanding local wind resource & potential impact on turbine available power assessment

Next Step:

- Similar analysis using REAL turbine data (Lewes, DE: VERTEX Campaign Sept/Oct 2016)
- VWP climatology in Ocean City, MD
Thank you! Questions?

Acknowledgements:
Maryland Energy Administration, 2014-2015 JCET Fellowship, NOAA-CREST, Cristina Archer (UD), Leosphere/Renewable NRG Systems, CB&I/Coastal Planning and Engineering Environmental and Infrastructure
References


EXTRA
**Uncertainty: Offshore Wind Resource**

- Coastal atmospheric boundary layer (CABL) may be dynamic, thus VWP shape *may deviate significantly from theory*

**Warm Air Flow Over Cooler Water**

- Can occur ~ 200km offshore (Frank et al. 2000)
- Drives acceleration in surface flow $\rightarrow$ internal boundary layers $\rightarrow$ Low-Level Jets

**Kettle (2014):**

- Classified 10-min average VWP
- ~25%
- ~44%

**Mahrt et al. (2014):**

- Weakly stable offshore (afternoon)
- Moderately stable offshore (morning)
- Very stable offshore (mid-day)

*Need to measure & predict unexpected VWP shapes to utilize REW power estimate tools*
Results: VWP Type & Turbine Available Power

- Type vs. $\Delta$ wind direction with respect to turbine hub-height

- Type IV-VI associated with greatest $\Delta$ in wind direction throughout rotor-layer
Results: VWP Type & Turbine Available Power

- Type vs. Δ wind direction with respect to turbine hub-height

- Type IV-VI associated with greatest Δ in wind speed throughout rotor-layer
# Windcube hub-height stats

<table>
<thead>
<tr>
<th>Type (10-min 40-220m)</th>
<th>Wind Speed</th>
<th>Windcube V2 (100m)</th>
<th>Wind Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Median</td>
<td>σ</td>
</tr>
<tr>
<td>I</td>
<td>6.968</td>
<td>6.788</td>
<td>3.050</td>
</tr>
<tr>
<td>II</td>
<td>6.227</td>
<td>5.794</td>
<td>3.071</td>
</tr>
<tr>
<td>III</td>
<td>4.136</td>
<td>4.136</td>
<td>2.569</td>
</tr>
<tr>
<td>IV</td>
<td>4.388</td>
<td>3.517</td>
<td>2.961</td>
</tr>
<tr>
<td>V</td>
<td>7.737</td>
<td>7.602</td>
<td>3.109</td>
</tr>
<tr>
<td>VI</td>
<td>7.313</td>
<td>7.091</td>
<td>3.396</td>
</tr>
<tr>
<td>VWP Classification</td>
<td>Fit /Expression</td>
<td>Criteria</td>
<td></td>
</tr>
<tr>
<td>--------------------</td>
<td>-----------------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td>Type 0</td>
<td>Unclassified</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Type I             | $u_{fit}(z) = u_{hub} \left(\frac{z}{z_{hub}}\right)^{\alpha_{fit}}$ | $RSS \leq 0.10$  
|                    |                 | $\alpha_{fit} = \text{positive (+)}$  |
| Type II            | $f(x) = mx + b$ | $RSS \leq 0.10$  |
| Type III           | $u_{fit}(z) = u_{hub} \left(\frac{z}{z_{hub}}\right)^{\alpha_{fit}}$ | $RSS \leq 0.10$  
|                    |                 | $\alpha_{fit} = \text{negative (-)}$  |
| Type IV            | Low-Level Wind Min (LLWMin)  
40m $> Min\_U_z < 220m$ |          |
| Type V             | Low-Level Wind Max (LLWMax)  
40m $> Max\_U_z < 220m$ |          |
| Type VI            | $f(x) = a_0 + a1 \cdot \cos(x \cdot w)$  
$b1 \cdot \sin(x \cdot w) +$  
$a2 \cdot \cos(2 \cdot x \cdot w) +$  
$b2 \cdot \sin(2 \cdot x \cdot w)$ | $RSS \leq 0.10$  |
Results: Campaign Average Hub-Height & Buoy 44009 Wind

WindcubeV2 Offshore 100m Median (July 17-August 31, 2013)

Day: 6AM-8PM Median: 6.34 m/s, 219.53
Night(8PM-6AM) Median: 6.88 m/s, 233.18
Results: VWP Classification vs. Buoy 44009

- Criteria for ‘dominant’ 10-min VWP Type per buoy hour
## Buoy 44009 vs. VWP Type stats

