Wind Characteristics and Resource Assessment

Owen Roberts,

National Renewable Energy Laboratory

August 15, 2009

Organization of Presentation

- Wind Assessment Basics
- Big Picture - Wind Mapping
- Web Information
- Turbine Power Calculations

WIND POWER RELATIONSHIPS

$$P = \frac{1}{2} \rho A V^3$$

- P → AVAILABLE POWER
- ρ → AIR DENSITY
- A → SWEPT AREA
- V^3 → WIND VELOCITY CUBED

EXAMPLE: SAME TURBINE, SEA LEVEL, DIFFERENT SITE

$$P = KV^3$$

WIND VELOCITY = v $\quad P_1 = Kv^3$

WIND VELOCITY = $2v$ $\quad P_2 = 8Kv^3$

$$P_2 = 8P_1$$

EXAMPLE: DIFFERENT TURBINE, SEA LEVEL, SAME SITE

$$P = CD^2$$

ROTOR DIAMETER = d $\quad P_1 = Cd^2$

ROTOR DIAMETER = $2d$ $\quad P_2 = 4Cd^2$

$$P_2 = 4P_1$$

NREL National Renewable Energy Laboratory

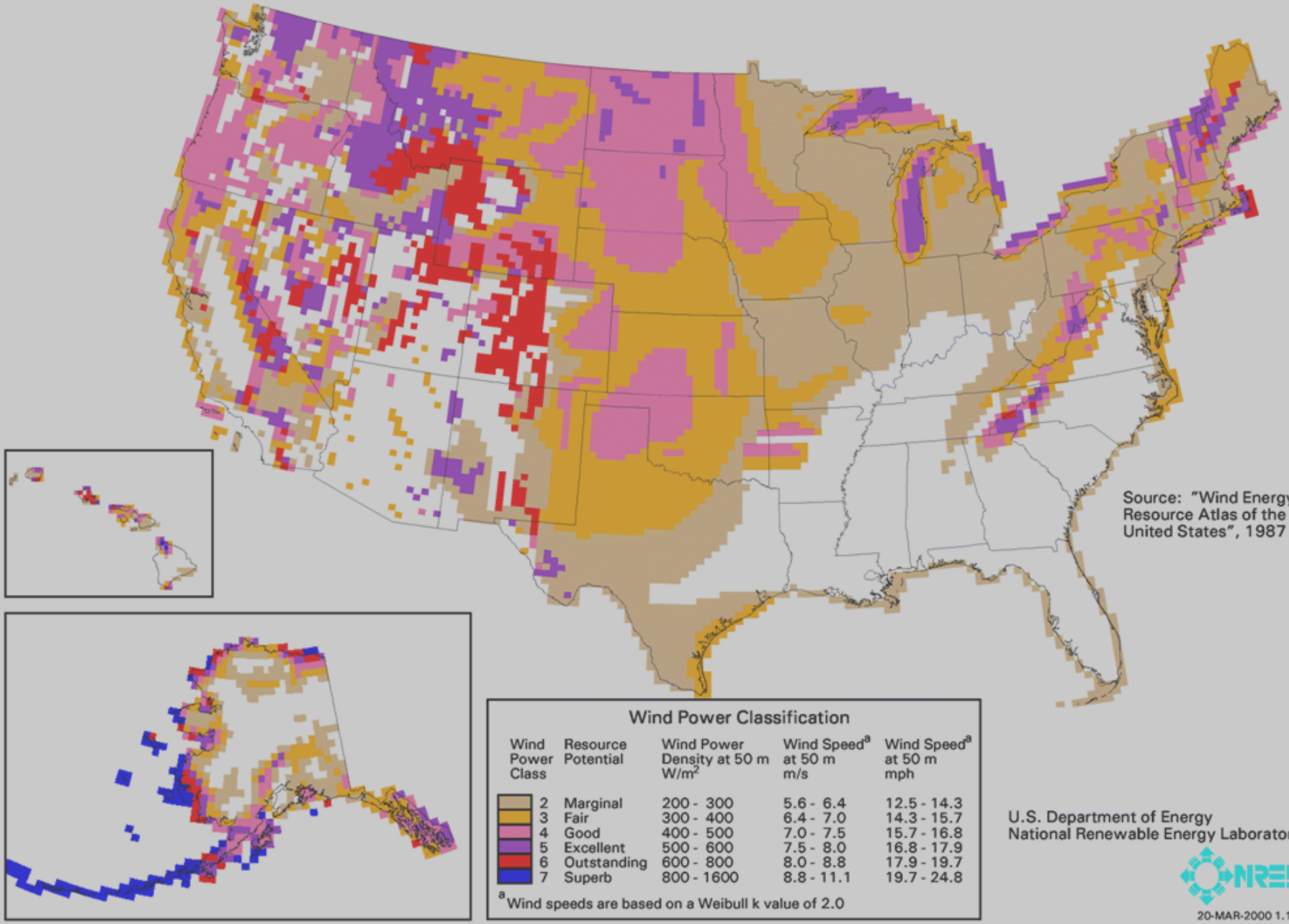
Why Use Power Density Instead of Speed for Mapping Wind Resources?

Comparison of Annual Average Wind Power at Four Sites with Identical Annual Average Wind Speeds at 10 m

Site	Annual Average Wind Speed, m/s (mph)	Annual Average Wind Power Density, W/m²	Wind Power Power Class
Constant Wind Speed (hypothetical)	6.3 (14)	150	2-3
Culebra, Puerto Rico	6.3 (14)	220	4
Tiana Beach, New York	6.3 (14)	285	5
San Gorgonio, California	6.3 (14)	365	6

Wind power varies with distribution of wind speeds, and air density (elevation, air temperature and pressure)

United States - Wind Resource Map (1987)

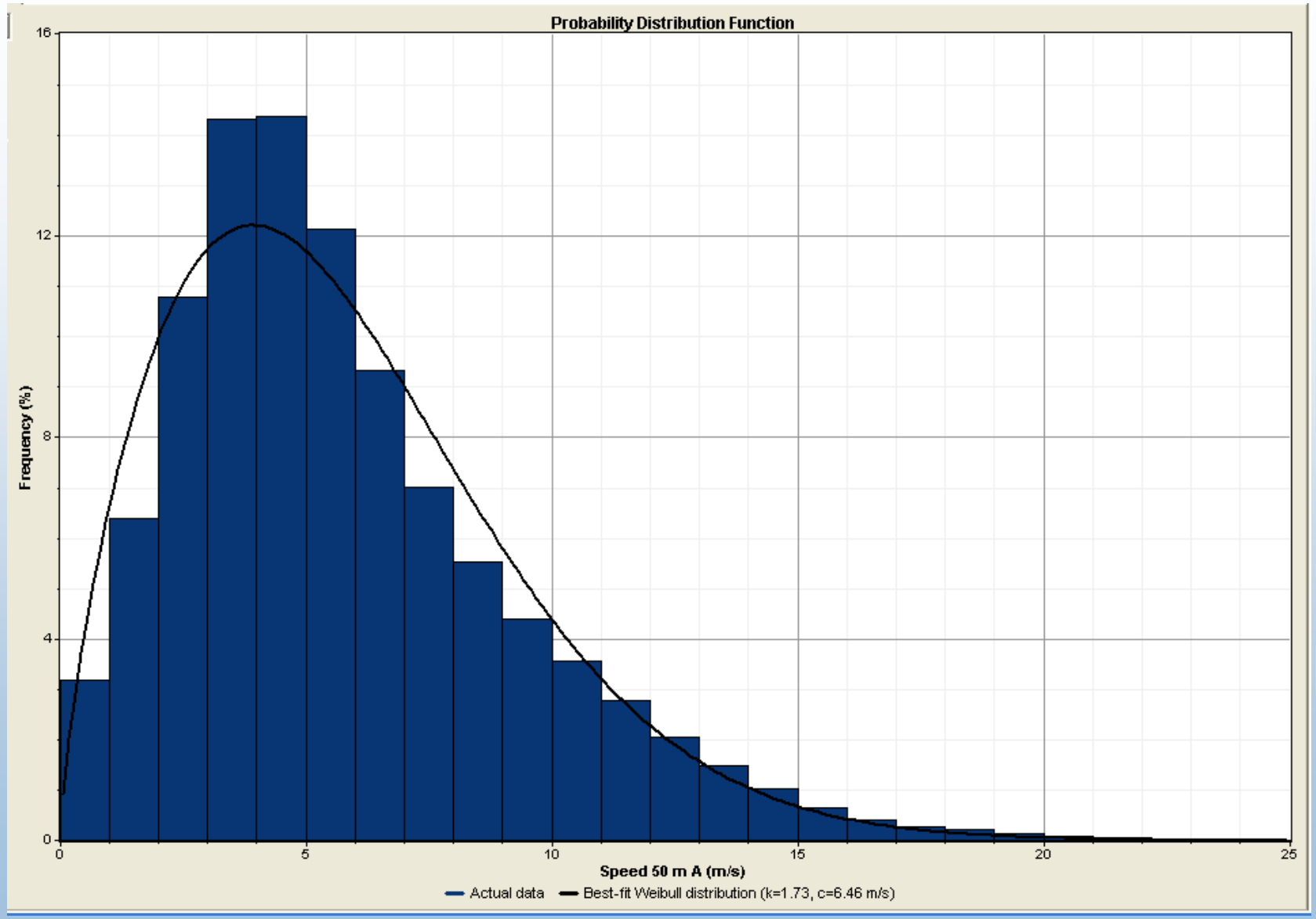


Wind Power Classification

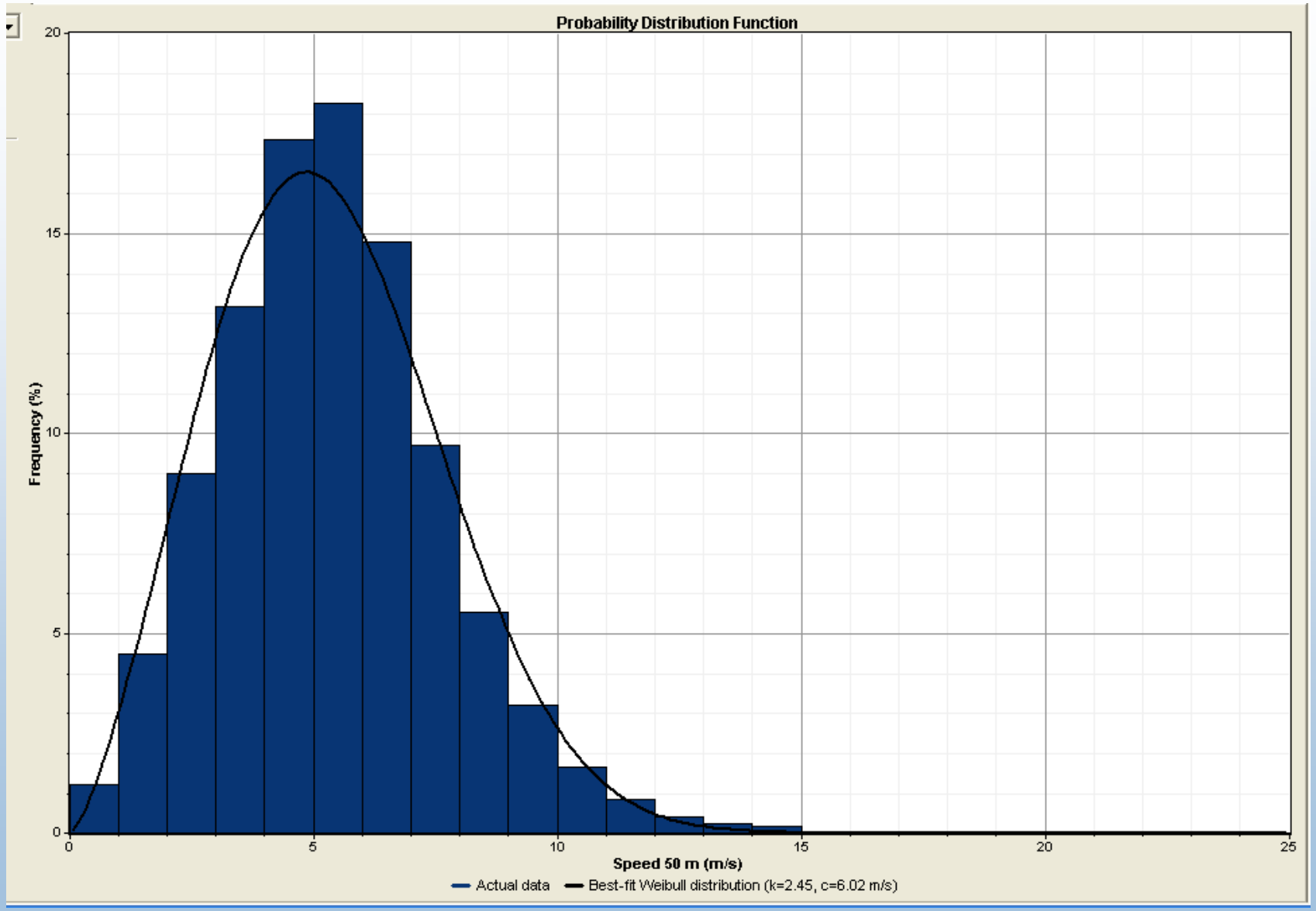
Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m ^{2}	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
1	Poor	0 - 200	0.0 - 5.6	0.0 - 12.5
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	> 800	> 8.8	> 19.7

