A Wind Resource Assessment of the Mississippi Delta

Jessica Dealy

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A wind resource assessment of the Mississippi Delta

By

Jessica Dealy

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A wind resource assessment of the Mississippi Delta

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The hypothesis tested was that a site in Leflore County, Mississippi, located on the bluff above the Mississippi River flood plain (the Delta) would experience wind speeds adequate for power generation. Wind measurements were collected at a height of 55 m (above ground level) between October 2011 and October 2012. Winds at this height were predominately southeasterly with a mean wind speed less than 4 m/s. Winds did not accelerate above this bluff. Low surface friction of the Delta was not beneficial due to the predominant wind direction.

To better understand Delta wind patterns, an $S$-mode varimax-rotated principal component analysis (RPCA) was performed on monthly 30 m North American Regional Reanalysis (NARR) wind data. Three areas for future wind resource assessment measurements were determined. Each pattern highlighted more energetic wind speeds areas, none of which included the measurement site. The RPCA method was successful in delineating homogeneous wind speed patterns.
ACKNOWLEDGEMENTS

The author would first like to express an immense amount of thanks and gratitude to Dr. Brenda Kirkland for daily reminding me that this work matters, and for keeping this research focused on one task at a time.

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CHAPTER I

INTRODUCTION

Objectives and Hypothesis

The objectives of this Mississippi Delta wind assessment research project are:

1. To determine the wind resource available to a site location in Leflore County, Mississippi by the means of collecting data from an anemometer installed on a communication tower at a height of 55 m Above Ground Level (AGL) for a period of one year.

2. To determine the characteristics of the wind resource at that location by calculating the 55 m mean wind speed and max wind speeds, and creating wind roses, diurnal profiles, and wind distribution graphs using the software program, Windographer®.

3. To improve understanding of dominant wind patterns in the Mississippi Delta by separately evaluating the National Center for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) 30 m monthly wind data using an S-mode varimax rotated principle component analysis (RPCA).

The following hypotheses are tested:

1. Average 55 m wind speeds along the Delta – non-Delta interface in Leflore County meet Wind Power Class 2 requirements.
2. The increased elevation of the Delta – non-Delta interface at the site location (106.6 m Above Mean Sea Level) experiences higher 55 m winds than those observed in the Delta’s floodplain (on average, 91 m ABSL).

3. Mississippi Delta 55 m winds at the measurement site will be predominately Westerly, allowing winds to experience lower surface roughness and friction.

4. An S-mode varimax rotated principal component analysis (RPCA) will display the dominant wind patterns in the Delta, and highlight areas where future research should be conducted.

Wind Assessments

Wind energy site assessments are used to evaluate the potential for a site location to produce energy from wind turbines (Bailey, 1997). Initial analysis regions may be geographically extensive, for instance, the analysis region may include a utility service territory or even an entire state (Bailey, 1997). The analysis of available wind data such as National Climatic Data Center (NCDC) archives or high-resolution wind resource estimate maps help provide a general description of an analysis area (Bailey, 1997).

The wind resource at a site directly affects the amount of energy that a wind turbine can extract, and therefore controls the economic viability of the venture (Michael W. Tennis, 1999; Rose, 2000). Wind resource is primarily quantified by the mean wind speed at the turbine hub height (50-120 m) for any given site (Justus, 1978); although turbulence intensity, the probability distribution of the wind speed, and the prevailing wind direction are also important components (Celik, 2004). The U.S. Department of Energy classifies wind energy as Classes 1 to 7. Before 2009, Class 3 winds (~6.5 m/s
mean wind speed) were considered the minimum required Class for effective power generation (Markus and Thienpont, 2012; Southern Company, 2013). After 2009, two factors have helped lower the mean wind speed installment threshold:

1. Many of the more energetic areas had installed wind farms, and
2. A new fleet of larger rotor diameter turbines can operate efficiently at lower wind speeds (Markus and Thienpont, 2012).

The downward trend in mean wind speed of installed wind plants is expected to continue, opening up new geographic regions with less attractive wind resources to the possibility of wind power generation. To investigate one of these less attractive areas, a wind assessment was initiated in the northwest corner of Mississippi as a preliminary investigation of viable wind energy development in the Mississippi Delta. The research area has been ignored due to the widely accepted notion that Mississippi does not experience mean wind speeds of 6.5 m/s or greater at the average commercial wind turbine hub height (D. L. Elliott, 1987; P Gardner, 2004; Southern Company, 2013).

The results of this research provide new data concerning specific study-site location wind patterns at the standard meteorological tower height (~60 m); and, also provide a broad estimate of Northwest Mississippi’s residential-scale turbine hub height (30 m).

Wind Energy Site Assessment Process

A private company, government entity, or utility company that is interested in producing wind energy in a particular region typically initiates wind energy development (Lackner, 2008). The process generally begins with a “preliminary area identification,” which entails identifying a relatively large area where wind energy development is viable
(Bailey, 1997). A wind atlas, such as the “Wind Energy Resource Atlas of the United States” (D. L. Elliott, 1987), or wind resource maps such as those developed by AWS Truepower and the National Renewable Energy Laboratory (NREL) or 3Tier, can be used for this purpose.

Next, a specific site or series of sites within the preliminary area is selected for consideration for wind energy development. Ideally, the sites are selected according to topographic features, proximity to transmission/distribution lines and other factors that would suggest a successful project; although zoning regulations and the level of community support can dictate the actual locations (Bailey, 1997; Kahn, 2000). Sites are then evaluated for their potential to produce wind energy by measuring the wind resource. The process of assessing the potential for a specific site to produce energy from wind turbines is the site assessment process.

The focus of this research is the measurement of the wind resource and an assessment of a specific site in the Mississippi Delta for wind energy development. The larger question of regional 30 m wind patterns is also addressed.

**Measurement of the Wind Resource**

Wind resource evaluation is the first major step in the wind energy site assessment process. The evaluation uses measured wind speed data to estimate the long-term hub height wind resource at the location of each turbine in the wind farm. The wind resource is usually characterized by the mean wind speed and the Weibull parameters (Gunturu and Schlosser, 2012).

In the traditional site assessment process, the wind resource at a site is measured using one of several meteorological towers (met towers) (Figure 1-2). Meteorological
towers are equipped with wind speed and direction sensors (usually cup anemometers and wind vanes) positioned at two or more heights on the tower (Figure 2). The sensors record the wind speed and direction every ten seconds, the average of the ten second observations is then taken and reported every 5-15 minutes depending on how the anemometer was programmed.

Figure 1  Top down view of a meteorological tower.

Notes: Ideally, the two anemometers at any height are on the upwind side of the tower, 60 degrees apart. This diagram shows them 180 degrees apart. (Figure courtesy of Will Hobbs, Southern Company)
The standard practice in almost all site assessments (Christian J. Myers; R.D. Prasad, 2009) is to install temporary tubular meteorological towers or, to mount sensors on a previously constructed tower at a chosen site for at least a year (Bailey, 1997). The wind resource at a site tends to have pronounced seasonal variations; therefore, one year of data is needed to capture these seasonal effects (Akpinar and Akpinar, 2005). Greater then one year of data allows the capture of inter-annual variations in the wind resource as well; although, rarely is the wind resource evaluated for more than two years (Bailey, 1997). Usually, the one or two years of data are then adjusted based on long-term, nearby reference data, such as from an airport.
CHAPTER II
LITERATURE REVIEW

Wind Characteristics

Solar energy affects the atmosphere by warming the air and creating the wind as a function of thermal disequilibrium (Stull, 2000). The earth’s orbit, rotation, tilt, and round surface cause differential heating which, in turn, create atmospheric pressure differences (Stull, 2000). Winds, therefore, are the movements of air that attempt to equalize pressure differences within the atmosphere. The air mass movements are a combination of five different horizontal forces: advection (AD), the pressure-gradient force (PG), the Coriolis force (CF), centrifugal force and turbulent drag (TD) (Stull, 2000). Steady-state winds in the Atmospheric Boundary Layer (ABL), are usually slower than geostrophic (i.e., subgeostrophic) because of the frictional and turbulent drag of the air against the surface (Stull, 2000). The friction force acts against the air movement creating different wind profiles for different locations (Figure 3). For the first tens of meters in the atmosphere, wind profile structure significantly varies with height depending on the type of land surface (Stull, 2000). The height at which wind speed is no longer influenced by the surface roughness is named gradient height; wind at this height is called geostrophic wind (Stull, 2000).
Figure 3  Wind profiles for different surfaces.

Notes: From left to right the wind profiles indicate a smooth surface (low friction) to a rough surface (high friction) (Stull, 2000). $z_g$ represents gradient height.

The two main models attempting to capture vertical wind profile variations (assuming a statically neutral environment) are the power law and logarithmic profile:

$$U_z = U_r \left( \frac{z}{z_r} \right)^\alpha$$  \hspace{1cm} (1)

**Power Law Equation.**

$$U_z = \frac{u^*}{k} \ln \left( \frac{z}{z_0} \right)$$  \hspace{1cm} (2)

**Logarithmic Profile**

where $U_z$ is the wind speed at height $z$, $U_r$ is the wind speed at a reference height $r$, $\alpha$ is the wind shear exponent, $u^*$ is the friction velocity, $k$ is the von-Karman constant (0.4), and $z_0$ is the roughness length (Justus, 1978; Stull, 2000).

**Wind Diurnal Profile Evolution**

During fair weather, winds demonstrate a diurnal cycle (Figure 4) over land (Stull, 2000). During early morning hours, for example around 9:00 AM, a shallow
mixed layer (~300 m) is often present (Stull, 2000). In the shallow mixed layer, surface winds are non-zero and ABL winds are uniform with height (Stull, 2000). Surface heating causes the mixed layer to deepen throughout the day so that, by ~3:00 PM a deep layer of homogeneous subgeostrophic winds fills the ABL. Turbulence created by buoyancy causes faster winds to mix down into the ABL, keeping winds above zero near the surface.

