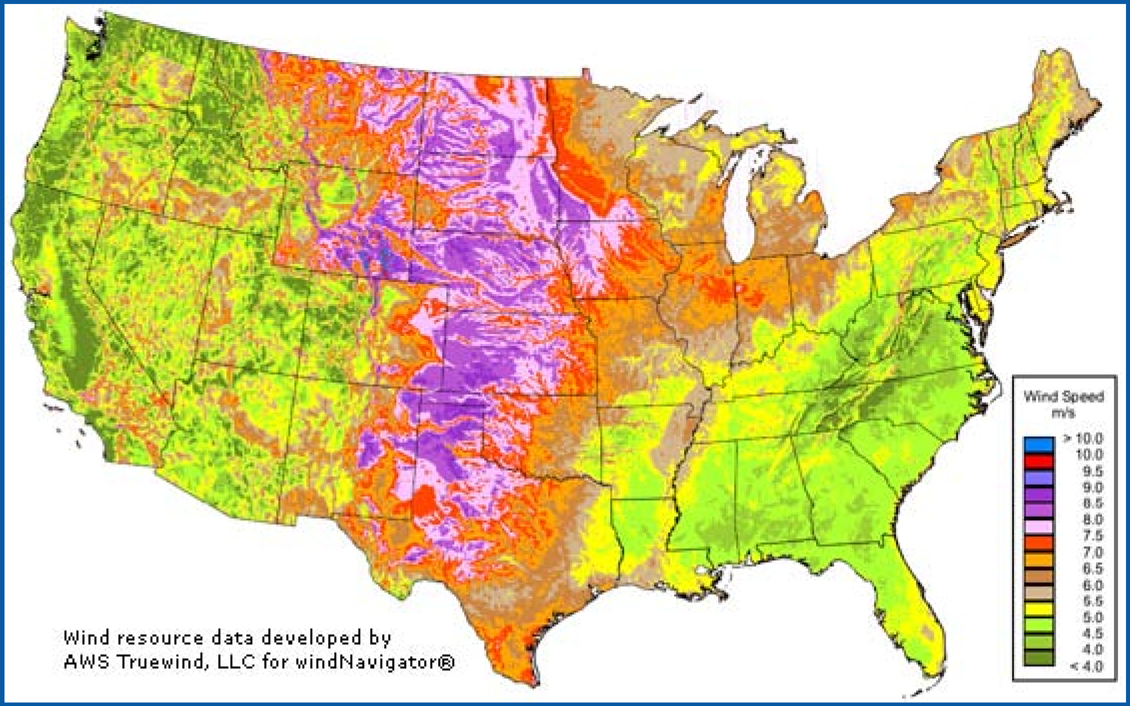
National Renewable Energy Laboratory
Innovation for Our Energy Future

Wind Resource Assessment



Dennis Elliott

Presentation to:

BLM WEATS

August 31, 2010

Wind Resource Assessment Topics for BLM

- **New Wind Resource Maps and Potential Estimates (Land Areas):**
  - 48 contiguous states, 80-100 m heights, wind speed maps, wind potential from model capacity factor data, environmental and land-use exclusions
  - NREL validation of model wind speeds with 300+ tall tower measurement sites
  - How to use the new maps and potential estimates - not to be used for micrositing, not to be substituted for measurement data

- **Important Wind Characteristics:**
  - Wind shear, spatial and temporal variations, terrain influences
  - Seasonal and diurnal wind patterns
  - Wind direction and speed frequencies
  - Turbulence and importance of measuring, terrain influences

- **Tower Measurements and Remote Sensing Measurements:**
  - What tower measurements are most appropriate, when and how long
  - What is Remote Sensing (Sodar/Lidar) technology, when and how to use it
  - Best practices for remote sensing, when and how to use with towers