[a] Wind speeds are based on a Weibull k value of 2.0

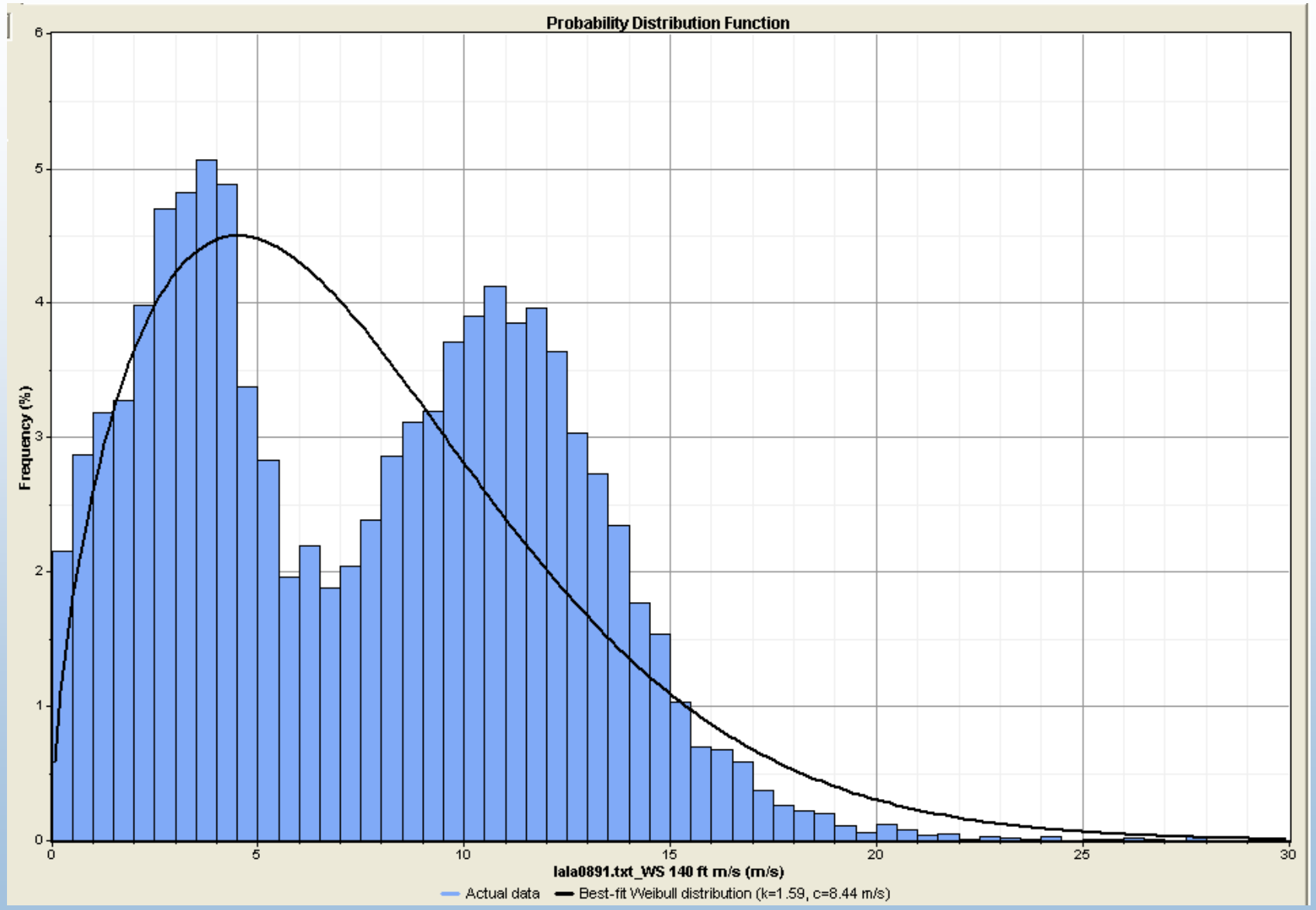
South Central Colorado



Caribbean / Coastal



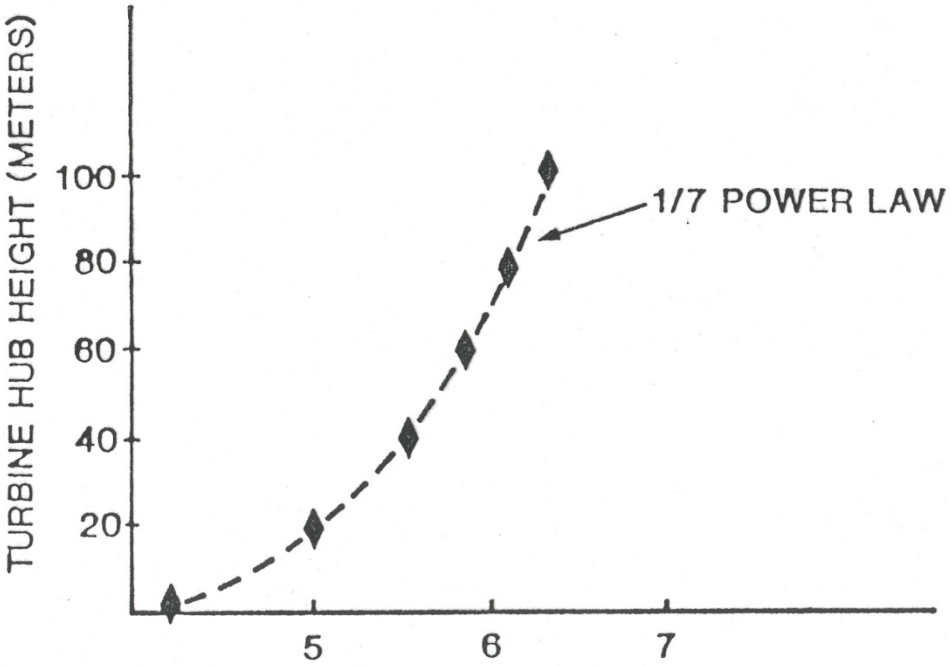
Hawaii Downslope Winds



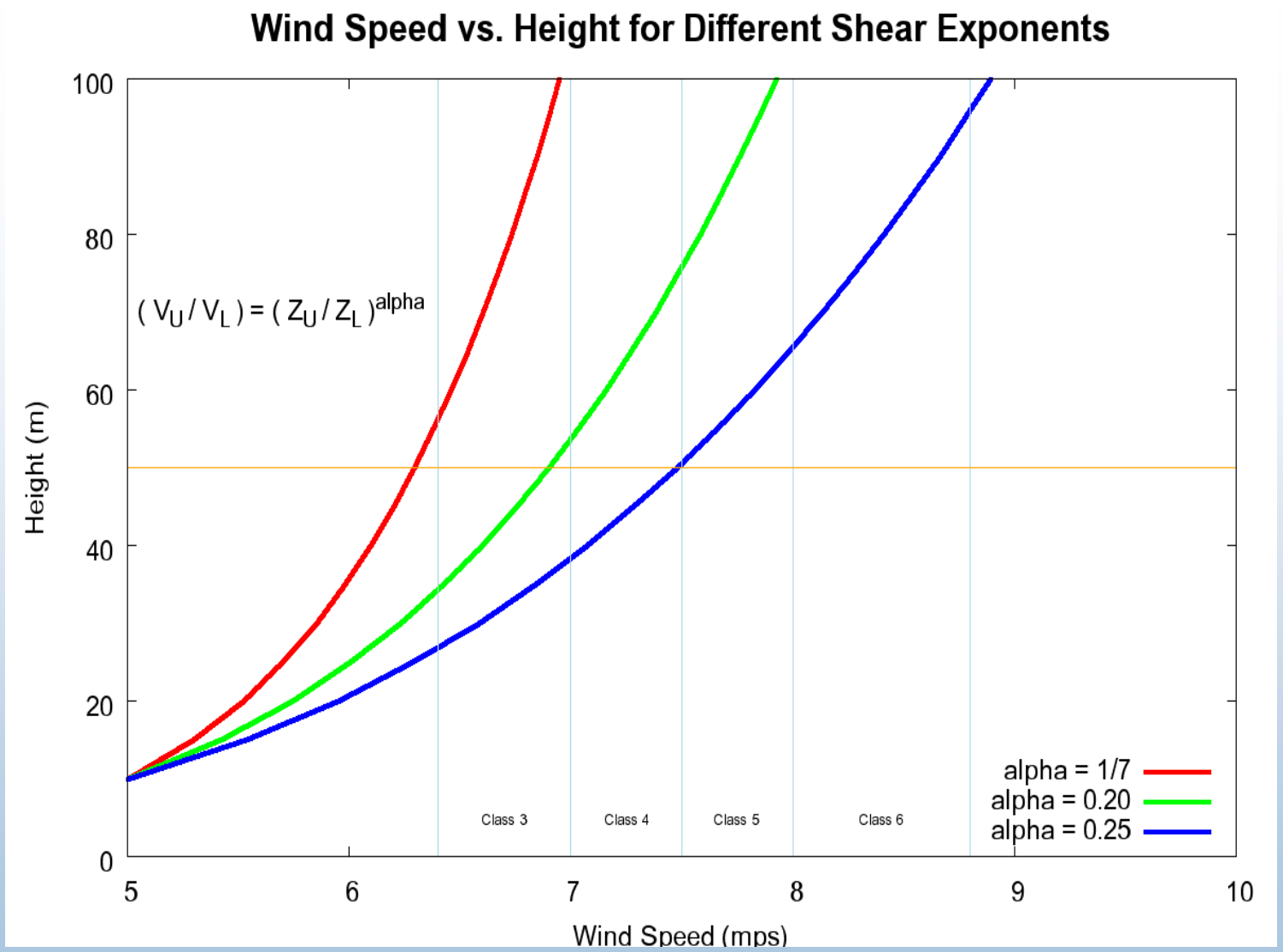
Wind Speed Versus Height

$$\frac{V}{V_o} = \left(\frac{H}{H_o}\right)^n$$

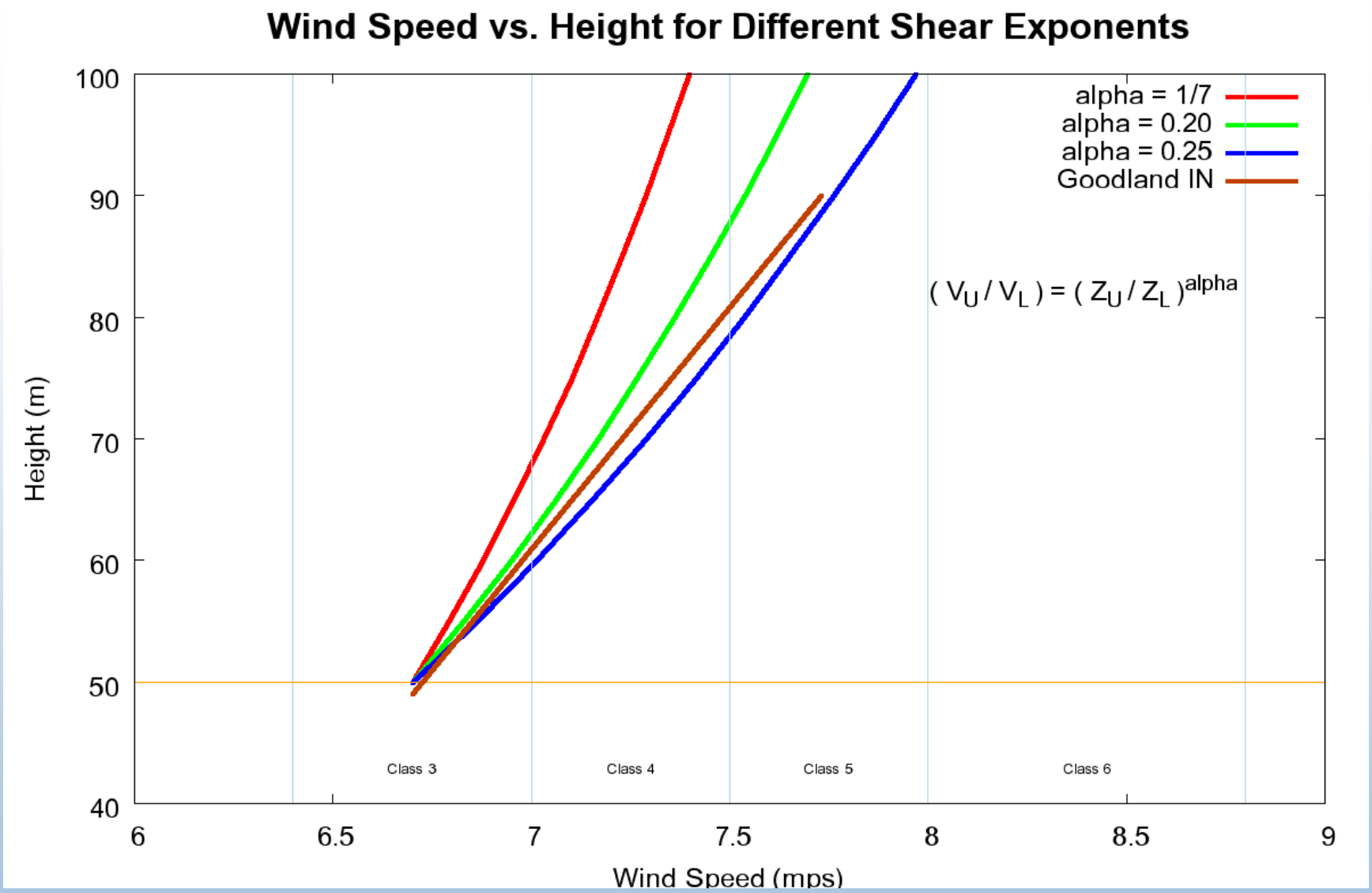
WHERE: V_o = REFERENCE WIND VELOCITY
H_o = REFERENCE HEIGHT
n = DEPENDENT EXPONENT



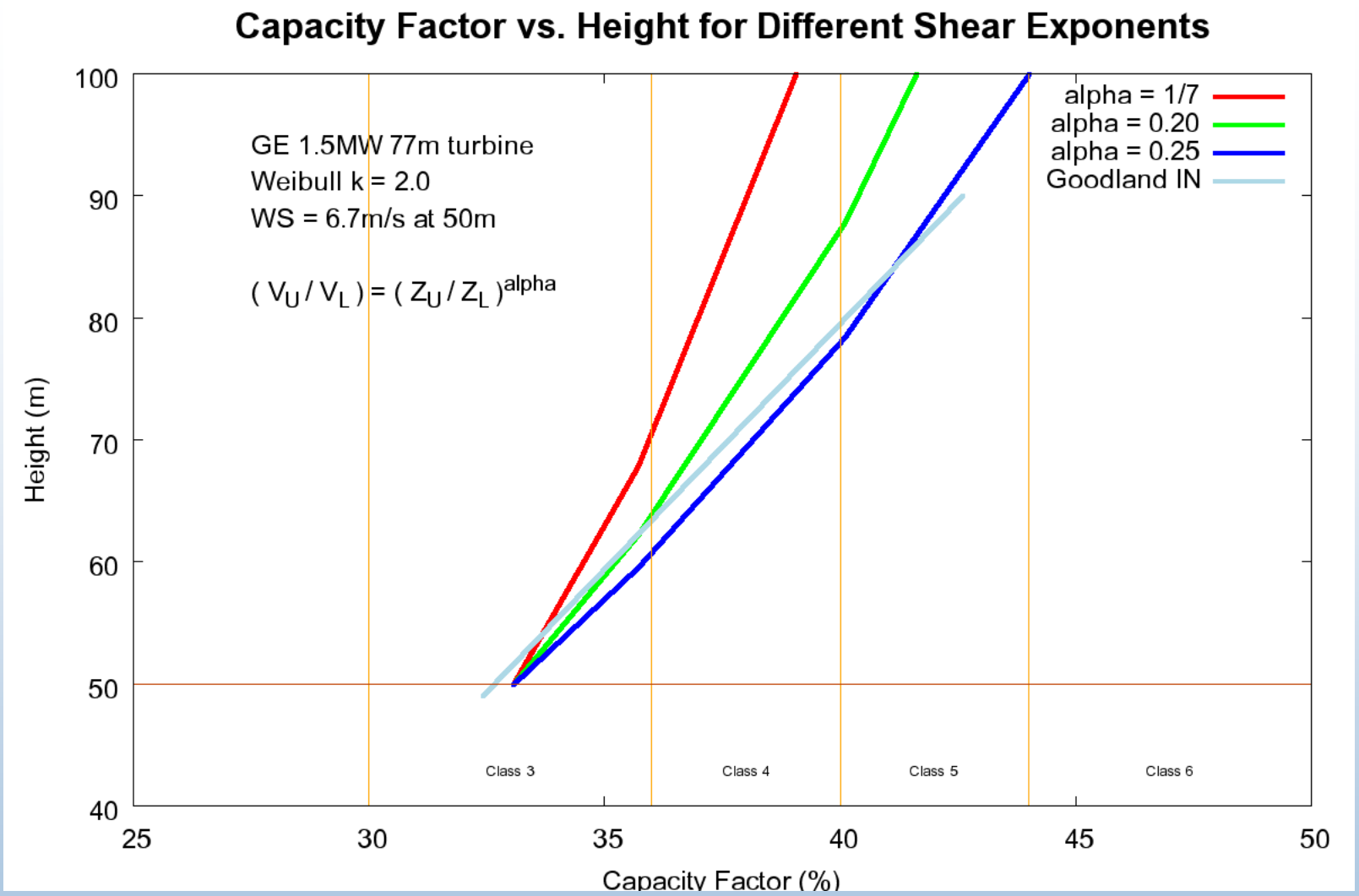
Wind Speed (m/s)



Annual average shear exponents can vary from 1/7 to 0.25, causing considerable uncertainty in vertical extrapolations of wind resource



- **Even if 50-m wind resource is known, potential variations in shear exponents cause considerable uncertainty in wind resource at heights of 80-100 m**
- **Measured shear exponent at Goodland is 0.235, with much higher wind resource at 90 m than estimated by 1/7 shear estimate**



- **High wind shear locations can have considerably higher capacity factors at 80-100 m than low shear locations, given similar capacity factors at 50 m**
- **Goodland's capacity factor of 42.5% at 90 m is considerably higher than would be estimated by using typical shears of 1/7 to 0.2**

NREL National Renewable Energy Laboratory

Data Analysis

Wind Monitoring

- What do we monitor?
  - Wind speed (average and gusts)
  - Wind Direction
  - Temperature
- How often do we record it?
  - Every 10 minutes is best
- For how long?
  - 2 years is good
  - 1 year is a minimum (exceptions exist)

Wind Monitoring, How to Collect Data?

- Numerical Model Datasets (AWS, 3Tier, WindLogics, etc)
  - Atmospheric model extrapolated to surface
  - ~$3k per site
  - Accuracy depends on location and terrain type
- Met Tower
  - Guyed towers industry standard
  - $50-60k Installed with data processing and delivery
  - Mechanical sensing problems, setup important
- SODAR
  - Not bankable… yet
  - Remote sensing, used to check met tower data and explore shear above tower
  - 2-3 month deployment = $12-20k
- LIDAR
  - 3-5X cost of SODAR