Turbulence decreases after sunset, decreasing mixing, and allowing the atmosphere to become stratified. Surface wind speeds are reduced due to drag; however, in the middle of the ABL wind speed increases, since surface drag is no longer a factor. By the early morning, vertical shear is at a maximum; winds a few hundred meters above the ground can be supergeostrophic, even if surface winds are calm (Stull, 2000).
Figure 4    Typical ABL wind-profile evolution during fair weather over land (Stull, 2000).

Note: $G$ is geostrophic wind speed & $M_{BL}$ is average ABL wind.

For viability determination, it is important to understand the diurnal cycle or, hourly distribution of wind speed and energy output of a proposed wind project. Both monthly and hourly distributions can be compared to wholesale power prices and electric loads of the same region (Markus and Thienpont, 2012). If the peak energy output of an area coincides with the peak energy demand of the region on a seasonal or hourly basis, additional value is placed on the proposed wind farm (Markus and Thienpont, 2012). Conversely, less value is given if the resource is highest during non-peak demand periods (Markus and Thienpont, 2012).
Wind Speed Profiles and Stability

Vertical wind speed profiles change with the stability of the atmosphere (Figure 5). Wind speeds increase logarithmically with height in the bottom 5% of the statically neutral ABL (surface layer) (Stull, 2000). A statically stable atmosphere typically creates a more linear profile (Stull, 2000). During unstable conditions, winds near the surface have faster speeds than winds aloft, thereby creating an exponential power-law relationship with height (Stull, 2000).

Figure 5 Typical wind speed profiles in the surface layer for different static stabilities (Stull, 2000).

Notes: SL is bottom 5% of the ABL. Radix layer (RxL) is bottom 20% of the ABL. Order-of-magnitude depths for the radix layer and surface layer given by zRxL and zSL (Stull, 2000). $M_{BL}$ is the vertically averaged steady-state ABL wind.
**Turbulence**

Non-turbulent air flow is referred to as laminar, and often occurs when wind movement is parallel to the surface wind flow (Stull, 2000). Alternatively, when air movement is displaced against the prevailing wind direction, moving in eddies and waves, then the flow is turbulent. Turbulence appears as short variations of wind speed and may be caused by obstacles in the flow such as buildings, trees or temperature differences in the air (creating buoyancy).

Wind turbulence can have a significant impact on turbine performance and loading (Markus and Thienpont, 2012; S. Wharton, 2010). The most common indicator of turbulence is the standard deviation ($\sigma$) of the wind speed calculated from 2-second samples over a 10-minute recording period (Markus and Thienpont, 2012). Normalizing this value with the mean wind speed gives the turbulence intensity (Markus and Thienpont, 2012). The turbulence intensity at 15 m/s is commonly used to give a preliminary indication of the suitability of a turbine model for the project site (Markus and Thienpont, 2012).

**Terrain Effects on Wind Flow**

At the local level, wind is influenced partially by terrain roughness, obstacles, and orography (Justus, 1978). Surface roughness is usually quantified (Table 1) with a parameter known as the roughness length ($z_0$) (Stull, 2000). Reduction in wind speed may be seen locally due to buildings or high forest. Such reductions may exist vertically up to three times the height of the obstacle and downstream to 30-40 times the height (I. Troen, 1989). In regards to wind farms, (W. Frost, 1977) defined “flat terrain” as having the following characteristics:
(a) “elevation differences between the wind turbine site and surrounding terrain within a radius of 12 km (≈7 mi) no larger than 60 m (200 ft),” and
(b) “all hill height-to-width ratios h/l < 0.016 within 4 km (2.5 mi) length should have elevation difference between highest and lowest point which is 1/3 or less of the height difference between the bottom of the rotor disk and the lowest point in the terrain strip.”

In short, lower surface roughness values equate to faster wind speeds regardless of air stability (Justus, 1978; Stull, 2000), and wind systems perform best with faster wind speeds and low turbulence (S. Wharton, 2010). Furthermore, faster winds over rougher surfaces cause greater kinematic stress, increasing friction velocity.

Table 1 The Davenport-Wieringa Roughness-Length Classification (Stull, 2000).

<table>
<thead>
<tr>
<th>$z_0$(m)</th>
<th>Classification</th>
<th>Landscape</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0002</td>
<td>Sea</td>
<td>Sea, paved areas, snow-covered flat plain, tide flat, smooth desert</td>
</tr>
<tr>
<td>0.005</td>
<td>Smooth</td>
<td>Beaches, pack ice, morass, snow-covered fields</td>
</tr>
<tr>
<td>0.03</td>
<td>Open</td>
<td>Grass prairie or farm fields, tundra, airports, heather</td>
</tr>
<tr>
<td>0.1</td>
<td>Roughly open</td>
<td>Cultivated area with low crops and occasional obstacles (single bushes)</td>
</tr>
<tr>
<td>0.25</td>
<td>Rough</td>
<td>High crops, crops of varied height, scattered obstacles such as trees or hedge-rows, vineyards</td>
</tr>
<tr>
<td>0.5</td>
<td>Very rough</td>
<td>Mixed farm fields and forest clumps, orchards, scattered buildings</td>
</tr>
<tr>
<td>1.0</td>
<td>Closed</td>
<td>Regular coverage with large size obstacles with open spaces roughly equal to obstacle heights, suburban houses, villages, mature forests</td>
</tr>
<tr>
<td>$\geq$ 2</td>
<td>Chaotic</td>
<td>Centers of large towns and cities, irregular forests with scattered clearings</td>
</tr>
</tbody>
</table>

Orographic Effects on Wind Flow

Orographic effects on wind flow depend upon steepness of slope and may serve to increase or decrease wind speed (Figure 6) (Justus, 1978). Gentle slopes and shapes
can increase wind flow (Figure 6-a), whereas sharp edges or crests (Figure 6-b and c) can cause lower flow (less than undisturbed) (Justus, 1978).

![Figure 6](image)

Figure 6 Typical flow patterns over two-dimensional hills (Justus, 1978; W. Frost, 1977).

Bailey (1997) highlighted topographic features (Figure 7) that are likely to be “windier” in the “Wind Resource Assessment Handbook.” Analysis of topographic maps was recommended as an effective means of streamlining the site assessment process (Bailey, 1997). Maps on a 1:24,000 scale (1 in = 2,000 ft) available from the U.S. Geological Survey (USGS) were considered the best source of information for identifying suitable terrain features (Bailey, 1997). Due to increased possibility for orographic influences deleterious to preferred consistent wind flow necessary for viable
energy production potential, locations to be avoided in site assessment include areas immediately upwind and downwind of higher terrain, the lee side of ridges, and excessively sloped terrain (Bailey, 1997).

**Ridges oriented perpendicular to the prevailing wind direction**

**Highest elevations within a given area**

**Locations where local winds can funnel.**

Figure 7  Locations likely to be windier according to “The Wind Resource Assessment Handbook.”

**Wind Resource Measurement**

The traditional wind resource site assessment, described in the Introduction, can rely on the use of meteorological towers equipped with wind speed and direction sensors, or remote sensing equipment such as LIDAR and SONAR (Bailey, 1997). The wind
resource assessment conducted during this study utilized a tower and both wind speed and direction sensors; therefore, elements associated with meteorological tower assessments will be discussed more thoroughly than elements associated with remote sensing techniques.

**Meteorological Towers**

Meteorological towers are the most common means of assessing the wind resource at a location that is under consideration for wind energy development (Lackner, 2008). Meteorological towers range in height, starting from 30 m (commercial-scale) up to 400 m (400 m is the tallest lattice tower), with diameters of approximately 15-20 cm (6-8 in) (Bailey, 1997; Lackner, 2008; SecondWind). There are two different principal types of meteorological towers (SecondWind): Tubular tilt-up towers (Figure 8) and lattice towers (Figure 9).

![Meteorological Tower Diagram](image)

**Figure 8**  Tubular tilt-up meteorological tower diagram.
Tilt-up towers are used for short-term applications or lower-height wind resource assessment studies and require no foundation. Tilt-up towers are made of rolled steel or pipe segments that are erected and secured with guy wires (SecondWind). The overall footprint of tilt-up towers can be wider in diameter than the tower is tall due to the guy wires. Lattice towers are named for the three or four vertical elements that are cross-braced with welded supports and require a foundation (SecondWind). Tubular towers are
easy to assemble and erect; however, lattice towers can reach higher heights. Lattice towers are preferred over tilt-up towers due to their longer expected lifetime (SecondWind).

Wind assessments have also been completed by mounting wind sensor equipment on communication towers previously constructed for other purposes (AWS Truepower, 2012). Unlike tubular towers, which come in a fixed set of dimensions and for which standard monitoring configurations have been developed, communication towers occur in a variety of sizes and lattice designs (Markus and Thienpont, 2012). In order to minimize the effects of the tower and its equipment, such as dishes or antennas, analysis should be conducted on the tower itself (Markus and Thienpont, 2012). Analysis of the tower’s dimensions determines the correct length of booms and helps determine the best location to mount sensors. Proper analysis of communication towers used for wind resource assessments ensures tower-specific monitoring recommendations: specifically, appropriate heights for wind direction, wind speed, and temperature measurements, as well as determining the best directional orientations for the anemometer booms (Markus and Thienpont, 2012).

*Cup Anemometers and Wind Vanes*

Calibration, maintenance, and proper installation of wind sensors are all important issues to consider while selecting wind sensors (Bailey, 1997). Different makes of anemometers, wind vanes, and temperature sensors are available, but it is desirable to select the same make of anemometers to ensure the site has conformity of data (Bailey, 1997). Normally, at least one anemometer is placed at a minimum of two levels on a met tower. Ideally, two anemometers will be placed at three to four heights with a wind vane...
at each level (Bailey, 1997). Typically only one temperature sensor is utilized and is commonly placed at a height ~10 m. All sensors involved produce data that give the average wind speed and wind direction over assigned time intervals. All the sensor data are recorded and stored by a data-logger box located at the bottom of the tower.