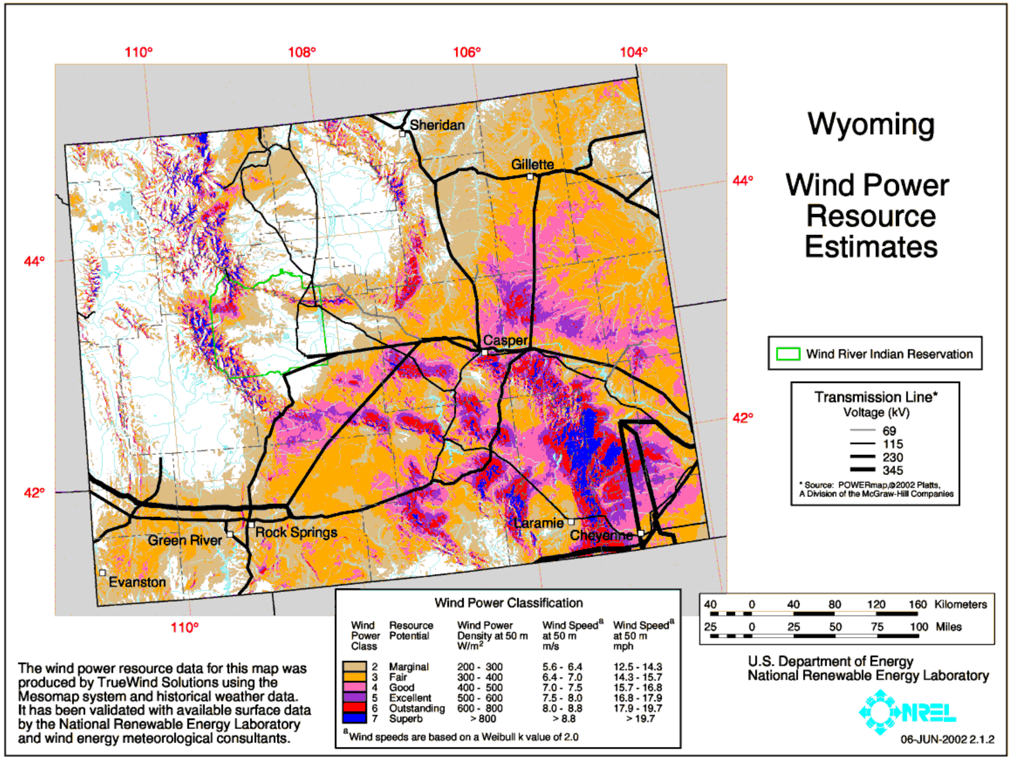
US Wind Mapping - Statement of the Problem

Accurate information about the wind resource in each state required

- For federal and state policy discussion, analysis, and implementation
- To support the 20% wind future
- To facilitate wind prospecting
- To support state, regional and national wind integration analyses

NREL validation of resource maps is essential to ensure confidence by stakeholders in accuracy of map estimates

Supports the Program’s mission of eliminating barriers to wind energy.



Technical Approach - Wind Mapping & Validation

Mapping is based on:

- Numerical modeling (AWS Truewind)
- Empirical and analytical methods (NREL validation)
- 1 km^2 or finer horizontal resolution wind resource maps

Preliminary maps are validated by NREL and modified using public and private wind measurement data

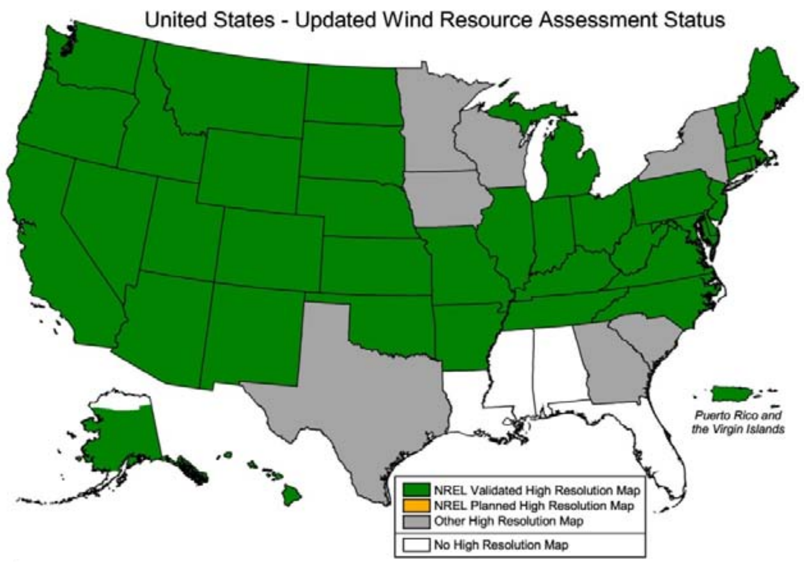
Develop and validate maps at 50-m height for 39 states