  - Higher study heights, versitle
  - Higher power requirements

Wind Data Analysis

- Statistics
  - Annual average Wind Speed and Power Density
  - Seasonal and Diurnal Patterns
  - Wind Direction Information
    - Frequency and Speed by Direction
  - Wind Shear (change of wind speed with height)
  - Wind Power Density Rose
- How do we analyze the data?
  - Spreadsheets (e.g., Excel)
  - Custom software (e.g., WindPro, Windographer)
- Quality Control
  - Remove periods of bad data (icing, etc.)
  - Tower flow effects

WindPRO version 2.5.0.60 Dec 2005

Project:
Pine Ridge

Description:
Data from file(s)
Y:\5000\shared\Anemometer_Loan_Programs\Native American Loans\SD - Pine Ridge - SD\Pine Ridge Raw Wind Data\00070204.N02
Y:\5000\shared\Anemometer_Loan_Programs\Native American Loans\SD - Pine Ridge - SD\Pine Ridge Raw Wind Data\00070527.N02
Y:\5000\shared\Anemometer_Loan_Programs\Native American Loans\SD - Pine Ridge - SD\Pine Ridge Raw Wind Data\00070706.N02
Y:\5000\shared\Anemometer_Loan_Programs\Native American Loans\SD - Pine Ridge - SD\Pine Ridge Raw Wind Data\00071029.N01
Y:\5000\shared\Anemometer_Loan_Programs\Native American Loans\SD - Pine Ridge - SD\Pine Ridge Raw Wind Data\00071231.N01

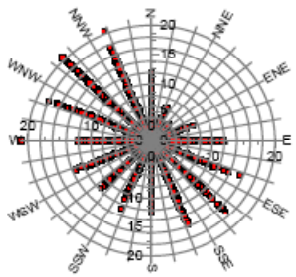
Printed/Page
5/2/2007 9:29 AM / 2

Licensed user:
National Renewable Energy Laboratory
1617 Cole Blvd. (MS3811)
US-GOLDEN, CO 80401
+1 303-384-7027

Calculated:
5/2/2007 9:29 AM/

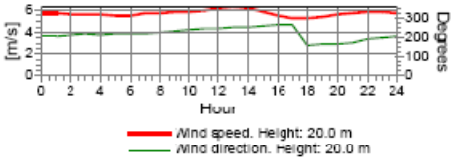
Meteo data report, height: 20.0 m

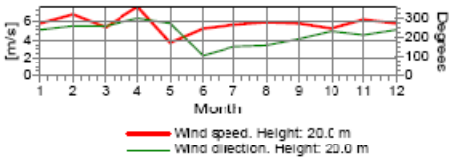
Name of meteo object: Pine Ridge #1 (KILI Radio Station)

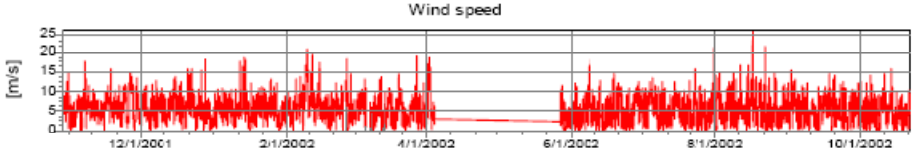


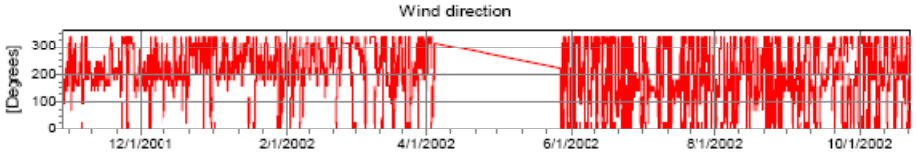
Monthly mean values of wind speed in m/s

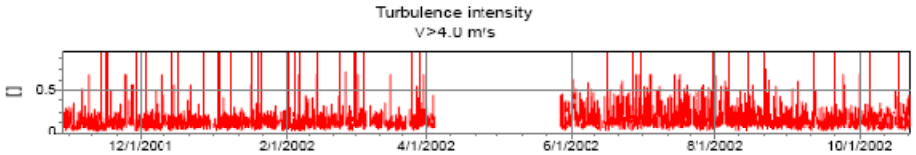
Month	2001	2002	mean	mean of months
Jan		5.8	5.8	5.8
Feb		6.7	6.7	6.7
Mar		5.3	5.3	5.3
Apr		7.6	7.6	7.6
May		3.7	3.7	3.7
Jun		5.2	5.2	5.2
Jul		5.6	5.6	5.6
Aug		5.9	5.9	5.9
Sep		5.7	5.7	5.7
Oct	6.5	5.1	5.2	5.8
Nov	6.1		6.1	6.1
Dec	5.8		5.8	5.8
mean, all data	6.0	5.7	5.7	
mean of months	6.1	5.7		5.8