Cup anemometers (Figure 10) are the most common type of anemometer used for wind speed measurements in wind energy site assessments, but their design specifications and operational performances vary (J. F. Manwell, 2009; Wyngaard, 1981). Wind direction is usually measured using a wind vane, (Figure 11) (Systems, 2012)

Figure 10 NRG Systems Cup Anemometer.
Boom Length and Tower Shadowing

Sensors are mounted on booms, which are attached to a meteorological tower at each height, extending horizontally. The booms are generally 2-3 m (6-9 ft) in length (Lackner, 2008). Tower shadowing, which occurs when the wake of the tower affects the measurement of an anemometer, may occur if anemometers and wind vanes are mounted too close to the tower (Bailey, 1997; Lackner, 2008; Orlando et al., 2011). An experiment investigating the effects of tower shadowing on cup anemometer wind speed readings in the wake of common meteorological tower geometries found significant wind speed deficit when the anemometer is located in the wake of the tower ranging from 35% for the low wind speed cases to 18% at the highest wind speed (Orlando et al., 2011).

LIDAR and SODAR Wind Speed Measurement Devices

Light Detection and Ranging (LIDAR) and Sonic Detection and Ranging (SODAR) were developed in the 1960’s and 70’s but are relatively new ground-based devices used for wind resource assessments (Bailey, 1997; Lackner, 2008; Sanz Rodrigo
et al., 2013). SODAR uses sound waves to measure wind speed, while LIDAR utilizes electromagnetic radiation to measure wind speed (Bailey, 1997; Sanz Rodrigo et al., 2013).

A study conducted by researchers at the University of Massachusetts and NREL found several advantages provided by utilizing LIDAR including portability, rapid deployment, small footprint (no permit required), ability to provide accurate hub-height wind data, and the capacity to minimize measurement uncertainty (Daniel W. Jaynes, 2007). SODAR systems are also more easily installed than a meteorological tower and have the advantage of measuring wind speed and direction at heights much higher than a meteorological tower (Sanz Rodrigo et al., 2013). Ground clutter can be a problem when using SODAR (Sanz Rodrigo et al., 2013). Several research projects, however, employed filtering methodology to remove corrupt data, resulting in SODAR measurements close to nearby anemometer measurements (Lackner, 2008; Sanz Rodrigo et al., 2013). The advantages associated with using LIDAR or SODAR measurements could help streamline wind resource assessments (Daniel W. Jaynes, 2007). LIDAR and SONAR measurements also help in characterizing attributes of the site such as shear profiles that extend higher than met towers typically measure.

**Wind Resource Characterization**

As altitude above ground level increases, wind velocity and consistency increases. Wind velocity logic underlies the reason utility-sized turbines are constructed at heights at, or above, 50 m. During the 1990’s, 50 m was the general turbine hub height (Gunturu and Schlosser, 2012). Technological advances raised hub heights to 60 m, 80 m, 100 m, and 120 m. Currently, turbines with 80 m hub height are most common (Gunturu and
Schlosser, 2012). The estimation and measurement of wind resource at these different heights is vital to understanding the behavior of wind power (Gunturu and Schlosser, 2012).

The estimation of wind energy resource, however, is associated with several unique problems. Unlike conventional fossil fuel reserves, the amount of energy available from the wind varies with season and time of day. Additionally, wind energy is more sensitive to topography variations than solar energy (Justus, 1978). Finally, no single method has been developed for estimating and presenting wind energy resource potential, as the amount of energy that can be produced significantly depends on turbine operating height, assumed performance characteristics, and horizontal spacing of turbines (Justus, 1978).

**Wind Power Density**

The basic formula for characterizing wind resource, independent of the wind turbine features is identified as “wind power density” or WPD (Gunturu and Schlosser, 2012; Justus, 1978). WPD is correlated to how much energy can be produced at a location by a wind turbine measured in W/m$^2$ (Gunturu and Schlosser, 2012). The WPD at each time step is calculated using the equation:

\[
P = \frac{1}{2} \rho V^3
\]  

where $P$, $\rho$ and $V$ are the wind power density, density of the atmosphere and the wind speed at the point location (Gunturu and Schlosser, 2012). Note that velocity is cubed, signifying a small decrease in wind speed equates to a large decrease in power.
Air density directly affects the energy production of a wind turbine: the greater the density, the greater the output of a wind turbine for the same speed distribution (Markus and Thienpont, 2012). Air is compressible; therefore, air density can vary over a wide range (Stull, 2000). Density decreases roughly exponentially with height in an atmosphere of uniform temperature (Stull, 2000). Air density at a given height can be estimated using the equation:

\[
\rho = \frac{P_o e^{-\frac{g z (1.0397 - 0.0000252 z)}{RT}}}{RT}
\]  

where \( \rho = \) Air density (kg/m\(^3\)), \( P_o = \) Standard sea-level atmospheric pressure in Pascals (101325 Pa), \( R = \) Specific gas constant for dry air (287 J/Kg K), \( T = \) Air temperature (K), \( g = \) Acceleration due to gravity (9.8 m/s\(^2\)), \( z = \) Elevation of temperature sensor above ground level(m).

### Wind Power Classes

Regional wind resource estimates can be obtained from the Wind Energy Resource Atlas of the United States (D. L. Elliott, 1987). The atlas provides estimated wind resource values by integrating pre-1979 wind measurements with topography and landform characteristics (D. L. Elliott, 1987). Updates were made to the original resource values using 270 post-1979 data sites, including nearly 200 that were instrumented specifically for wind energy purposes (Bailey, 1997). The updated wind resource values were displayed on gridded maps with a resolution of 1/4 degree latitude by 1/3 degree longitude (Bailey, 1997).

Wind resource estimates from the atlas are expressed in wind power classes ranging from Class 1 to Class 7 (Bailey, 1997; D. L. Elliott, 1987). Each class represents
a range of mean wind power density or equivalent mean wind speed at specified heights (30 m and 50 m) above the ground (Bailey, 1997; D. L. Elliott, 1987). Table 2 defines the wind power classes in terms of the upper limits of mean wind power density and mean wind speed at 30 m and 50 m above ground level.

Table 2  Classes of Wind Power Density.

<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>Wind Power Density (W/m²) and Wind Speed m/s (mph) at 30 m (98 ft)</th>
<th>Wind Power Density (W/m²) and Wind Speed m/s (mph) at 50 m (164 ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>≤160 (5.1) (11.4)</td>
<td>≤200 (5.6) (12.5)</td>
</tr>
<tr>
<td>2</td>
<td>≤240 (5.9) (13.2)</td>
<td>≤300 (6.4) (14.3)</td>
</tr>
<tr>
<td>3</td>
<td>≤320 (6.5) (14.6)</td>
<td>≤400 (7.0) (15.7)</td>
</tr>
<tr>
<td>4</td>
<td>≤400 (7.0) (15.7)</td>
<td>≤500 (7.5) (16.8)</td>
</tr>
<tr>
<td>5</td>
<td>≤480 (7.4) (16.6)</td>
<td>≤600 (8.0) (17.9)</td>
</tr>
<tr>
<td>6</td>
<td>≤640 (8.2) (18.3)</td>
<td>≤800 (8.8) (19.7)</td>
</tr>
<tr>
<td>7</td>
<td>≤1600 (11.0) (24.7)</td>
<td>≤2000 (11.9) (26.6)</td>
</tr>
</tbody>
</table>

Grid cells designated as Class 3 and greater are generally considered suitable for turbine applications. Class 2 areas are considered marginal and Class 1 areas are considered unsuitable for wind energy development. The gridded wind resource estimates are only broad estimates; therefore, an analyst should not rule out the possibility that a Class 2 area may contain smaller-scale features possessing more energetic (Class 3 or greater) wind resource (Bailey, 1997).

**Weibull Density Function**

The variation of wind velocity is normally described using the Weibull two-parameter density function (Justus, 1978; Stull, 2000; Weisser, 2003). The wind speed probability density function (Weibull distribution) can be calculated using the equation:
\[ f(v) = \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} \exp\left( -\left( \frac{v}{c} \right)^k \right) \]  

where \( f(v) \) is the probability of observing wind speed \( v \) (m/s), \( c \) is the Weibull scale parameter (units of speed) and \( k \) is the dimensionless Weibull shape parameter.

The scale parameter, \( c \), indicates the ‘windiness’ of an observed location, whereas the shape parameter, \( k \), controls the width of the wind distribution (for example, if wind speeds are commonly close to a certain value, the distribution will have a high \( k \) value and be very peaked) (Gunturu and Schlosser, 2012; Justus, 1978). Values of \( k \) typically range from 1 to 3.5, with the higher values indicating a narrower distribution (Figure 12) (Markus and Thienpont, 2012). Both \( k \) and \( c \) can be calculated manually, but for the purposes of this study, the software program Windographer was used to find a best-fit Weibull distribution.
Figure 12  Several Weibull distributions, all with an average wind speed of 7 m/s, but with the Weibull K value varying from 1.5 to 3.5.