<table>
<thead>
<tr>
<th>Type</th>
<th>SST (C)</th>
<th>Air T (C)</th>
<th>Air T- SST (C)</th>
<th>MSLP (hPa)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>unclassified</td>
<td>24.10</td>
<td>24.60</td>
<td>0.50</td>
<td>1014</td>
<td>6.50</td>
</tr>
<tr>
<td>I</td>
<td>23.15</td>
<td>22.50</td>
<td>-0.70</td>
<td>1015.6</td>
<td>4.10</td>
</tr>
<tr>
<td>II</td>
<td>22.50</td>
<td>22.40</td>
<td>-1.10</td>
<td>1015.7</td>
<td>2.30</td>
</tr>
<tr>
<td>III</td>
<td>23.50</td>
<td>22.50</td>
<td>-1</td>
<td>1022</td>
<td>N/A</td>
</tr>
<tr>
<td>IV</td>
<td>23.65</td>
<td>23.25</td>
<td>0</td>
<td>1014.6</td>
<td>0.90</td>
</tr>
<tr>
<td>V</td>
<td>23.10</td>
<td>23.40</td>
<td>0.15</td>
<td>1015.4</td>
<td>4.00</td>
</tr>
<tr>
<td>VI</td>
<td>23.45</td>
<td>23.50</td>
<td>0.05</td>
<td>1015.3</td>
<td>3.10</td>
</tr>
</tbody>
</table>

### (40min/60min)

<table>
<thead>
<tr>
<th>Type</th>
<th>SST (C)</th>
<th>Air T (C)</th>
<th>Air T- SST (C)</th>
<th>MSLP (hPa)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>unclassified</td>
<td>23.30</td>
<td>23.70</td>
<td>0.20</td>
<td>1013.3</td>
<td>3.10</td>
</tr>
<tr>
<td>I</td>
<td>23.20</td>
<td>22.70</td>
<td>-0.50</td>
<td>1015.1</td>
<td>3.40</td>
</tr>
<tr>
<td>II</td>
<td>23.20</td>
<td>23</td>
<td>-0.10</td>
<td>1016.2</td>
<td>2.20</td>
</tr>
<tr>
<td>III</td>
<td>23.30</td>
<td>22.60</td>
<td>-0.70</td>
<td>1017.9</td>
<td>0.65</td>
</tr>
<tr>
<td>IV</td>
<td>23.15</td>
<td>23.05</td>
<td>0.15</td>
<td>1013.9</td>
<td>2.95</td>
</tr>
<tr>
<td>V</td>
<td>23.10</td>
<td>23.20</td>
<td>0.10</td>
<td>1016.6</td>
<td>3.90</td>
</tr>
<tr>
<td>VI</td>
<td>23.10</td>
<td>23</td>
<td>0</td>
<td>1015.2</td>
<td>3</td>
</tr>
</tbody>
</table>
Available Power (MW)

NREL 5MW Offshore Reference Turbine (July 17-August 31, 2013)
200s Lidar Scenarios
- PPI scans
- RHI slices
- DBS
- VWPs ~40m-220m

Ocean City, MD

* Azimuth angles displayed
Results

- Example of ‘Good’ Fit Using Residual Sum of Squares (RSS) ≤ 0.1
Clifton et al. 2016
### Table 1-1. Gross Properties Chosen for the NREL 5-MW Baseline Wind Turbine

<table>
<thead>
<tr>
<th>Rating</th>
<th>5 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Orientation, Configuration</td>
<td>Upwind, 3 Blades</td>
</tr>
<tr>
<td>Control</td>
<td>Variable Speed, Collective Pitch</td>
</tr>
<tr>
<td>Drivetrain</td>
<td>High Speed, Multiple-Stage Gearbox</td>
</tr>
<tr>
<td>Rotor, Hub Diameter</td>
<td>126 m, 3 m</td>
</tr>
<tr>
<td>Hub Height</td>
<td>90 m</td>
</tr>
<tr>
<td>Cut-In, Rated, Cut-Out Wind Speed</td>
<td>3 m/s, 11.4 m/s, 25 m/s</td>
</tr>
<tr>
<td>Cut-In, Rated Rotor Speed</td>
<td>6.9 rpm, 12.1 rpm</td>
</tr>
<tr>
<td>Rated Tip Speed</td>
<td>80 m/s</td>
</tr>
<tr>
<td>Overhang, Shaft Tilt, Precone</td>
<td>5 m, 5°, 2.5°</td>
</tr>
<tr>
<td>Rotor Mass</td>
<td>110,000 kg</td>
</tr>
<tr>
<td>Nacelle Mass</td>
<td>240,000 kg</td>
</tr>
<tr>
<td>Tower Mass</td>
<td>347,460 kg</td>
</tr>
<tr>
<td>Coordinate Location of Overall CM</td>
<td>(-0.2 m, 0.0 m, 64.0 m)</td>
</tr>
</tbody>
</table>