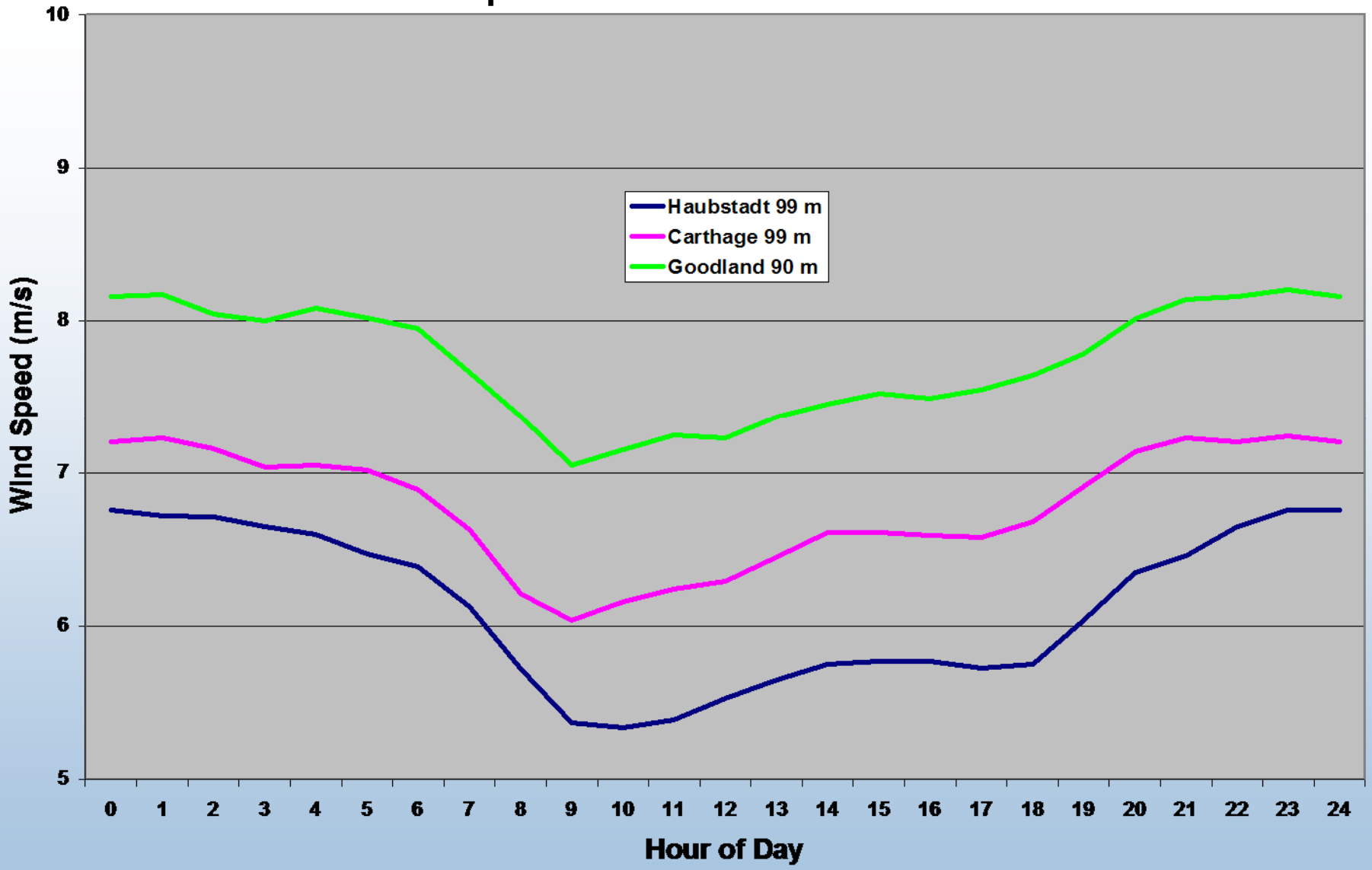


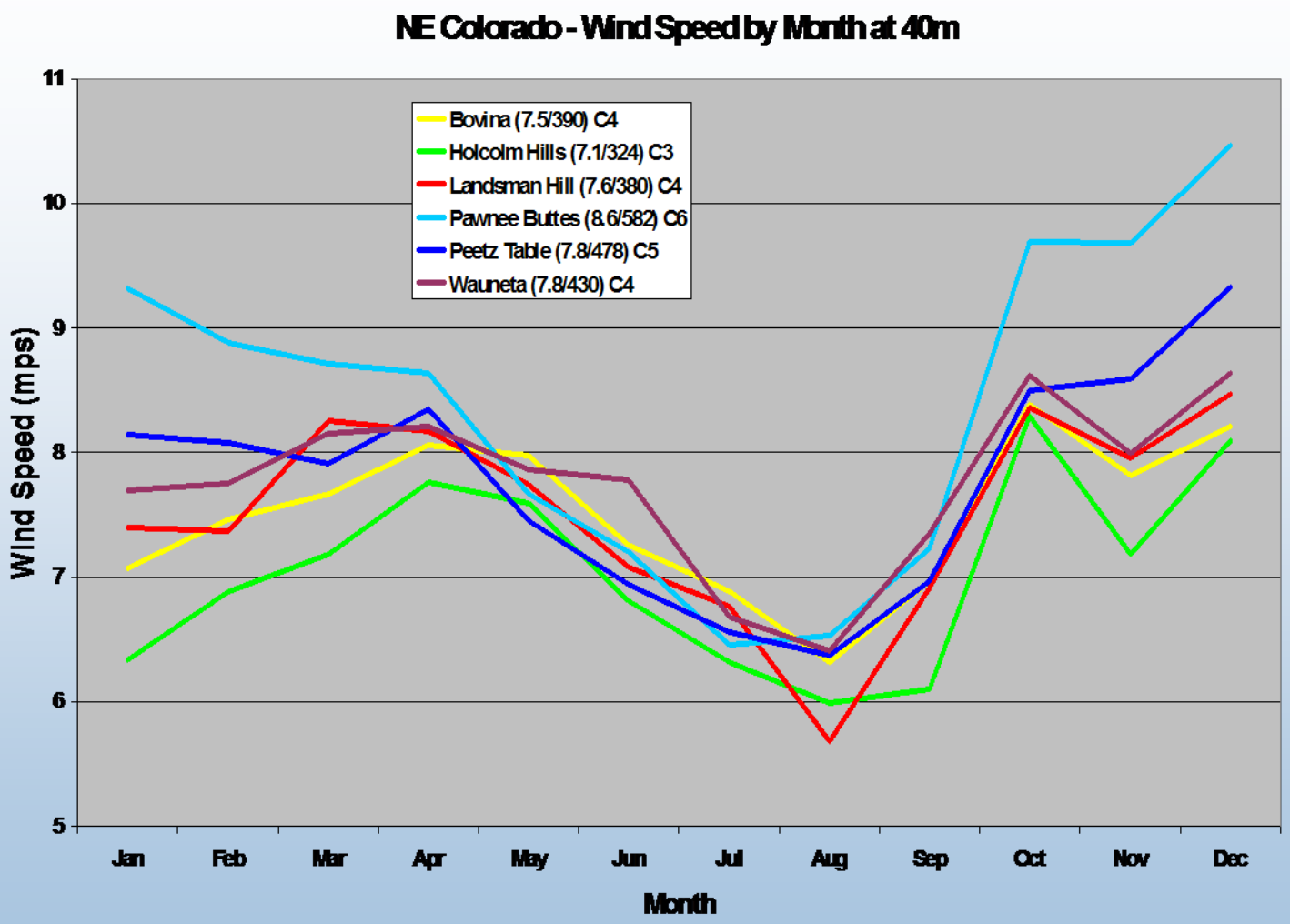




WindPRO is developed by EMD International A/S, Niels Jernesvej 10, DK-9220 Aalborg Ø, Tlf. +45 96 35 44 44, Fax +45 96 35 44 46, e-mail windpro@emd.dk

Diurnal wind speeds at three Indiana tall towers.





- Highest wind resource - Oct thru May
- Lowest wind resource - June thru Sept
- Winter resource - greatest in northern areas near WY border - Peetz Table and Pawnee Buttes

Wind Characteristics Conclusion

- The power in the wind varies as V^3
  - Small differences in wind speed result in large differences in power
  - Distribution of wind speeds are important
- Wind speed generally increases with height
  - Rate of increase with height (wind shear) can vary
  - Significant differences in wind speed occur when one uses different alpha values
- The checking of data quality is crucial to accurately assess the available wind resource

Wind Resource Mapping

US Offshore Wind Mapping Objectives

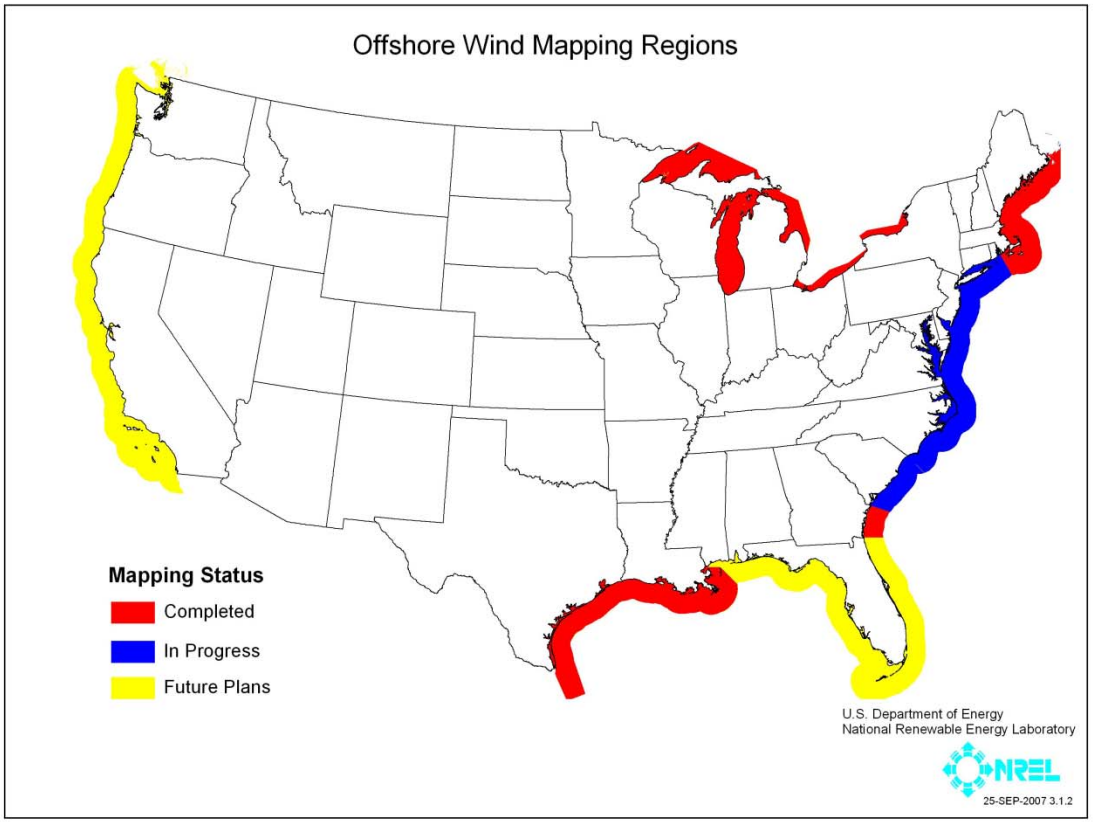
Develop high-resolution validated wind resource maps

- Ocean regions: coast to 50 nautical miles offshore
- Great Lakes: entire surface