Wind Resource Maps

Wind resource maps are commonly examined before installing any type of wind resource measurement device; this process is typically called the “Preliminary area identification” step (Bailey, 1997). Before 1995, manual spatial analysis techniques were utilized during the creation of 50 m wind resource estimates in support of the Department of Energy’s (DOE) Wind Energy Program (Heimiller and Haymes, 2001). Since 1995, collaborative processes among AWS Truepower, NREL, and consulting experts have greatly improved U.S. wind resource maps. The wind resource maps are vital to wind resource assessments as utilities, private investors, and researchers may consult a map before installing wind measurement devices.
NREL 50 m Wind Energy Resource Estimate Maps

NREL developed the first U.S. national wind energy resource estimate maps in 1987 (D. L. Elliott, 1987; Gunturu and Schlosser, 2012). Several data sources were used to collect the wind data with the National Climatic Data Center (NCDC) archives constituting the majority of the data (Gunturu and Schlosser, 2012).

The original maps and atlas used wind density, not wind speed, as a measure of the resource because the former utilizes the effect of changing air density (Gunturu and Schlosser, 2012). Air density estimates were calculated using measured temperature and station pressure and the equation of state (Gunturu and Schlosser, 2012). For areas without temperature or pressure data, air density values at the height of the wind speed record were extrapolated from an assumed surface air density of 1.225 kg m$^{-3}$ (Gunturu and Schlosser, 2012). Seasonal and geographical variations of density were not taken into consideration; therefore, the wind resource has been overestimated in the wind atlas and original maps (Figure 13) (Gunturu and Schlosser, 2012).
The wind resource assessment group at the NREL began developing an automated GIS Wind Resource Assessment Model (WRAM) in 1995 (Heimiller and Haymes, 2001). The Midwestern U.S. 50 m wind resource was remapped at a higher resolution (1-\(km^2\)) before any other area in the U.S., as initially, this area was seen to have the greatest onshore wind resource in the U.S. (D. L. Elliott, 1987; Gunturu and Schlosser, 2012; M. Schwartz, 2001). Notable differences of the 50 m maps are depicted by comparing the North and South Dakota digital 50 m wind map from the 1987 U.S. Wind Map and the newer (2000) high-resolution (1-\(km^2\)) 50 m wind map (Figure 14). WRAM was used to remap the 50 m wind resource in 36 states (Figures 15 and 16).
Figure 14  Comparison of North and South Dakota’s 1987 Wind Map (left) and 2000 High-Resolution (right).

Notes: The legend for Figure 13 and 14 are the same.

Figure 15  States with Completed High-Resolution 50-Meter Wind Maps highlighted in green.

Notes: No 50 m high-resolution map was created for the state of Mississippi.
Figure 16  Remapped High-Resolution NREL 50 m Wind Resource Map.

**AWS Truepower NREL 80 m Wind Resource Map**

The more commonly used and viewed U.S. resource estimate maps now incorporate wind speed (m/s) rather than WPD to characterize wind resource. During a DOE webinar (DOE, 2012), NREL developers stated that the switch from WPD to wind speed resulted mainly from public confusion over WPD. The new resource maps were developed through a collaborative project between the NREL and AWS Truepower (DOE, 2012) and show the predicted mean annual wind speeds at 80 m heights (Figure 17). Displayed at a spatial resolution of 2.5 km, the maps are derived from 200-m
resolution maps developed by AWS Truepower for the windNavigator system (DOE, 2012).

Figure 17 U.S. Wind Map at 80 m Developed by NREL.

During the creation of AWS Truepower NREL maps, a mesoscale model, MASS1, ran at a higher resolution with boundary conditions from NCEP Reanalysis (NNRP) (AWS Truewind, 2012). MASS1 simulates weather conditions for 366 days while, during the next phase, WindMap2 refines the wind fields created in MASS1 in order to capture the local influences of topography and surface roughness changes at a resolution of 200 m (Figure 18) (AWS Truewind, 2010). The simulated winds were
downscaled using a statistical model to a resolution of 50 m × 50 m (AWS Truewind, 2012). The estimated wind fields are then adjusted using direct measurements from a large network of wind monitoring stations, i.e., validation points (AWS Truewind, 2010).

Figure 18   AWS Truepower windNavigator Flow Chart.

NREL conducted a preliminary review and validation of AWS Truepower’s 80 m map estimates for 19 selected states (6 Western states, 6 Midwestern states, and 7 Eastern states) (DOE, 2012). The reviews and validations were based on tower measurements at heights of about 50 m and above from more than 300 locations (DOE, 2012). Mississippi does not have a validated 80-m wind resource map.

**NCEP/NCAR Reanalysis (NNRP) Limitations**

The windNavigator may be underestimating or overestimating wind speeds in states such as Mississippi due to the lack of validation measurements. Without validation
measurements, the wind resource is grossly estimated heavily by NCEP/NCAR Reanalysis data. It can be assumed that, because AWS Truepower develops global wind resource maps, the company chose the coarser NNRP Reanalysis’ global dataset (2.5-degree latitude × 2.5 longitude, 28 vertical levels) for windNavigator instead of the higher resolution North American Regional Reanalysis (32 km, 0.3 degrees, 45 vertical levels) dataset. Due to the low resolution of the NCEP/NCAR grid, the entire state of Mississippi has only two data points from which the rest of the state’s meteorological data is interpolated. The two data points in Mississippi are not located in the Northwest corner of the state (the research area of this study). One is located on the Mississippi-Tennessee border; the other is near Jackson, Mississippi. Thus, the model derives wind speeds for the Delta without any data in the area.

*Mississippi 80 m Wind Resource Map*

The 80 m wind potential profile map that was created for the state of Mississippi using windNavigator shows that the northwest corner of Mississippi (the Delta region) possesses 80 m annual average wind speeds ranging from 4.5 m/s to 6.0 m/s (Figure 19). Areas with annual average wind speeds around 6.4 m/s and greater at 80 m height are generally considered to have a suitable wind resource for wind development (DOE, 2011). The AWS Truepower NREL 80 m wind maps were created from a 2.5-degree latitude and longitude grid map and were interpolated to an implied resolution of 2.5 km. Because the wind resolution is interpolated and not measured, the estimated standard error for these maps is 0.75 m/s. Consequently, both AWS Truewind and the DOE stress the need for an on-site analysis to fully determine the full potential of a site location (DOE 2011, AWS Truewind, 2010).
Figure 19  Wind resource estimates developed by AWS Truepower LLC for windNavigator® spatial resolution of wind resource data: 2.5km.

Notes: The Northwest corner (the Delta) is estimated to have a higher wind resource than other locations in the state.
Mississippi 30 m Wind Resource Map

During the summer of 2012, the DOE and the NREL published 30 m, high-resolution wind resource maps for the United States and all 50 states. The 30 m map for Mississippi (Figure 20) indicates that the Delta region has the best wind resources with mean wind speeds ranging from 4 – 5 m/s. The 30 m wind resource maps were created to assess the viability of small wind project development within a state. The mean wind speeds indicated on the maps are model-derived estimates (Energy, 2013).

Areas with good exposure to prevailing winds and annual average wind speeds around 4 m/s and greater at 30 m heights are considered to have appropriate wind resource for small wind projects (Energy, 2013). Small wind turbines most often have hub heights between 15 and 40 m. (Energy, 2013).
Figure 20  AWS Truepower NREL Mississippi 30 m Annual Average Wind Speed Map.
**Mississippi Delta**

The area of study is confined to the Mississippi River alluvial flood plain, (hereafter referred to as the Delta) a flat, highly agricultural region. The Delta is comprised of 19 counties, with the western counties adjacent to the Mississippi River extending south to Vicksburg, Mississippi, and the northern-most counties bordering Memphis, Tennessee. The Delta covers ~17,110 square miles, 200 miles from north to south and 88 miles from east to west at its widest point.

A line of bluffs defines the eastern side of the Delta. The bluffs reach up to 200 feet in height (Cobb, 1992) and extend south from Memphis, Tennessee, to Greenwood, Mississippi, and southwesterly along the Yazoo River, meeting the Mississippi River at Vicksburg, Mississippi. The Delta is topographically smooth and has an average elevation near to that of Mean Sea Level.

Topography along the Delta bluffs may possess topographical features that are likelier to be windy, as highlighted in “The Wind Resource Assessment Handbook” and Figure 7. Bailey et al. (1997) identified ridges oriented perpendicular to the prevailing wind direction and highest elevations within a given area as features that are likely to experience a greater mean wind speed than the general surroundings. Winds with a westerly component would be perpendicular to the bluffs, potentially creating a windier location. The elevation of the bluffs is considerably higher than the general surrounding area, once again potentially creating a windier location. It may be, however, that the flat flood plain located to the west of the bluffs possesses faster wind speeds due to the low surface roughness values (mostly crop land, $z_o \approx 0.03$).
The Mississippi Delta is part of the larger Mississippi River Alluvial Plain. The plain is divided into four main sections (Figure 21). The section of the alluvial plain located to the west of the Mississippi River is commonly referred to as the Mississippi Embayment and runs through eastern Arkansas, southeastern Missouri, westernmost Tennessee, westernmost Kentucky and southern Illinois. Wind resource assessments have recently been conducted at sites located in the Mississippi Embayment, and are discussed in the next section.

Figure 21  The Mississippi River alluvial plain.

Notes: Green represents the Mississippi Delta, pink represents the Mississippi Embayment, purple represents the Mississippi River Delta, and blue represents the most recent river mouth (source: Wikipedia http://en.wikipedia.org/wiki/Mississippi_Alluvial_Plain).
Previous Wind Assessments

Wind resource in the southeast is not, in an economic sense, currently considered significant (D. L. Elliott, 1987; Raichle and Carson, 2009). The research conducted for this study assesses the wind resource at a site location in the Mississippi Delta and outlines other areas in the Mississippi Delta that experience higher-than-average wind speeds. The previous studies highlighted in this section will, therefore, be focused on tall tower measurements and site assessments conducted in the Southeast and in the Mississippi River Alluvial Plain.