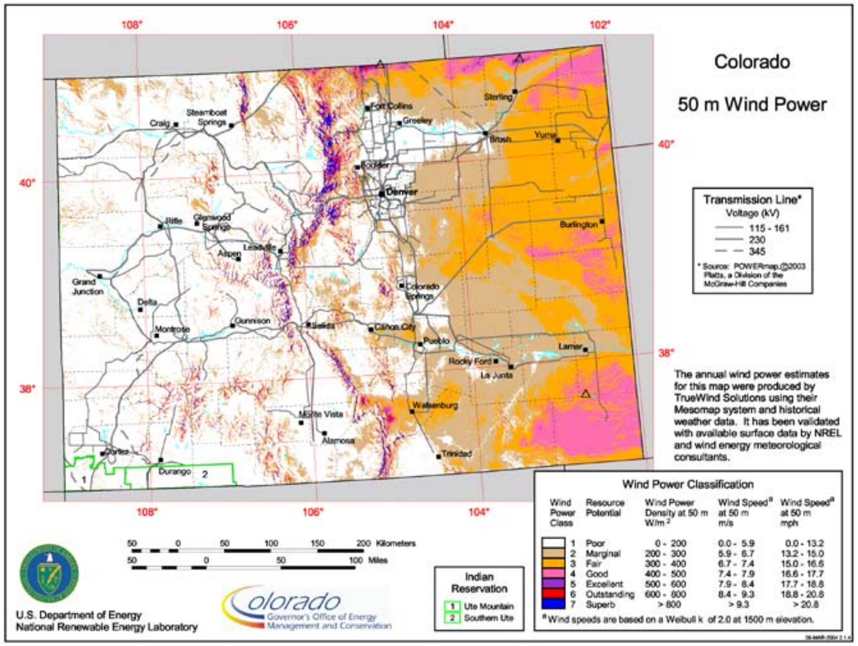
Expand mapping to 48 states with wind speed maps at 80-m height

- Develop wind potential estimates (net of exclusions) at 80 and 100-m heights based on capacity factors

Publish on WPA website

Provide related TA to stakeholders





US Wind Mapping – Accomplishments / Results

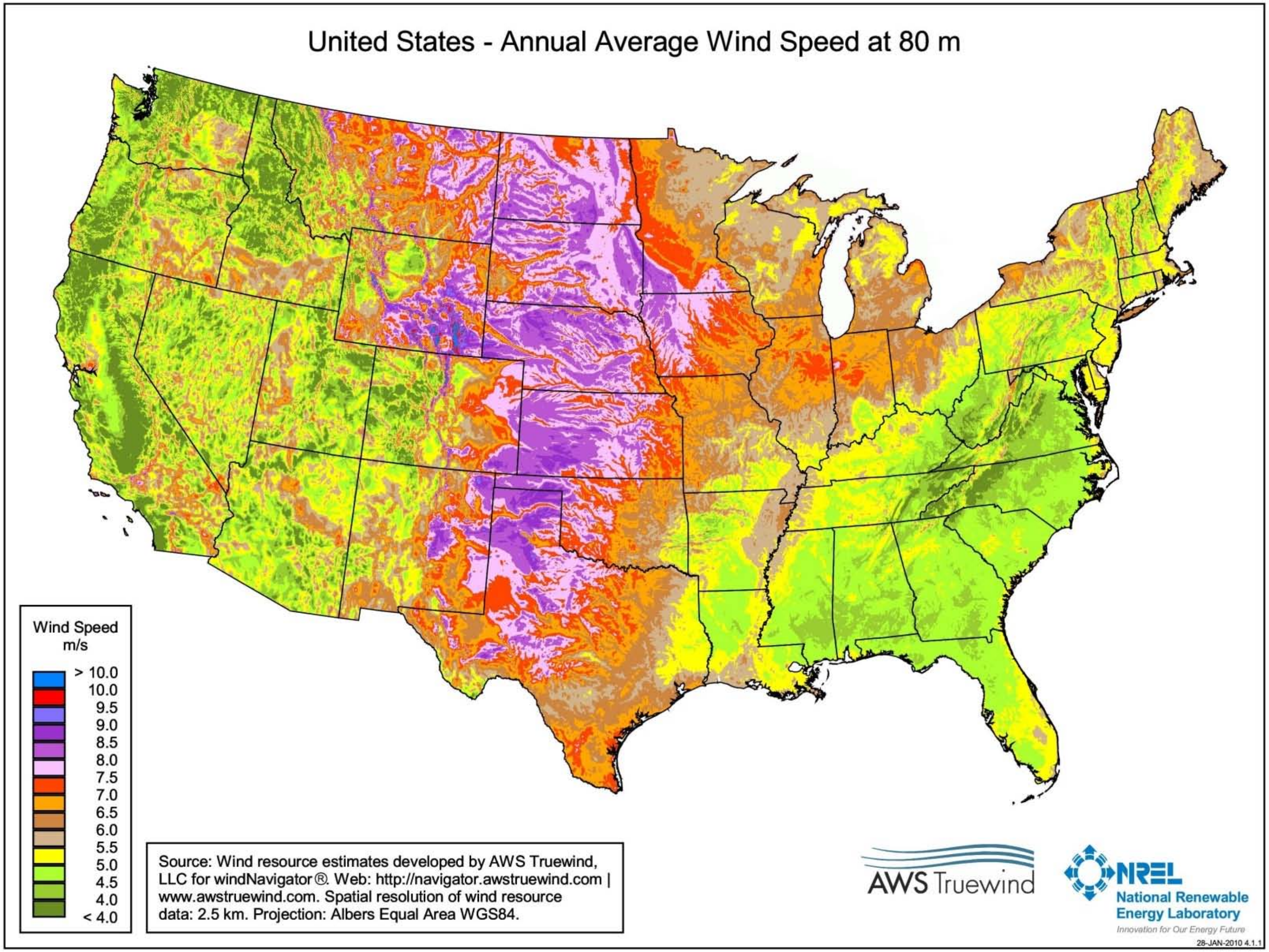
50-m mapping and validation – total of 39 states & 2 territories