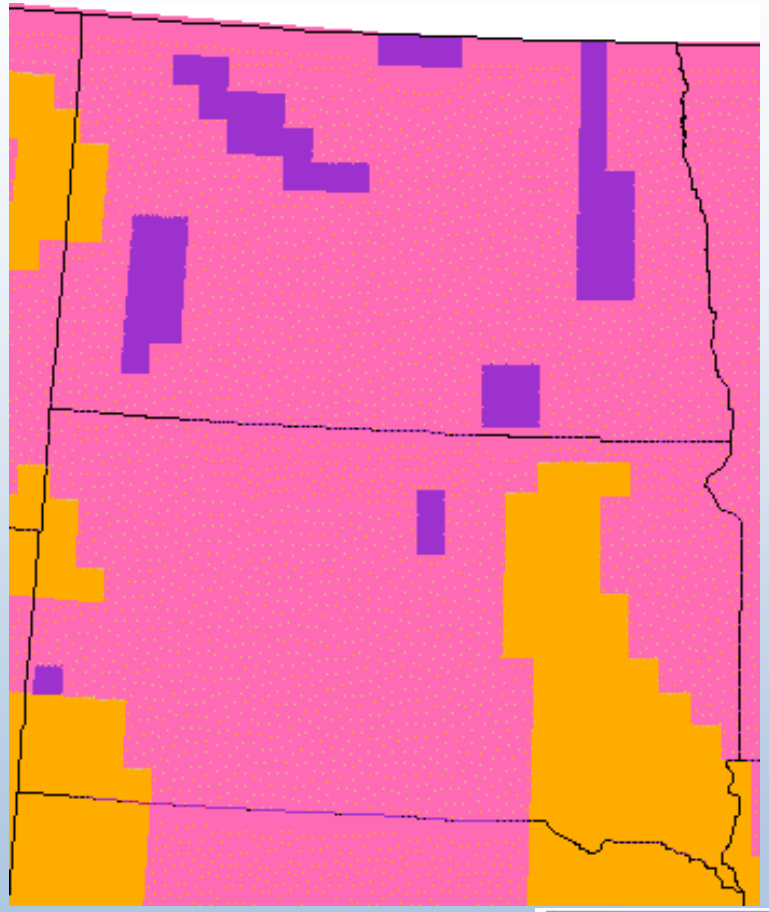
Project jointly funded by DOE/NREL, states, and other organizations

Priority offshore regions:

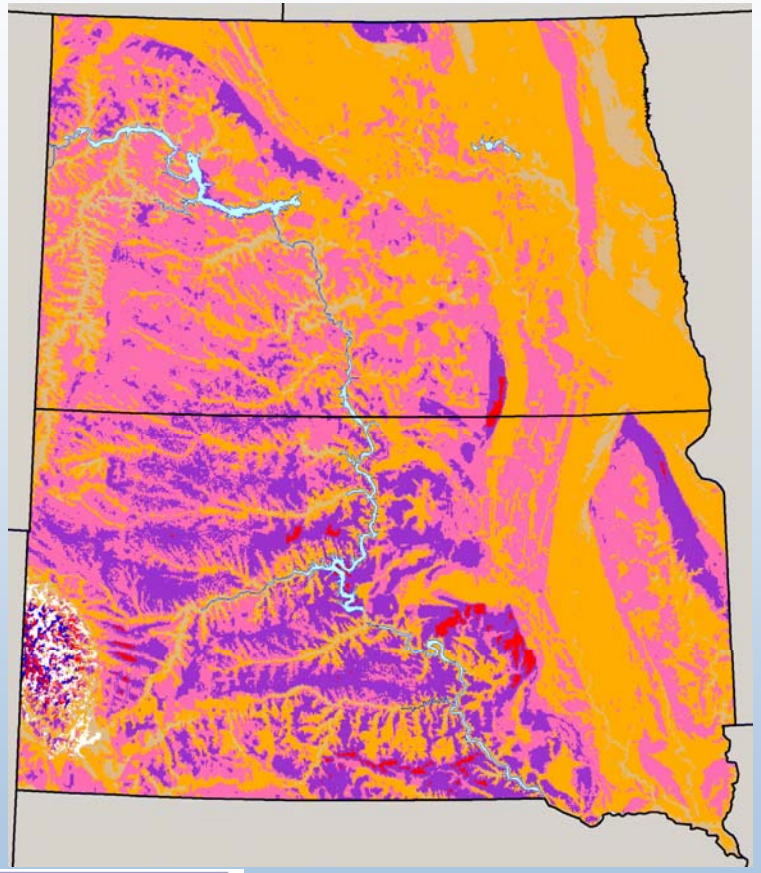
- Great Lakes
- Eastern coast areas from Maine to northern Florida
- Western Gulf of Mexico (Texas and Louisiana)



Comparison of Digital Wind Map from 1987 U.S. Wind Atlas and New (2000) High-Resolution (1-km^2) Wind Map North and South Dakota



1987



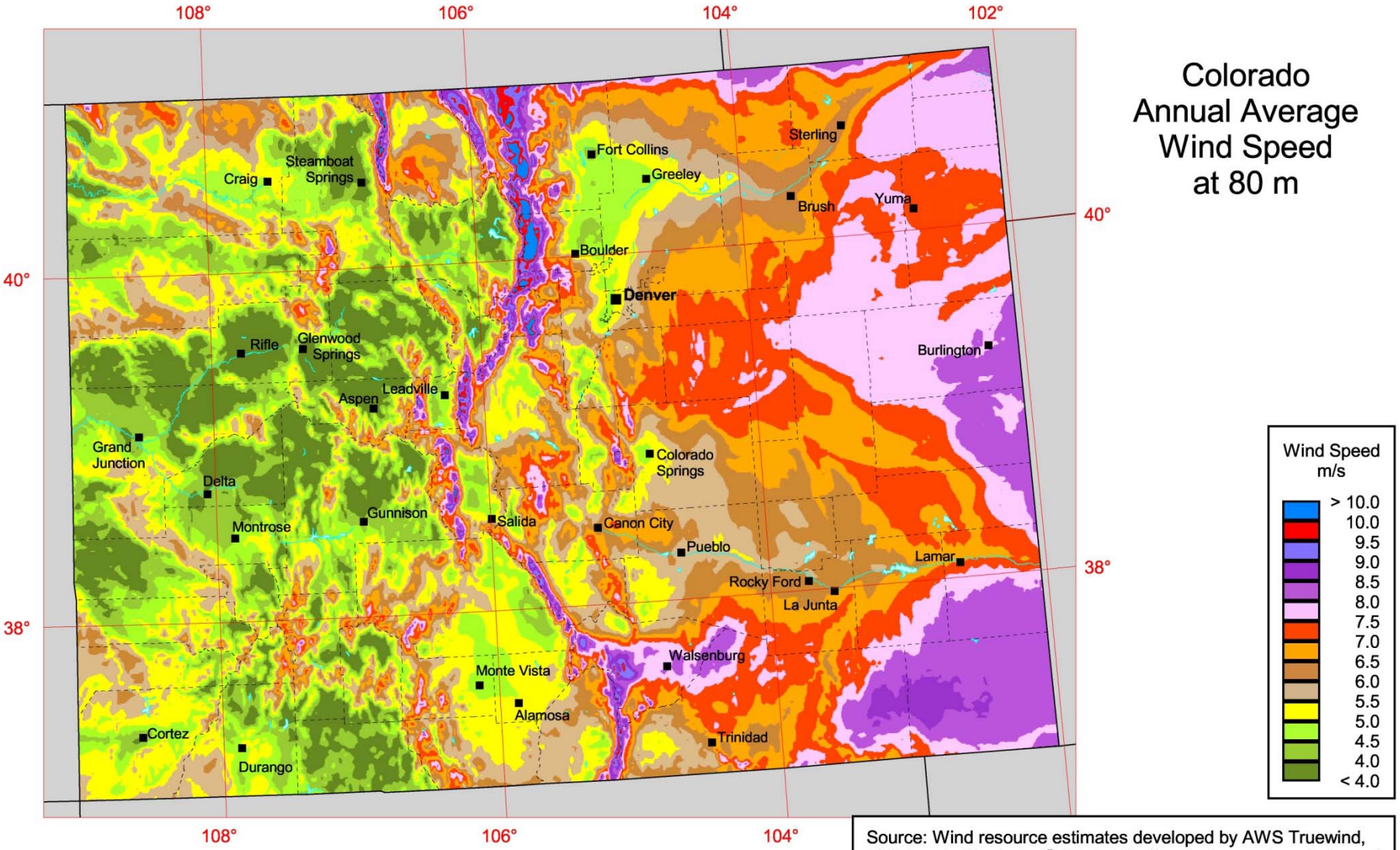
2000

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

Colorado Annual Average Wind Speed at 80 m



50 0 50 100 150 200 Kilometers

50 0 50 100 Miles

Source: Wind resource estimates developed by AWS Truewind, LLC for windNavigator®. Web: http://navigator.awstruewind.com | www.awstruewind.com. Spatial resolution of wind resource data: 2.5 km. Projection: UTM Zone 12 WGS84.

AWS Truewind

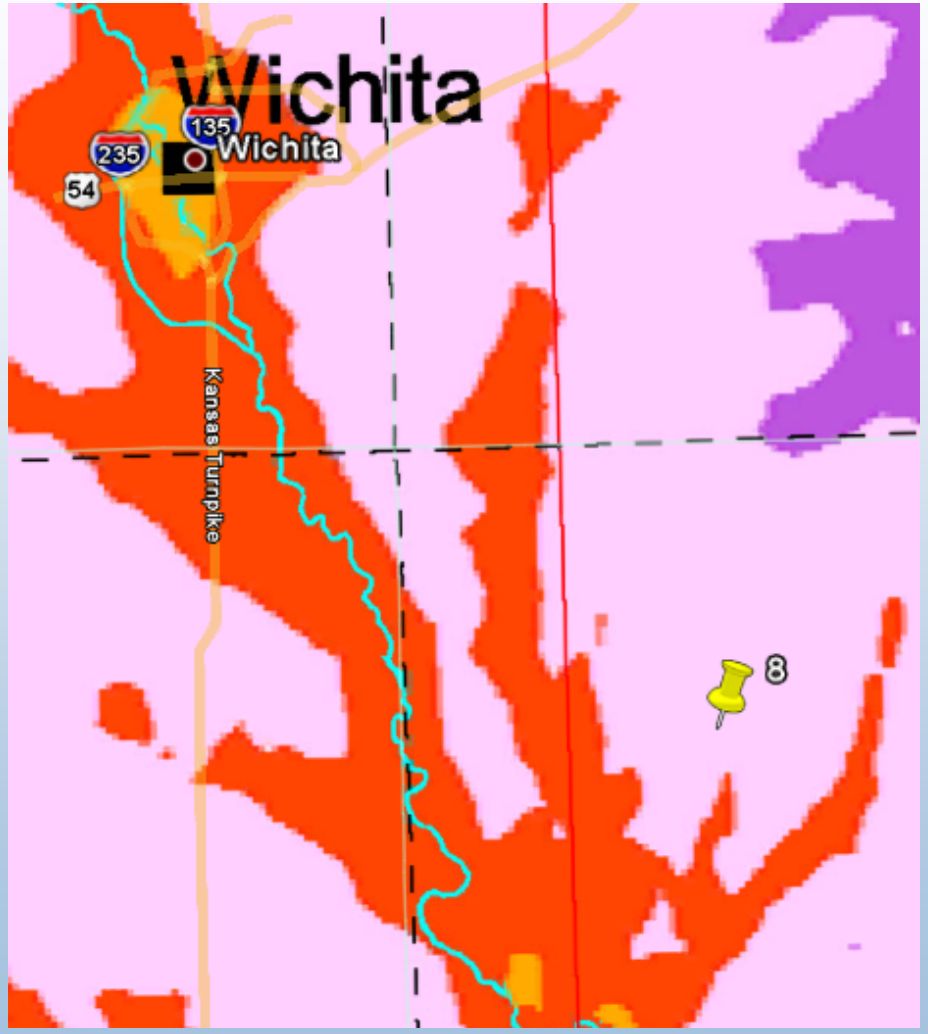
NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