Arkansas Tall Tower Wind Resource Assessment

The Arkansas Energy Office, a division of the Arkansas Economic Development Commission, commissioned AWS Truepower, LLC to conduct a Tall Tower Wind Measurement Study for the State of Arkansas (Markus and Thienpont, 2012). Data were measured for one year “using existing communication towers at geographically diverse locations” (Markus and Thienpont, 2012). Five communication tower sites (Figure 22), ranging in height from 90 to 120 m, were selected for the study (Markus and Thienpont, 2012). Data collection and equipment installation began between March 22, 2011, and May 5, 2011 (Markus and Thienpont, 2012).
Figure 22  Arkansas Tall Tower Monitoring Sites.

The wind resource at ARK1, located in the northeastern portion of the State and within the Mississippi River floodplain, was found to be the “most attractive” (Markus and Thienpont, 2012). ARK1’s annualized mean wind speed was calculated as 6.54 m/s (14.63 mph) at 76.3 m (Markus and Thienpont, 2012). ARK1 is a 91.7 m (301 ft) guyed, lattice tower located 2.5 km east of Lepanto, Arkansas (Markus and Thienpont, 2012). The tower is mostly surrounded by flat, open farmland, with the exception of a line of
trees located about 80 m to the west (Markus and Thienpont, 2012). A view of the area near the tower looking south, the prevailing wind direction, is seen in Figure 23.

Figure 23    ARK 1 Monitoring Tower.

The observed wind shear exponent was lowest at ARK1 (0.288) as was the observed turbulence intensity at 15 m/s (0.107) (Markus and Thienpont, 2012). Equation 4 was applied to each site’s 10-minute data record for each site, and a weighted average
was calculated in which the weight was proportional to the energy content of the wind (Markus and Thienpont, 2012). Air density estimations ranged from 1.182 kg/m$^3$ to 1.198 kg/m$^3$ (Markus and Thienpont, 2012). The observed $k$ value from ARK1 was 2.28, indicative of a mostly consistent wind resource with occasional high wind events (Figure 24) (Markus and Thienpont, 2012).

![Figure 24](ARK1 Observed Wind Speed Frequency and Fitted Weibull Curve.)

Monthly average variation ranged from 2.8 m/s at ARK4 and ARK5 to 4.6 m/s at ARK1 (Figure 25) (Markus and Thienpont, 2012). Strongest winds typically occurred in early spring and late fall, while the weakest winds were observed during the summer, consistent with normal conditions resulting from strong atmospheric temperature and pressure gradients in the region (Markus and Thienpont, 2012).
All sites observed the strongest winds between the late evening and early morning hours (Figure 26) (Markus and Thienpont, 2012). On average, wind speed varied by about 1.7 m/s throughout the day at the top monitoring level on each tower (Markus and Thienpont, 2012).
The variation in mean wind shear exponent at the five sites was calculated (Figure 27). Lower wind shear patterns were found during the daylight hours and higher values at night (Markus and Thienpont, 2012).
Figure 27   Arkansas Tall Tower Sites Hourly Wind Shear Distribution.

Wind roses (Figure 28) indicate that the prevailing wind direction is south-southeast (Markus and Thienpont, 2012). Approximately 29% to 37% of the energy available from the wind on an annual basis is found in these two direction sectors (Markus and Thienpont, 2012).
Figure 28    Arkansas Tall Tower Wind Roses.
Long-term 80 m mean wind speed estimates were calculated using a method known as measure-correlate-predict, or MCP (Markus and Thienpont, 2012). In MCP, a linear regression or other relationship is established between two meteorological stations (Markus and Thienpont, 2012). Observed mean wind speeds taken from fourteen National Weather Service (NWS) Automated Surface Observing System (ASOS) surface stations were extrapolated using the power law equation (Equation 1). The resulting long-term 80 m mean wind speed estimates ranged from 5.25 m/s (11.74 mph) at ARK5 to 6.46 m/s (14.45 mph) at ARK1 (Markus and Thienpont, 2012). The corresponding 150 m values ranged from 6.56 m/s (14.68 mph) at ARK5 to 7.68 m/s (17.18 mph) at ARK1 (Markus and Thienpont, 2012).
The long-term projected wind speeds at the five monitoring sites suggest a modest wind resource throughout a large portion of Arkansas. A perspective of how the wind resource in Arkansas compares to that where significant wind development has occurred is given in the Arkansas Tall Tower report (Figure 29) (Markus and Thienpont, 2012). The dark trendline denotes the mean wind speed of installed wind plants by year and displays a downward trend over time (Markus and Thienpont, 2012). The downward trend was presumed to be caused by two factors: “1) the most attractive wind resource and energetic sites were developed in the early part of the 10-year period and consequently developers must now focus on sites with less attractive wind resource, and 2) the new generation of turbines with much larger rotors has reduced the wind speed threshold necessary for wind project commercial viability and allowed wind penetration into regions with more modest wind resources” (Markus and Thienpont, 2012).
The estimated long-term 80 m wind speeds of the five Arkansas sites are also plotted and highlighted on the lower right portion of the graph. The report noted that, while the 80 m mean wind speed of the five sites, 5.72 m/s, is lower than the average speed of installed wind farms in the past several years, more than a few wind farms have been installed in recent years at these speeds (Markus and Thienpont, 2012). The continuing trend toward the deployment of larger rotor diameter turbines was considered, and it was expected that more future wind farms will be installed with mean wind speed comparable to those observed in Arkansas (Markus and Thienpont, 2012). The results of this assessment suggest that wind development within the modest resource areas of Arkansas is feasible (Markus and Thienpont, 2012).
Significance of Research

Mississippi wind resource at common turbine hub heights has not been validated by measurements. The wind speed of wind farm installations is trending down due to increased turbine rotor size and a decrease in optimal installation areas. The downturn of wind speed needed for installation may reach mean wind speeds that are experienced in the flat floodplain of the Mississippi Delta. The 55 m anemometer data created during this study was the first wind resource dataset measured in the Mississippi Delta. The composites of wind anomalies created during the RPCA portion of this research depict other areas in the Delta that are located outside of this research’s test site experience high wind speeds, indicating further wind assessment research is warranted.

Constructing and operating a wind farm in the Delta may have significant economical benefits. Agriculture is the primary use of land in the Delta. Wind installations do not disturb agriculture and financially benefit land owners willing to lease their land (Borst, 2007). Furthermore, unemployment rates in the Delta have been 51% higher than the national average (Latanich, 2001). Wind installations could increase employment rates in one of the nation’s poorest regions.

The Delta’s wind resource is one of the best onshore wind resources Mississippi possesses. The possible economic benefits, environmental benefits, and results of this study should serve as strong incentives to research the wind resource of the Delta until the potential of wind installation in that area has been properly and legitimately rejected or accepted.
CHAPTER III
DATA AND METHODS

Tall Tower Measurement Site Selection, Anemometer Procurement, and Monitoring Configuration

Tall Tower Measurement Site Identification and Selection

The wind resource is ultimately the most significant element determining whether wind development at a particular site location or within a certain region will be economically viable. The AWS Truepower NREL 80 m Mississippi Wind Resource Map was used to identify the most energetic wind regions in Mississippi. Besides the coastal areas, the Mississippi Delta possesses the highest winds in the state (Figures 19 and 20). The high elevation of the bluffs was hypothesized to have high wind speeds; therefore, the main area of interest was along the Delta – non-Delta interface.

In addition to selecting a measurement area, the site selection process also had to take into account the availability of a tall tower to support the wind resource monitoring equipment. Several highway patrol towers and communication towers were located along the Delta – non-Delta interface; however permission to mount equipment free of cost was only granted at one communication tower owned by Leflore Communications Inc.

Tall Tower Overview

The tall tower selected for the measurement site is a guyed, lattice-type, communication tower (Figure 30). The tower is located approximately 8.5 miles
northeast of Greenwood, Mississippi. The abrupt increase in elevation along the bluff is depicted well (Figure 31) using Google Earth’s path profile tool. A 3-D elevation map facing east, towards the measurement site (Figure 32), provides perspective of the Delta – non-Delta interface. A map of the tower’s location in Mississippi (Figure 33) gives a broad view of the site. Tower specifics may be seen in Table 3.

Table 3  Tower Site Information.

<table>
<thead>
<tr>
<th>Site description</th>
<th>Southeast of Greenwood, Mississippi; atop first predominant bluff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude/longitude</td>
<td>33.539167°N, -90.035556°W</td>
</tr>
<tr>
<td>Site elevation</td>
<td>106.6 m</td>
</tr>
<tr>
<td>Anemometer type</td>
<td>Campbell Scientific Wind Sentry 03002-L</td>
</tr>
<tr>
<td>Datalogger type</td>
<td>Campbell Scientific, 15 minute time step</td>
</tr>
<tr>
<td>Tower type</td>
<td>Leflore Communications Antenna Structure</td>
</tr>
</tbody>
</table>
Figure 30  Leflore Communications lattice tower, measurement site.

Notes: The two men pictured were in the process of mounting the sensor equipment on October 13, 2011.
Figure 31  Google Earth Elevation Path Profile.

Notes: The profile begins at Greenwood, Mississippi, (left) and end at the measurement site (right). Notice the flat flood plain and the abrupt elevation increase of the Delta – non-Delta interface.
Figure 32  Google Earth 3-D elevation view facing east, depicting measurement site location.

Figure 33  Google Earth elevation map depicting measurement site location.
Monitoring Equipment Procurement

The Mississippi State University Delta Research Institute agreed to partner in this research by loaning one Campbell Scientific wind sentry 03002-L anemometer and wind vane (Figure 34), one Campbell Scientific CR200 datalogger (Figure 35), associated cables, and a five-foot boom used to mount the anemometer and wind vane. Mounting two anemometers at multiple heights was not an option due to time constrictons, lack of proper wind resource assessment knowledge, and funding.