- Culmination of a long-term project that began in 2001 jointly funded by states and other organizations
- Updated the national 50-m wind map
- 50-m wind potential estimates for selected states and US (to support 20% vision study)
- Discussed at WPA summit meetings and key regional/state meetings

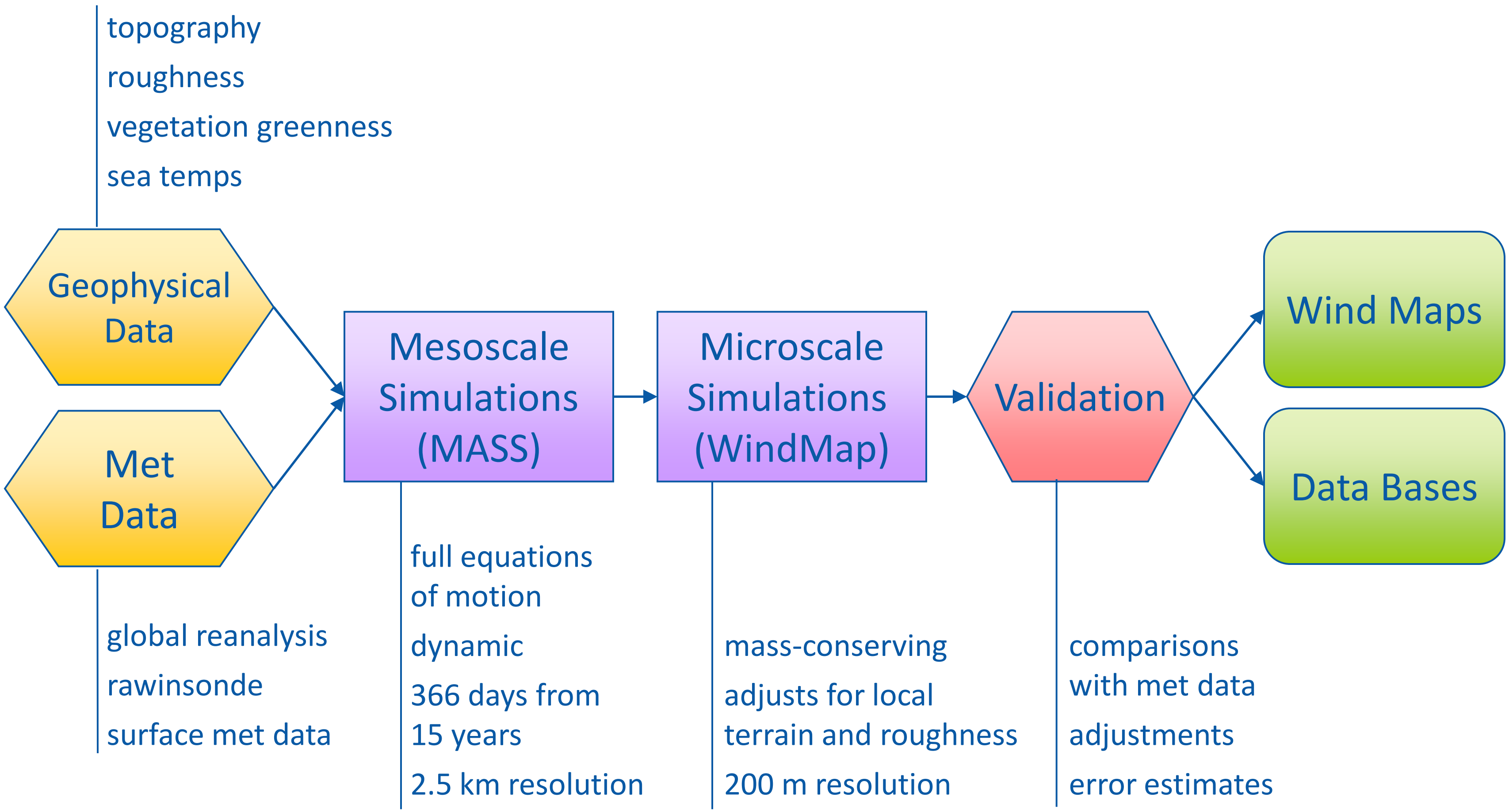
80-m mapping and potential estimates (2009-2010)