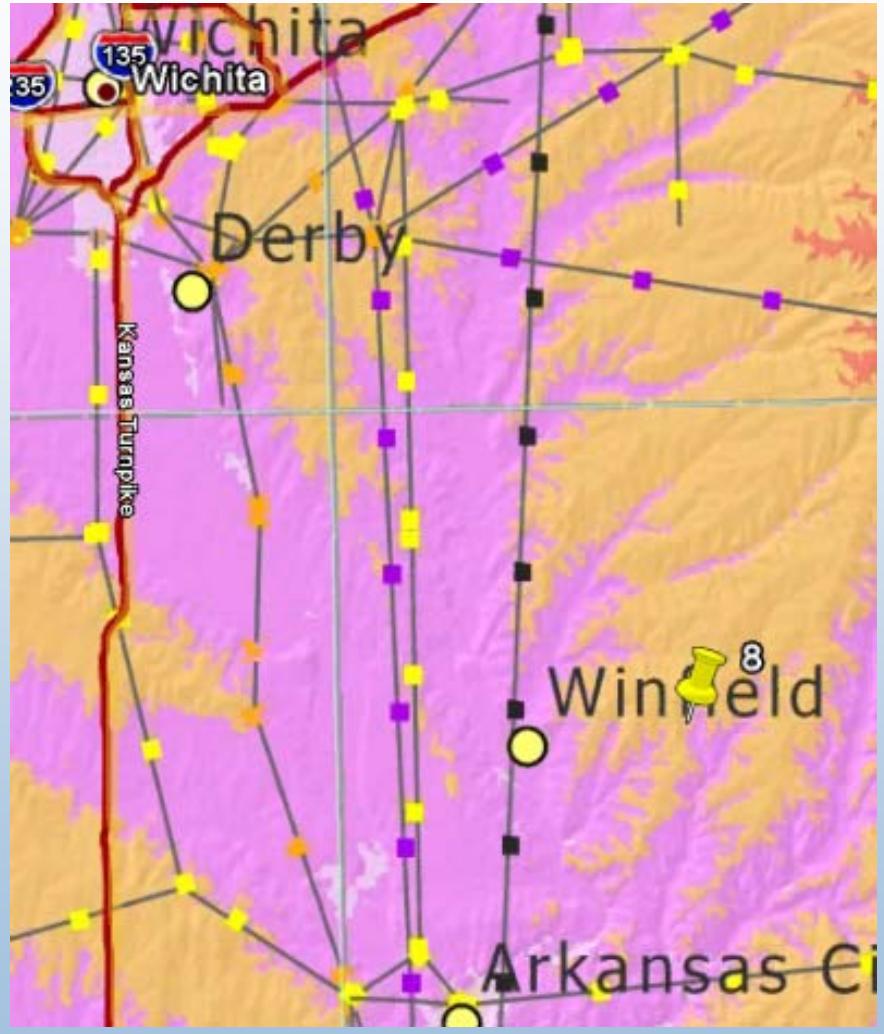
15-JAN-2010 6.1.1

High-Resolution Wind Mapping

- Combination of numerical model and empirical and analytical methods (NREL validation)
- 80m maps are 2km averaged cells
- Old 50m maps are 200m cells, look here for local topographic influences
- Accuracy of maps depend on location
- All wind speed maps are inherently compromised (density, altitude, distribution)
- Wind power density much better measure

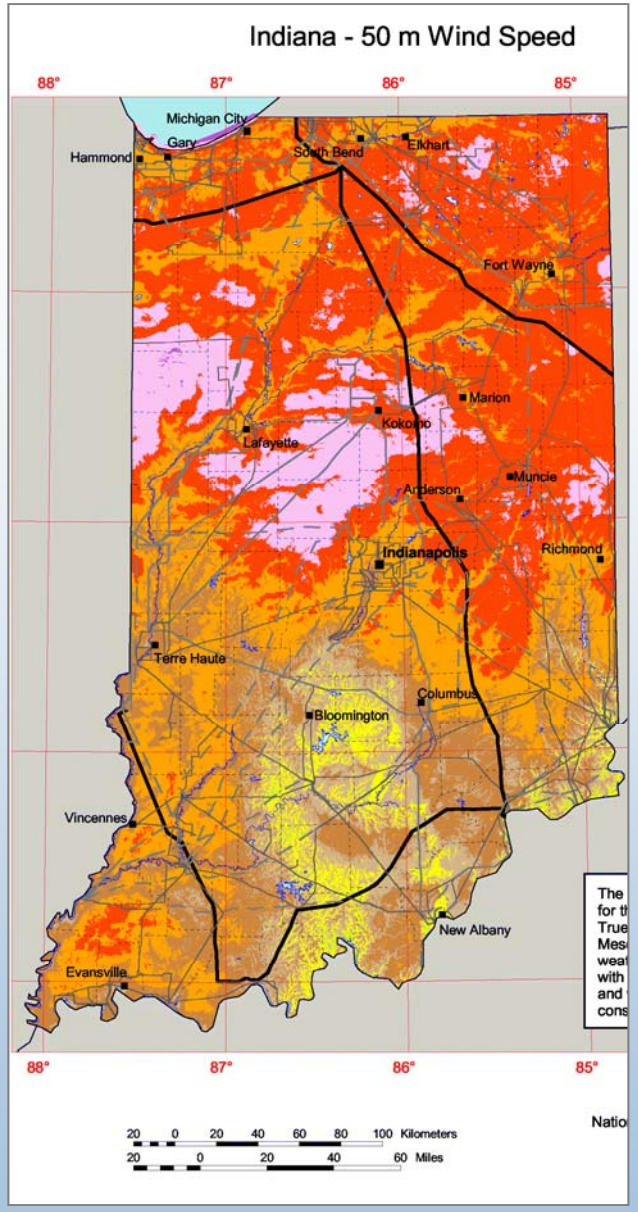
50m vs 80m maps

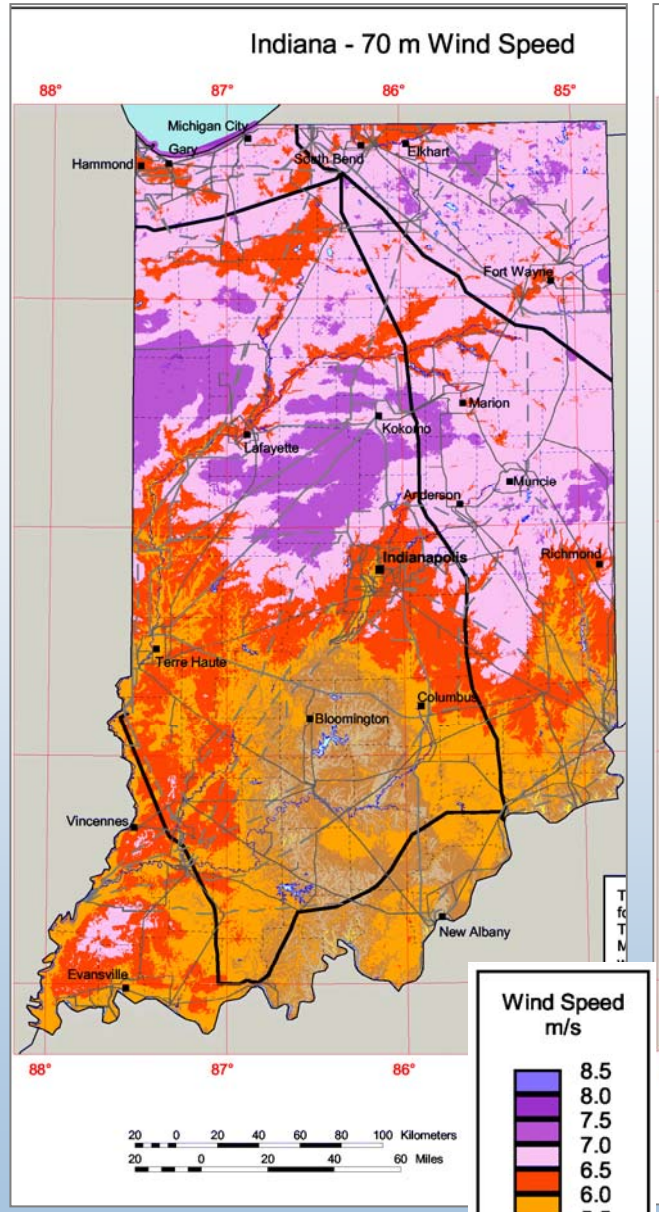


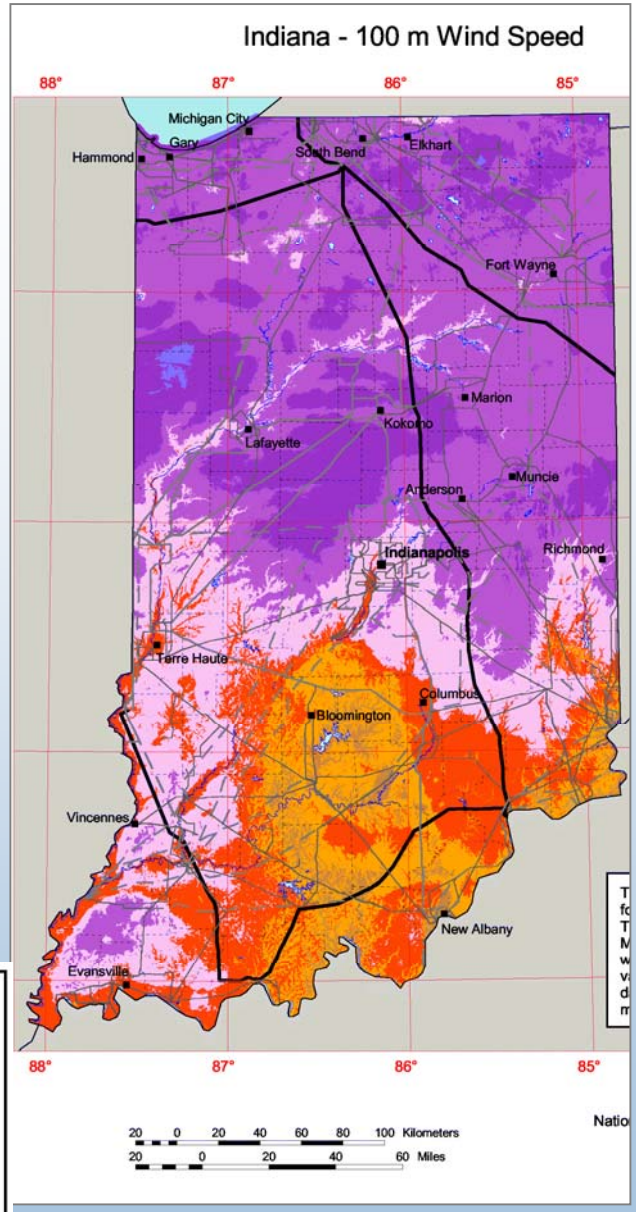


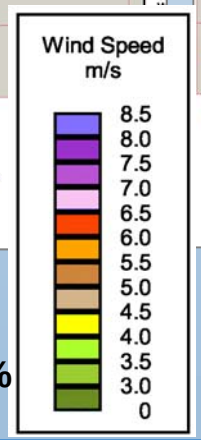
Major Data Sets Used in Validation

- Federal, state, and utility wind measurement programs
- Developer wind data (proprietary sources)
- Meteorological station data from NOAA/NCDC
  - Airports and military bases
  - Coast guard stations, lighthouses, buoys
- Other wind data
  - Highway (State DOT)
  - Forest Service (RAWS)
  - Anemometer loan programs