Figure 34  Campbell Scientific Wind Sentry 0302-L anemometer and wind vane.
Monitoring Height Considerations

Initially, it was decided that the height of the monitoring equipment should be between 60 m and 80 m. The communication tower, unfortunately, did not have available space above 70 m due to previously installed equipment. The height of 60 m was, therefore, chosen due to the large amount of turbines with coinciding hub heights. During the installation, however, the cords needed to attach the sensors to the datalogger only reached 55 m. Funding and time were not available to purchase and install longer cords, so, a 55 m monitoring height was selected.

Sensor Directional Orientation

Westerly winds were hypothesized to be the prevailing wind direction of the region. The anemometer boom was oriented roughly west – southwest to face the hypothesized wind direction and to minimize the impact of wind flow around the tower on the speed measurements.
Equipment Installation

Personnel from Leflore Communications stated that one company should be used to mount the equipment onto the selected tower due to insurance stipulations. Diamond K Towers, of Greenville, Mississippi, was approached in October 2011 and asked to install the sensors at a discounted price. Diamond K Towers agreed to install the equipment free of charge, on October 13, 2011. Installation began on the 13th of October and was completed on the same date.

An employee of the Delta Research Institute was present during the installation. The employee manually calibrated the directional sensors and verified that the anemometer accurately recognized true North.

Wind Resource Characteristics

Wind data collection began October 13, 2011, at 1 PM Central Standard Time. The data collection process concluded October 17, 2012. Wind speed and direction measurements were taken every 10 seconds, the anemometer then averaged the speed and direction data every 15 minutes. The data logger then recorded the 15-minute wind speed mean, maximum and, minimum, as well as the wind direction average. Throughout the text, the anemometer will be referred to as “55 m anemometer” in place of the “anemometer at a height of 55 m” for simplification reasons. The data were imported into the software program, Windographer, a leading tool for analyzing wind resource data developed by Mistaya Engineering.

Once imported, the data were manually given location coordinates. Windographer recognized the data, in that three columns were created for maximum, mean, and minimum wind speeds with a sampling frequency of 15 minutes. Each wind speed
column was manually given an elevation of 55 m. The wind direction column was also recognized as directional data and was shown to have a measurement height of 55 m.

In order to visualize and describe the wind resource, Windographer was used to produce wind speed profiles, wind roses, and to calculate the best-fit Weibull k function.

Data Recovery

Data were subjected to quality control tests to ensure sensor failures did not occur. The data were received in Microsoft Excel format monthly throughout the monitoring period. Over the monitoring period, the sensors performed up to their specifications. The wind data values were converted to m/s from mph before they were imported into Windographer as a .txt file.

Wind Speed Data

In order to understand the monthly and hourly distributions of wind speed, diurnal wind speed profiles and monthly wind speed profiles were created using Windographer. The 55 m anemometer wind speed data consist of a one-year time series taken at 15-minute time intervals. Minimum, maximum, median and mean values were recorded.

Mean Diurnal Profiles

Seasonal mean wind speed profiles are used to visualize the mean wind speeds of each month over the course of the measurement time frame. The mean wind speed data column was selected to display the annual mean wind speed profile of the 55 m anemometer data by selecting the time series tab and plotting the monthly means.

Windographer’s Diurnal Profile tab displays the average daily profile of one or more data columns. Windographer calculates the mean daily profile of a set of data points
by finding the average value of all the points that occur within the hour of 12:00 am to 1:00 am, and so on for each of the 24 hours of the day. Selecting the single profile option created the mean diurnal profile.

Choosing the ‘by month’ option created a diurnal profile for each month of the year. The monthly diurnal profile displays the mean wind speed of each hour, of each day, over the course of a month.

*Probability Distribution Function*

Windographer uses the maximum likelihood algorithm to fit a Weibull distribution to a measured wind speed distribution. The maximum likelihood method (Stevens and Smulders, 1979) fits a Weibull distribution to a set of observed wind speeds. This method utilizes the following equation to calculate, in an iterative fashion, the Weibull $k$ parameter:

$$k = \left[ \frac{\sum_{i=1}^{N} u_i^k \ln(u_i)}{\sum_{i=1}^{N} u_i^k} - \frac{\sum_{i=1}^{N} \ln(u_i)}{N} \right]^{-1}$$  \hspace{1cm} (6)

where $U_i$ is the wind speed in time step $i$ and, $N$ is the number of time steps.

After the shape parameter $k$ has been found, the following equation gives the value of the scale parameter $c$:

$$c = \left[ \frac{\sum_{i=1}^{N} u_i^k}{N} \right]^{\frac{1}{k}}$$  \hspace{1cm} (7)

This iterative algorithm was used to calculate the best-fit Weibull distribution of the 55 m anemometer wind speed data.
Wind Direction

The 55 m anemometer wind direction data consist of a one-year time series taken at 15-minute time intervals. Windographer’s Wind Rose capabilities offer several types of graphs showing occurrences or frequencies by speed or direction.

To observe the frequency of wind speeds, a mean wind speed frequency rose was created. A wind rose typically displays wind direction. Windographer, however, also offers the option to create a wind rose that displays the frequency of wind speed. Plotting wind speed against frequency helps visualize what direction the fastest wind speeds occur. The option to plot speed and frequency also highlights possible tower distortion by displaying areas with abnormally low wind speeds and frequency.

The 2011-2012 wind rose was created using the frequency versus all direction sensors option. Despite having only one direction sensor, this option displayed a wind rose depicting the dominant wind direction of the 55 m sensor.

The frequency versus direction and month option was chosen to create monthly wind roses. A separate analysis for each month of the year was conducted. The monthly wind roses displayed what wind direction was dominate during winter and summer months.

Wind Power Density

The 55 m anemometer data did not include temperature or pressure data. WPD was estimated using pre-defined values programmed into Windographer. For any dataset containing wind speed data, Windographer uses the ideal gas law in the form of solving for density:
\( \rho = \frac{M}{MR} \frac{p}{T} \)  \( (8) \)

where \( p \) is pressure (kPa), \( \rho \) is density (kg/m\(^3\)), \( R \) is the universal gas constant (8.314472 m\(^3\) kPa K\(^{-1}\) kmol\(^{-1}\)), \( M \) is the molar mass (kg/kmol), and \( T \) is the temperature (K).

Windographer does not account for the effect of humidity on air density. The molar mass of dry air, 28.9664 kg/kmol, is therefore used to write the equation as:

\[ \rho = 3.4837 \frac{p}{T} \]  \( (9) \)

Windographer used the above equation to calculate the air density in every time step, and added that time series to the 55 m anemometer data as a pre-defined calculated data column. The 55 m anemometer data did not include temperature data; therefore, Windographer estimated the temperature column based on the site elevation according to the International Standard Atmosphere. Similarly, because the data did not include an air pressure column, Windographer estimated the air pressure according to the International Standard Atmosphere. The estimated air density column is then used to calculate wind power density.

Windographer calculates the WPD from the wind speed and air density using the following equation:

\[ \frac{P_A}{A} = \frac{1}{2} \rho U^3 \]  \( (10) \)

where \( \frac{P_A}{A} \) is the wind power density, or the power per unit area, within the time step \((W/m^2)\), \( \rho \) is the air density with the time step \((kg/m^3)\), and \( U \) is the average wind speed within the time step \((m/s)\).
The WPD column was added to the 55 m anemometer data as a pre-defined calculated data column.

In order to simplify the 55 m anemometer data measurements, a data table was created to display an organized synopsis of the 55 m data dates, estimated wind power class, estimated wind power density, mean, median, and max wind speed, and Weibull distribution parameters.

**Principal Component Analysis**

Principal component analysis (PCA) is a useful method of identifying modes of spatial variations in atmospheric flow.

**Data**

To detect the leading modes of wind variability in the Mississippi Delta, a Rotated Principal Component Analysis (RPCA) was conducted on the 30 m wind data. The 30 m Delta wind data were extracted from the North American Regional Reanalysis (NARR) dataset. The NARR data contained monthly wind direction and speed data from 1979 to 2011 (396 months). The data are spread between 32 – 35 °N and 89 - 91° W with 32 km (0.3 degrees) grid spacing between each grid point. Each grid point represents the monthly mean wind speed and direction.

**RPCA Method**

All calculations were computed in “R”, a software program commonly used for statistical computing and graphing. The anomaly patterns detected were displayed on maps using GRaDS, a tool often used for displaying earth science data.

The PCA equation is given as
\[ Z = FA^t, \]  

(11)

where \( Z \) represents a standardized anomaly matrix of the input data, \( F \) represents a matrix of principal component (PC) scores and \( A \) represents a matrix of PC loadings (Wilks, 2011).

The RPCA process began by formulating the scaled matrix of the data \((Z)\). Matrix \( Z \) was a 396x56 matrix. The 56 columns represent the grid points; the 396 rows represent the months. Following the creation of \( Z \), the correlation matrix \( R \) of \( Z \) is computed using

\[
R = \frac{Z^t Z}{n-1}
\]

(12)

It is necessary to determine over which dimension of \( Z \) the correlation matrix should be computed. Correlating between the columns (events) or correlating between the rows (grid points) was considered. Correlating along the time dimension, which are the months in this study, is defined as a \( T \) mode correlation (Richman, 1986). Correlations computed along the gridpoint (spatial) dimension are defined as \( S \) mode (Richman, 1986). The relationships of wind magnitude over the Delta were of interest in this study, therefore the S-mode analysis was selected, yielding a 56 x 56 dimension \( R \) matrix.

The correlation matrix \( R \) is diagonalized into an eigenvalue matrix \( D \) with a related eigenvector matrix \( V \) given by

\[
R = VDV^t
\]

(13)

By definition, eigenvectors point in directions of maximum variability within a dataset (Mercer et al., 2012). The eigenvalue-variance relationship implies that a small subset of the original eigenvalues related to eigenvector matrix \( V \) explains most of the significant variability in \( Z \) (Mercer et al., 2012). Matrix \( V \) must, therefore, be condensed.
before the final computation of $F$ to retain only the eigenvalues that include the most variability (Mercer et al., 2012). If too few eigenvalues are retained, however, important information can be lost.

A scree test and congruence test are used to condense the eigenanalysis. The two methods of data dimensionality reduction allow the removal of noise (low-variability eigenvalues) (Mercer et al., 2012). When the scree test was applied to the eigenvalue series, it was suggested that the unrotated PCs, unlike all subsequent ones, contained non-random signals (Richman and Lamb, 1987). The scree test considers that the last pronounced discontinuity in the eigenvalue series before the values level off represents the separation between the unrotated PCs that contain non-random signals (those with larger eigenvalues) and the ones that do not (Richman and Lamb, 1987). A congruence test was also performed to confirm the eigenvalues that represented the most significant variability were retained. The congruence coefficient is represented as:

$$n = \frac{\sum xy}{(\sum x^2 \sum y^2)^{1/2}}$$  \hspace{1cm} (14)

where $x$ represents the vector of the correlation matrix corresponding to the largest magnitude loading for the given loading vector, and $y$ is the loading vector. Each loading is given one value, $n$. If the value for $n$ falls below 0.81, then the loading must be rejected (Richman and Lamb, 1987).

The condensed $V$ and $D$ matrices from this study were used to calculate the loading matrix $A$:

$$A = VD^{1/2}.$$  \hspace{1cm} (15)
The precise orientation of the associated eigenvectors may not truly point in the direction of the greatest localized variability due to the constraint of orthogonality of the eigenvectors, but may instead point *between* the highest areas of variability (Mercer et al., 2012). Meteorological parameters, such as wind, are, for example, influenced by synoptic and regional factors, giving some degree of non-orthogonality between wind patterns of neighboring locations in different groups. Such similarities are not accounted for in PCA solutions, making some of the derived PCA patterns physically unrealistic (Richman, 1986). To correct this problem in this study, the PC coordinate system was “rotated” using a Varimax PC rotation (Richman, 1986), thereby creating a new rotated loading matrix $B$ with the same dimensionality as $A$ that explains the same total variance as in $A$.

The congruence test was then reapplied to the correlation matrix and the rotated loading matrix $B$. The test was performed several times using a decreasing number of principal components until loading values remained above 0.81.

The score matrix $F$ was then computed using least squares approximation:

$$ F = Z^T \ast B \ast (B^T B)^{-1} $$

$F$ is a $3653 \times 4$ matrix that computes the scores for each set of loadings. $F$ represents temporal trends in $B$, or how wind magnitude varies at each grid point.

Finally, individual anomaly maps of the main variability patterns are created using $B$. A time series of the PC scores retained was plotted to identify if each variability pattern was increasing or decreasing with time. A trend line was fit to the RPC score patterns to assess any temporal trends within each loading map. The $P$ value of the linear regression indicated whether the slope of the trend line was significant. Variance explained was also calculated to determine the percent of time each pattern is dominant.
CHAPTER IV
RESULTS

Wind Resource Characteristics

Wind data collected from the 55 m anemometer, from the perspective of both mean wind speed and estimated mean power density, indicate a low wind resource. The 55 m mean wind speed of the 12 months of data collection was 3.883 m/s. The estimated mean air density at 50 m was 54 W/m², Class 1 (Poor). The highest maximum 15-minute mean wind speed recorded was 22.22 m/s and occurred in February 2012.

Data Recovery

The rate of recovery was 100%. The total possible number of records for the monitoring period was 35,512; the valid records were the same, 35,512.

Mean wind speeds were lowest (Figure 36) in the summer and highest in the winter, with a minimum mean wind speed in July (2.95 m/s) and a maximum mean wind speed in November 2011 (4.65 m/s).
Figure 36  Monthly mean wind speed profile.

Mean Diurnal Profile

Wind speed varied over the day (Figure 37), with mean wind speeds generally higher, above 4 m/s, between 9 PM and 7 AM, and lowest at approximately 6:30 PM (Figure 38).
Figure 37  Annual mean diurnal profile

**Monthly Mean Diurnal Wind Speed Profiles**

The seasonal mean wind speed profile (Table 4) shows that the highest monthly mean wind speed (4.65 m/s) occurred in November 2011, and the lowest monthly mean wind speed (2.943 m/s) occurred in July. The maximum 15-minute mean wind speed (14.54 m/s) occurred in February 2012. The monthly mean diurnal wind speed profiles (Figures 38 – 50) indicate November, January, February, March and April experienced mean wind speeds that remained above 4.0 m/s, indicating that the winter and spring seasons have the highest mean wind speeds.
### Table 4  55 m Mean Wind Speed Monthly Summary

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Median (m/s)</th>
<th>Min (m/s)</th>
<th>Max (m/s)</th>
<th>Weibull K</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Oct</td>
<td>3.94</td>
<td>0.13</td>
<td>8.59</td>
<td>3.089</td>
</tr>
<tr>
<td>2011</td>
<td>Nov</td>
<td>4.65</td>
<td>0.47</td>
<td>10.37</td>
<td>3.635</td>
</tr>
<tr>
<td>2011</td>
<td>Dec</td>
<td>3.81</td>
<td>0</td>
<td>12.22</td>
<td>2.394</td>
</tr>
<tr>
<td>2012</td>
<td>Jan</td>
<td>4.63</td>
<td>0</td>
<td>10.87</td>
<td>2.817</td>
</tr>
<tr>
<td>2012</td>
<td>Feb</td>
<td>4.19</td>
<td>0</td>
<td>14.54</td>
<td>2.576</td>
</tr>
<tr>
<td>2012</td>
<td>March</td>
<td>4.23</td>
<td>0</td>
<td>11.62</td>
<td>2.71</td>
</tr>
<tr>
<td>2012</td>
<td>April</td>
<td>4.13</td>
<td>0</td>
<td>10.21</td>
<td>2.912</td>
</tr>
<tr>
<td>2012</td>
<td>May</td>
<td>3.22</td>
<td>0</td>
<td>11.58</td>
<td>2.169</td>
</tr>
<tr>
<td>2012</td>
<td>June</td>
<td>3.63</td>
<td>0</td>
<td>14.49</td>
<td>2.371</td>
</tr>
<tr>
<td>2012</td>
<td>July</td>
<td>2.98</td>
<td>0</td>
<td>8.61</td>
<td>2.742</td>
</tr>
<tr>
<td>2012</td>
<td>Aug</td>
<td>3.3</td>
<td>0</td>
<td>11.67</td>
<td>1.998</td>
</tr>
<tr>
<td>2012</td>
<td>Sept</td>
<td>3.67</td>
<td>0</td>
<td>10.27</td>
<td>2.719</td>
</tr>
<tr>
<td>2012</td>
<td>Oct</td>
<td>3.67</td>
<td>0</td>
<td>8.2</td>
<td>2.969</td>
</tr>
</tbody>
</table>

**Figure 38**  October 2011 mean diurnal wind speed profile.
Figure 39  November 2011 mean diurnal wind speed profile.

Figure 40  December 2011 mean diurnal wind speed profile.
Figure 41  January 2012 mean diurnal wind speed profile.

Figure 42  February 2012 mean diurnal wind speed profile.
Figure 43  March 2012 mean diurnal wind speed profile.

Figure 44  April 2012 mean diurnal wind speed profile.
Figure 45  May 2012 mean diurnal wind speed profile.

Figure 46  June 2012 mean diurnal wind speed profile.
Figure 47  July 2012 mean diurnal wind speed profile.

Figure 48  August 2012 mean diurnal wind speed profile.
Figure 49  September 2012 mean diurnal wind speed profile.

Figure 50  October 2012 mean diurnal wind speed profile.
Probability Distribution Function

The wind probability distribution (Figure 51) shows that, most often (about 30% of the time), the wind was within the 4-5 m/s range. The observed $k$ value was calculated at 2.46, indicative of a mostly consistent wind resource with occasional high wind events.

Figure 51 Wind speed distribution of the 55 m anemometer data.

Mean Wind Speed Frequency Rose

Radius indicates frequency in this kind of graph. The mean wind speed rose (Figure 52) shows that the highest mean wind speeds, about 4.7 m/s, came from the southeast. The communication tower blocking the anemometer likely caused the noticeable lack of ENE wind speed.
Wind Direction

*Frequency versus Direction*

A south-southeasterly wind was observed about 12% of the time, a southerly wind about 9%, a south-southwesterly wind about 8%, a westerly wind about 2%, and a northerly wind about 3% of the time (Figure 53).
Figure 53  Mean wind directions at 55 m anemometer location.

Monthly Frequency Versus Direction and Wind Rose

During the monitoring period, each month experienced winds with a southerly component at least 10% of the time (Figure 54). The month with the highest mean and maximum wind speed, February, experienced the highest frequency of north-northwest winds. As stated before, winds that advected across the flat flood plain were expected to have higher wind speeds.
Wind Power Density

The estimated WPD at 50 m was calculated at 53 W/m², placing the wind resource at the Greenwood site location in the wind power class 1 (Poor). The wind power class, along with the meteorological tower data synopsis can be found in Table 5.
Table 5  Physical and estimated environmental parameters during wind collection period.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>N 33° 32' 21.750&quot;</td>
</tr>
<tr>
<td>Longitude</td>
<td>W 90° 2' 8.250&quot;</td>
</tr>
<tr>
<td>Elevation</td>
<td>157 m</td>
</tr>
<tr>
<td>Start date</td>
<td>10/13/2011 13:15</td>
</tr>
<tr>
<td>End date</td>
<td>10/17/2012 11:15</td>
</tr>
<tr>
<td>Duration</td>
<td>12 months</td>
</tr>
<tr>
<td>Length of time step</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Calm threshold</td>
<td>0 m/s</td>
</tr>
<tr>
<td>Mean temperature</td>
<td>14.0 °C</td>
</tr>
<tr>
<td>Mean pressure</td>
<td>99.45 kPa</td>
</tr>
<tr>
<td>Mean air density</td>
<td>1.207 kg/m³</td>
</tr>
<tr>
<td>Power density at 50m</td>
<td>53 W/m²</td>
</tr>
<tr>
<td>Wind power class</td>
<td>1 (Poor)</td>
</tr>
<tr>
<td>Power law exponent</td>
<td>0.183</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Roughness class</td>
<td>2.76</td>
</tr>
</tbody>
</table>

Rotated Principal Component Analysis

PCA Composites

A RPCA s-mode analyses was conducted using NARR 30 m wind magnitude data. The congruence test criterion of retaining factors with eigenvalues greater than 0.81 gave three significant eigenvectors. The scree test (Figure 55) and variance explained test (Table 6) indicated that three RPCA modes were significant.
Table 6  Variance explained results.