Best areas 6.5-7 m/s
Capacity factors 30-35%

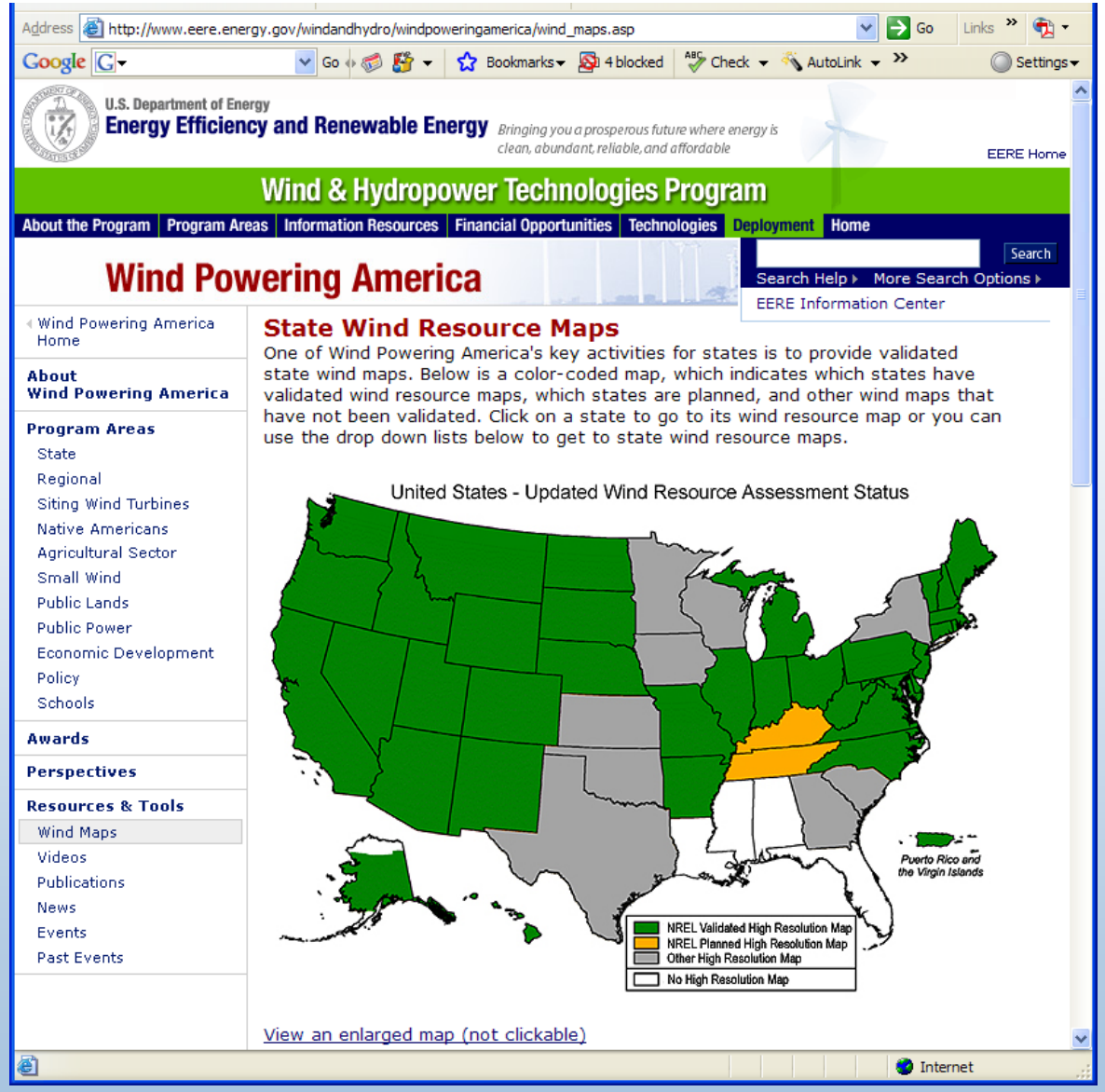
Best areas 7-7.5 m/s
Capacity factors 35-40%

Best areas 7.5-8.2 m/s
Capacity factors 40-45%

Web Wind Resource Information

Online Wind Information Availability

- High resolution mapping status and static maps
  - Wind Powering America web site
- Interactive map server
  - U.S. Renewable Energy Atlas
  - Non-NREL state and regional applications are also available (New England, Northwest, Texas, etc.)
- GIS wind resource map data
- Large area wind speed maps
  - AWS Truewind
  - 3TIER



Online Maps

- WPA site shows current high resolution maps
- Links provided to NREL validated and other (non-validated) wind maps

http://www.eere.energy.gov/windandhydro/windpoweringamerica

Wind Powering America: Colorado Wind Resource Map - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Back Search Favorites Media

Address http://www.eere.energy.gov/windandhydro/windpoweringamerica/maps_template.asp?stateab=co Go Links

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

EERE Home

Wind & Hydropower Technologies Program

About the Program | Program Areas | Information Resources | Financial Opportunities | Technologies | Deployment | Home

Search

Search Help ▸ More Search Options ▸

EERE Information Center

Wind Powering America

- Wind Powering America Home

About Wind Powering America

Program Areas
- State
- Regional
- Native Americans
- Agricultural Sector
- Small Wind
- Public Lands
- Public Power
- Economic Development
- Policy

Perspectives

Resources & Tools
- Wind Maps
- Software
- Publications
- News

Colorado Wind Resource Map

The Department of Energy's Wind Program and the National Renewable Energy Laboratory (NREL) recently published a new wind resource map for the state of Colorado. This resource map shows wind speed estimates at 50 meters above the ground and depicts the resource that could be used for utility-scale wind development. Future plans are to provide wind speed estimates at 30 meters, which are useful for identifying small wind turbine opportunities.

This map of Colorado shows the wind resource at 50 meters.

Viewing Options
Larger Jpeg: Click Map
Printable:(PDF 5.0 MB)
Download Acrobat Reader
Interactive Map

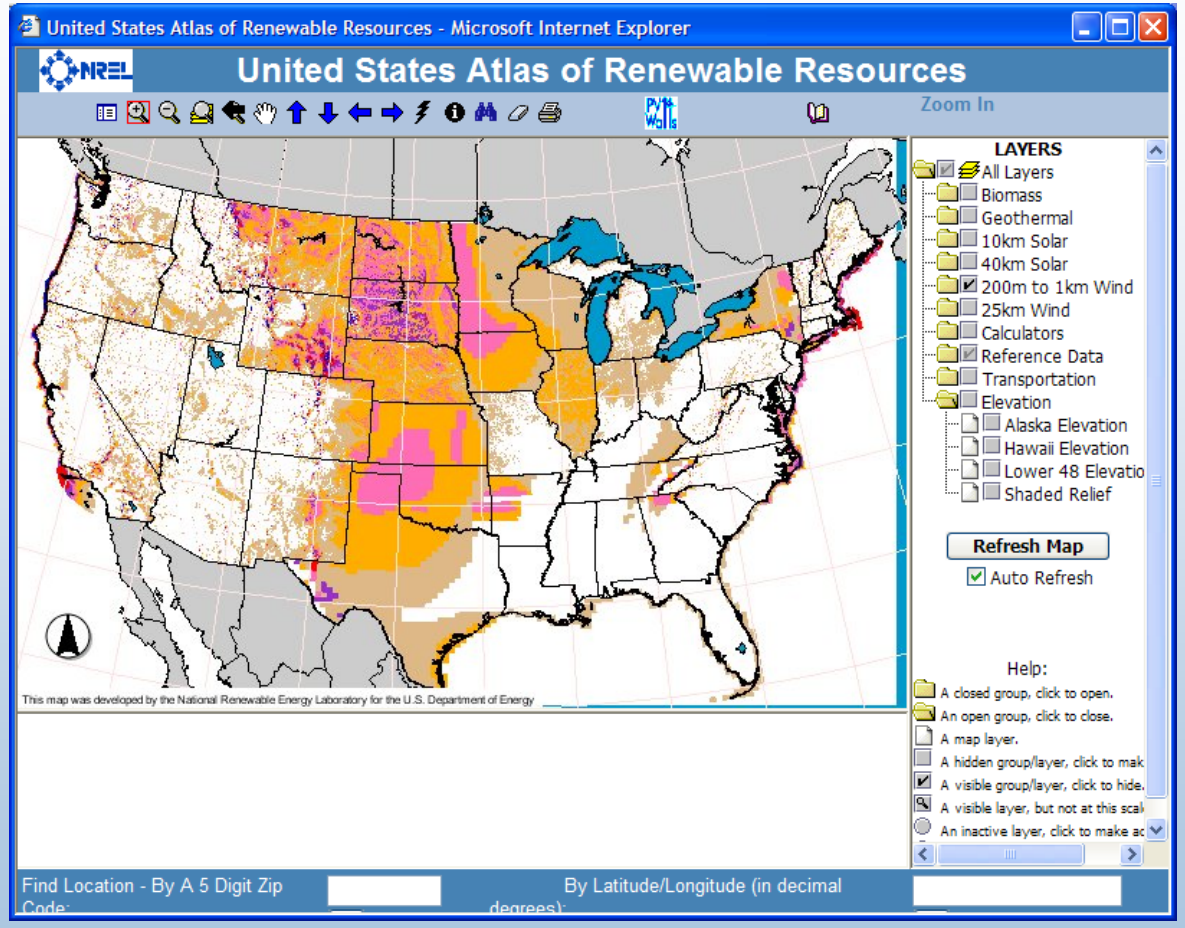
As a renewable resource, wind is classified according to wind power classes, which are based on typical wind speeds. These classes range from class 1 (the lowest) to class 7 (the highest). In general, wind power class 4 or higher can be useful for generating wind power with large turbines. Class 4 and above are considered good resources.

This map indicates that Colorado has wind resources consistent with utility-scale production. Significant contiguous areas of good

Link to Detailed PDF

Link to interactive map

Interactive Maps Online

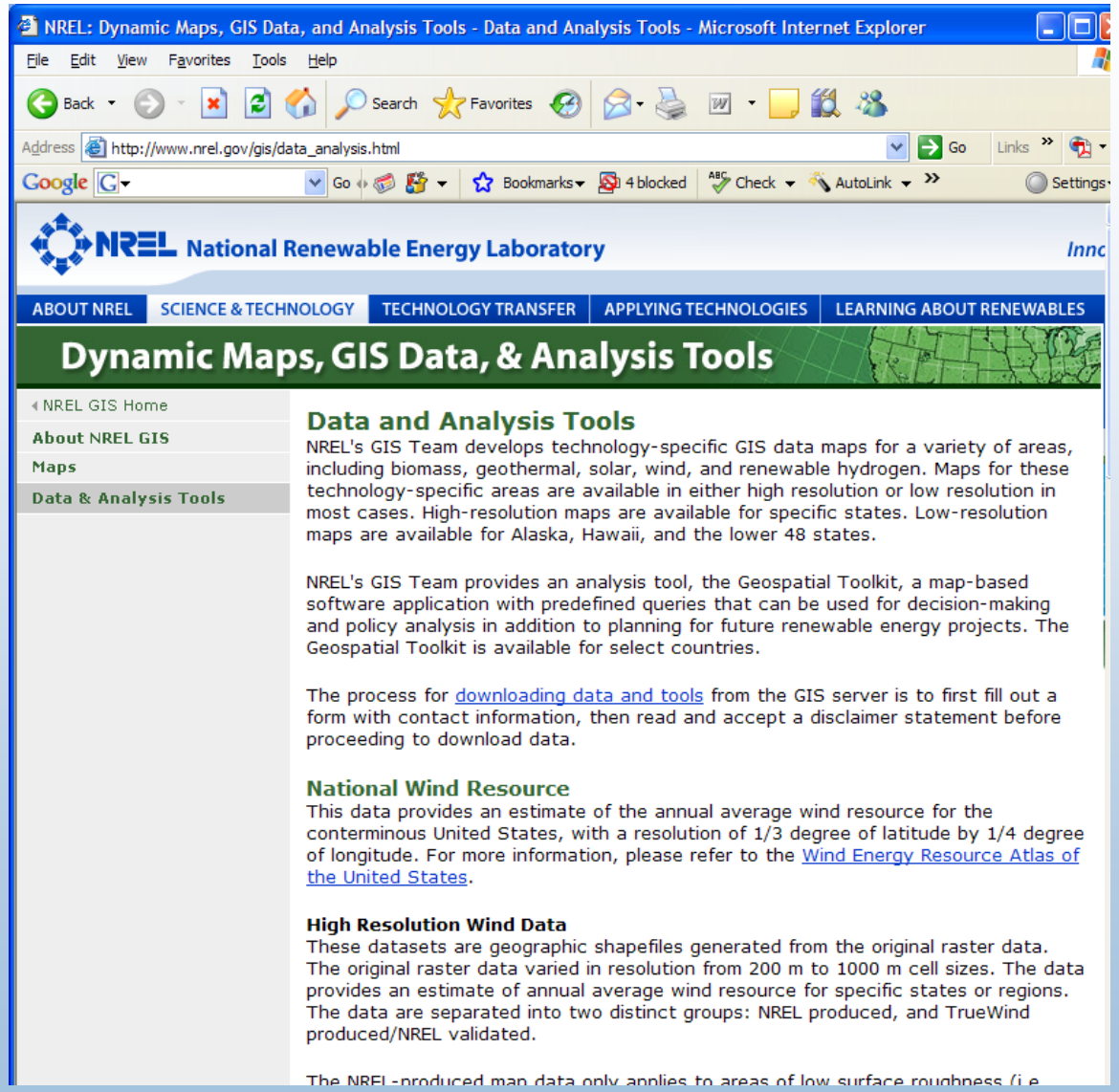


- Allows users to:
  - Zoom in to area of interest
  - Turn on/off map layers (county bounds, roads, zip code, etc.)
- Full U.S. including Alaska and Hawaii
- Other interactive maps are available for specific areas

http://www.nrel.gov/gis

- Interactive zoom tool

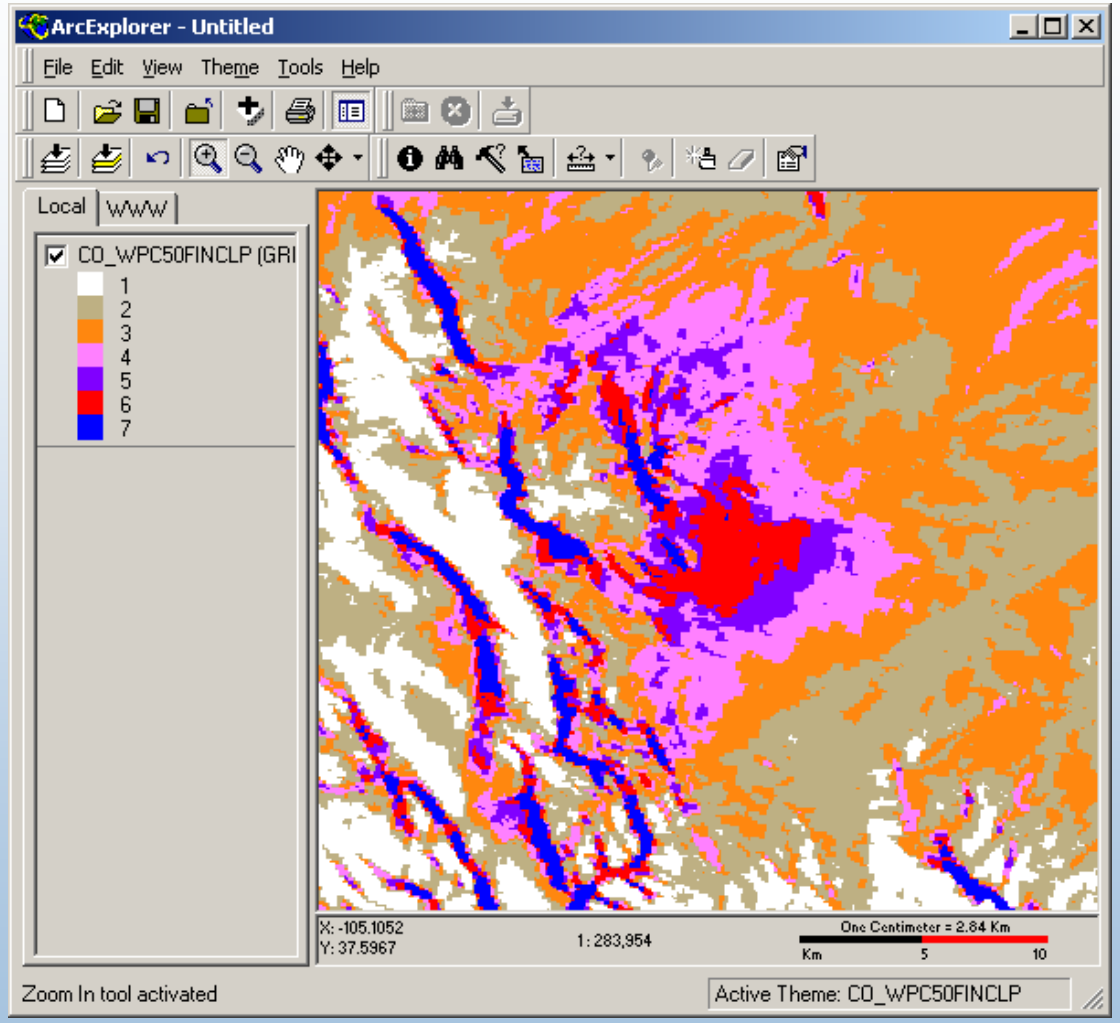
GIS Wind Resource Map Data



- NREL validated wind data only
- Geographic shapefiles of annual wind power class
- ESRI ArcGIS and ArcView format
- Importable to many other GIS packages

http://www.nrel.gov/gis/data_analysis.html

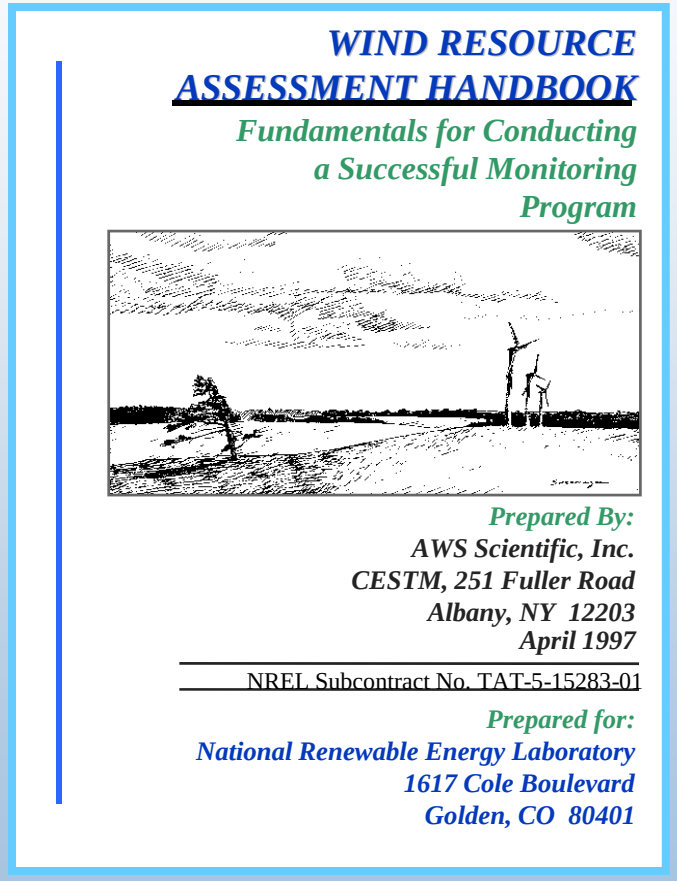
GIS Data Viewer - ArcExplorer



- Free from ESRI
- Allows you to view and query shapefile data
- Will not come with any reference data (roads, cities, etc)
- Displaying scale bar will show latitude/longitude coordinates

http://www.esri.com/software/arcexplorer/

Wind Resource Assessment Handbook



WIND RESOURCE ASSESSMENT HANDBOOK

Fundamentals for Conducting a Successful Monitoring Program

Prepared By:
AWS Scientific, Inc.
CESTM, 251 Fuller Road
Albany, NY 12203
April 1997

NREL Subcontract No. TAT-5-15283-01

Prepared for:
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401

- Handbook provides guidelines for planning and conducting a wind resource measurement program

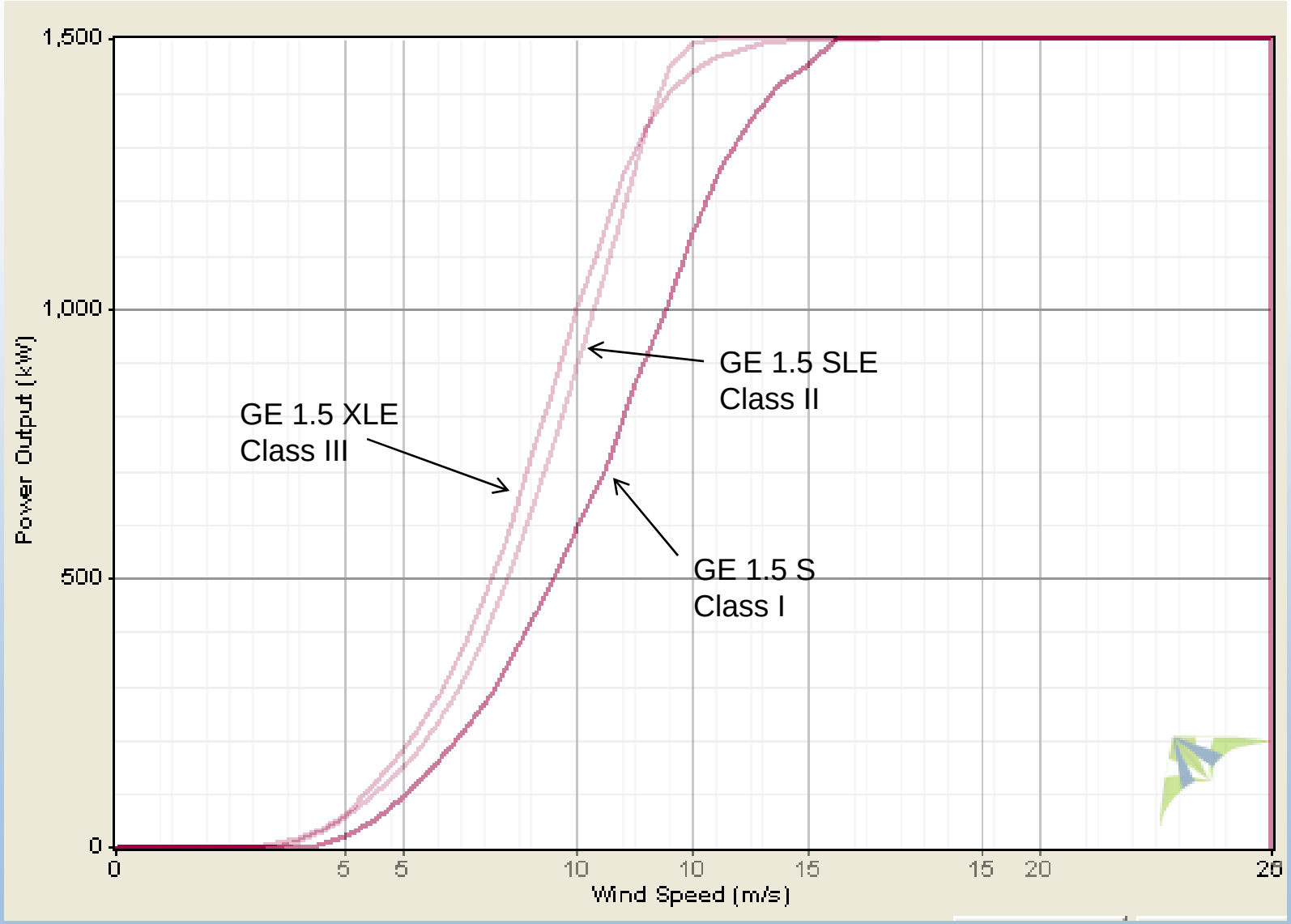
Web Site

- **http://www.nrel.gov/wind/resource_assessment.html**

Other Web Mapping Products

- AWS Truewind- Wind Navigator
- http://navigator.awstruewind.com/
  - Wind speed at 60 m, 80 m, and 100 m above ground
  - 2.5 km horizontal resolution for U.S.
- 3TIER- First Look
- http://firstlook.3tier.com/
  - Wind Speed at 20 m, 50 m, and 80 m above ground
  - 5 km horizontal resolution (global)

Turbine Output Comparison



Turbine Calculated Output Hawaii

Turbine	Hub Height (m)	Hub Height Wind Speed (m/s)	Time At Zero Output (%)	Time At Rated Output (%)	Mean Net Power Output (kW)	Mean Net Energy Output (kWh/yr)	Net Capacity Factor (%)
GE 1.5xle	80	6.9	21.92	8.99	464.9	4,072,842	31
GE 1.5sle	80	6.9	21.73	0.85	419.9	3,678,488	28
GE 1.5s	80	6.9	27.31	6.8	397.8	3,484,615	26.5

Wind Project Costs

- Turbines ~$1650/MW
  - Economies of scale for Tier 1 mfg starting at 50mw
- Installation Costs ~$400-3100/MW
  - Very large economy of scale
- O &M – Large Variable, ~$5-50/MWH
  - No one knows how these machines will work in 15 years, model gearbox replacement in economics
- Your REC costs in conjunction with 2x incentive replace private sector incentives…
- Wind cost of energy + 2x REC cost must be less than forecasted cost of energy for a project to work

Conclusions

- Cost of energy drives everything
  - Wind speed at 60 m, 80 m, and 100 m above ground
  - 2.5 km horizontal resolution for U.S.
- 3TIER- First Look
- http://firstlook.3tier.com/
  - Wind Speed at 20 m, 50 m, and 80 m above ground
  - 5 km horizontal resolution (global)

Contact Info:

Owen Roberts

Phone: 303-384-7151

Mailstop: 3811

NREL

1617 Cole Blvd

Golden CO 80401