<table>
<thead>
<tr>
<th>PC Loading</th>
<th>Variance Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC Loading 1</td>
<td>0.46406043</td>
</tr>
<tr>
<td>PC Loading 2</td>
<td>0.44354687</td>
</tr>
<tr>
<td>PC Loading 3</td>
<td>0.07928976</td>
</tr>
</tbody>
</table>

The variances accounted for by the first three RPCA modes were 46%, 44%, and 8% respectively (Table 6). Thus, the three significant RPCA modes accounted for 98% of the total spatial variance.
The anomalies from each of the 3 rotated PC were plotted into GRaDS, displaying the three main variance patterns that were detected. The warm colors are representative of positive anomalies while the cool colors are representative of negative anomalies. Negative anomalies represent periods of time with slower wind speeds. Inversely, positive anomalies represent periods of time with higher wind speeds. The interpretation of the composites can be slightly complex, as the sign of the anomaly may be the opposite of what is displayed, depending on the PC score values. For instance, a map showing negative anomalies may represent higher wind speeds if the PC scores are also negative. PC scores for each of the 3 principal components that were retained and rotated were plotted onto a time series, representing 30 m wind magnitude anomalies that occurred in the data.

PC 1

The time series of the first PC (Figure 56) does not display a clear cyclic pattern. The anomaly composite (Figure 57) has negative values. When displayed in GRaDS, the anomalies (Figure 57) have a negative value indicating that wind speeds are above average in the northwest corner of Mississippi. Highest wind values occur near Robinsville, Mississippi and run south along the Mississippi River until reaching an area just west of Greenville, Mississippi. A linear regression of the loading scores shows a significant positive slope with a p-value of 0.006656.
Figure 56  PC 1 time series results.
Notes: The x-axis represents 396 months; the y-axis represents the loading scores.

Figure 57  Anomaly composite 1.
Notes: Red dot is the approximate location of the tall tower measurement site.
PC 2

The time series of PC 2 loadings (Figure 58) does not display a clear pattern. The linear regression resulted in a trend line with an insignificant slope. When displayed in GRaDS, the anomaly values are negative. The negative loading values and negative anomaly values equate to the opposite of what is displayed (Figure 59), meaning a pattern of higher wind speeds in the southeast corner of Mississippi are dominant 44% of the time.

Figure 58   PC 2 time series results.

Notes: The x-axis represents 396 months; the y-axis represents the loading scores.
Figure 59  Anomaly composite 2.

Note: The red dot is the approximate location of the tall tower measurement site.

**PC 3**

The time series of PC 3 loadings (Figure 60) does not indicate a clear cyclic pattern. The linear regression resulted in a trend line with an insignificant increasing slope. The GRaDS image (Figure 61) displays positive anomalies. The interpretation is, therefore, that higher winds are seen in the northeast corner of the Delta 8% of the time (Figure 61).
Figure 60  PC 3 time series results.

Note: The x-axis represents 396 months; the y-axis represents the loading scores.

Figure 61  Anomaly composite 3.

Notes: The red dot is the approximate location of the tall tower measurement site.
CHAPTER V
DISCUSSION

The primary goals of this work were to determine the 55 m wind resource and wind characteristics at a site location in the Mississippi Delta and to outline areas for future wind resource assessments by defining other locations in the Delta with higher than average wind speeds. The first goal was accomplished through the collection of limited 55 m wind resource data from one communication tower located near Greenwood, Mississippi. The quality of the data is considered limited because only one wind speed and direction sensor was used instead of the more common multiple sensors at multiple height levels method. The 55 m height is also less than ideal, as it does not reach the standard 60 m or 80 m hub height. Turbulence, wind shear, and tower distortion could not be calculated due to the lack of multiple height measurements. Some of the inputs for WPD (temperature and pressure) had to be estimated, but the most significant component, wind speed, was measured, not estimated; this resulted in an estimated 50 m WPD of 53 W/m².

Data recovery was 100%, well above the industry standard of 90% (Markus and Thienpont, 2012). The recorded data was analyzed using Windographer, an industry leading software package used for wind resource analysis. The mean wind speed of the Leflore Communications tower measurement site, over a one-year monitoring period,
was 3.883 m/s, well below the hypothesized 6.5 m/s. The mean diurnal profiles created from the 55 m anemometer data showed that wind speeds are typically faster (above 4 m/s) in the overnight hours and slower during the late morning and early afternoon hours. Monthly diurnal profiles indicated that wind speeds are fastest (above 4 m/s) during the winter and spring months.

The wind roses created from the 55 m anemometer data showed that winds were predominately south-southeast. The site, therefore, did not benefit from the increase in elevation, and the hypothesis of a predominant westerly wind direction was rejected. Winds experienced the higher surface friction associated with Mississippi pine forests and rolling hills instead of the low surface friction of the flood plain.

The second goal of this research was accomplished by creating high-resolution (32 km) wind magnitude composites using 30 m NARR data. RPCA solutions extracted three dominant RPCA modes from the 30 m wind magnitude NARR data, accounting for 98% of wind magnitude variance.

The composites revealed features that were not illustrated with the lower resolution wind resource estimate maps created by NREL and AWS Truepower. The first composite revealed that, over a 33 year time period, 30 m wind speeds are higher than the mean in the northwest corner of the Delta 46% of the time, similar to what is depicted on the NREL AWS Truepower map. The second composite indicated that, unlike what is shown on the NREL AWS Truepower map, the southeast corner of the Delta experiences higher than average wind speeds 44% of the time. The third composite revealed the northeast corner of the Delta experiences higher than average wind speeds 8% of the time, a feature that was also not depicted on the NREL AWS Truepower map.
The results from this study also showed that RPCA could be used to delineate homogeneous wind speed patterns. In the case of the Mississippi Delta, three areas with higher wind speeds were identified. The identification of the three spatial zones is of significance in ensuring the accurate identification of possible wind resource measurement areas. The locations identified would also be useful in the planning and management of a larger scale wind resource assessment, similar to the study conducted in Arkansas (Markus and Thienpont, 2012).

This study did not employ an industry standard wind resource assessment (Bailey, 1997) due to initial lack of knowledge concerning wind resource assessments, funding, and time. The 55 m anemometer data may not accurately depict the wind resource at the site chosen for this research due to tower shadowing. The data collected, however, are the first of their kind in Mississippi and can serve as insight into wind energy level patterns in an area that may possess wind speeds viable for wind generation.

According to array-average wind speed information from wind farms installed within the United States during the past 10 years (Markus and Thienpont, 2012), the mean wind speed of installed wind plants is decreasing over time. The downward trend is likely due to the early development of more attractive wind resource sites, and new generation of turbines with much larger rotors has reduced the wind speed threshold necessary for wind project commercial viability. Considering that the trend toward the development of larger rotor diameter turbines is expected to continue, future wind farms may be installed in areas with mean wind speeds comparable to those available in the Mississippi Delta. For example, states such as Arkansas believe 5.72 m/s wind speeds
may be feasible for wind energy installation; this suggests that further wind energy
research is warranted in Mississippi.

The trend toward the deployment of larger rotor diameter turbines is expected to
continue, thereby creating the need for accurate wind resource assessments in areas with
estimated wind resources, such as Mississippi.
CHAPTER VI
CONCLUSIONS

1. The wind resource at a site location in the Mississippi Delta was measured from October 2011 to October 2012 using a wind sensor mounted on a communication tower. The wind resource at the measurement site experienced a mean wind speed of 3.883 m/s, lower than the 6.5 m/s industry mean wind speed of installed wind plants.

2. The 50 m WPD of the measurement site had an estimated value of 53 W/m², classifying the wind resource as Class 1 (Poor).

3. The added elevation along the Delta – non-Delta interface did not help to increase wind speeds at the measurement site. Winds were not predominately westerly and were, instead, southeasterly. The southeasterly winds did not benefit from the lower surface friction of the flat floodplain; instead, the winds experienced the higher surface friction of the Mississippi pine forest.

4. The wind probability distribution of the 55 m anemometer data showed that, most often (about 30% of the time), winds speeds were within a 4-5 m/s range. The observed $k$ value was calculated at 2.46, indicative of a mostly consistent wind resource with occasional high wind events.
5. The RPCA composites revealed that, over a 33 year time period, 30 m wind speeds are higher in the northwest corner of the Delta 46% of the time, that the southeast corner of the Delta experiences higher wind speeds 44% of the time, and that the northeast corner of the Delta experiences higher wind speeds 8% of the time. These areas, especially the northwest corner and southeast corner of the Delta, should be further investigated for possible wind power potential.

6. The RPCA methodology was proven useful in highlighting more attractive and energetic wind resource areas. Future wind resource assessments could use this methodology, which is currently not used in the wind industry, during the preliminary area identification portion of a wind resource site assessment.
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