- New products for the contiguous United States and each state developed through a collaborative project with AWS Truewind
- Wind speed maps at 80 m
- Selected state maps validated using tower measurement data from 300+ locations
- Wind potential estimates at 80 and 100 m based on capacity factor categories
- Posted new products to WPA web site (broke all-time records for most hits)
- Hosted webinar to discuss new products and methodology (almost 100 attendees)
- Presented at Windpower 2010 conference
- Responded to many media and stakeholder requests about the new products

80-m Wind Resource Map – United States



AWS Truewind's MesoMap Process



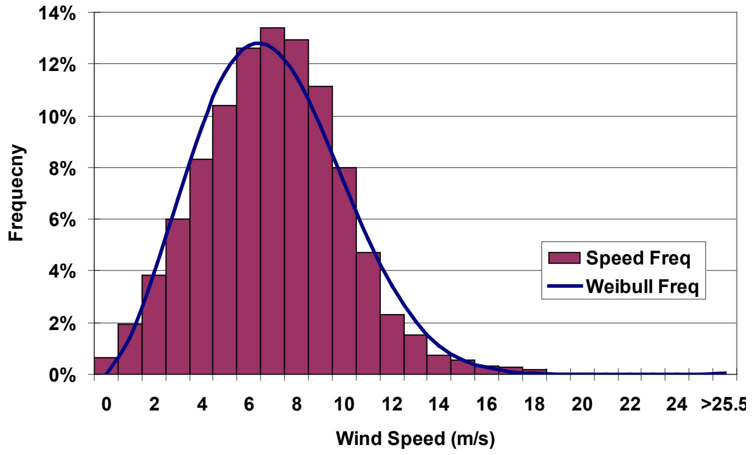
Validation of Wind Resource Estimates

- NREL's validation of model 80-m wind speeds
  - Purpose to identify gross disagreements between model estimates and measured data
  - Limited to 19 states (6 western, 6 midwestern, 7 eastern)
  - Data from 304 towers at 45 m and higher used in validation
  - Average wind speed from towers compared to model estimates

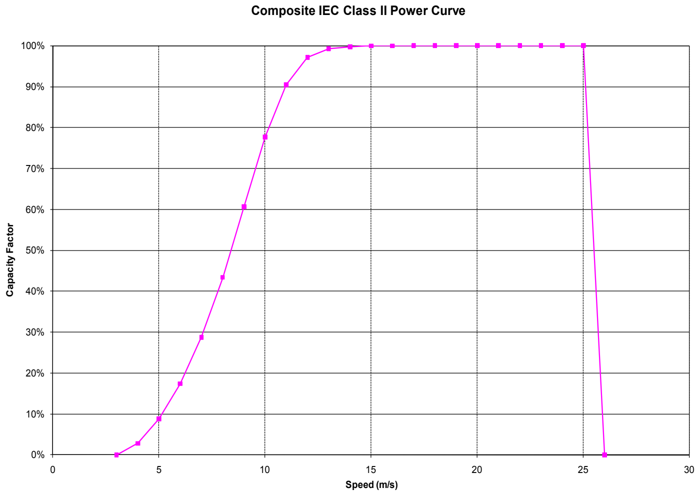
- Results of validation
  - No gross differences found between measured and model data to preclude use of these model data for wind potential estimates
  - National network of measurements near turbine hub-height needed to estimate wind potential with greater accuracy
  - Regions where additional measurements are crucial
    - Ridge crests sites in eastern U.S.
    - Interior sites in western U.S.

AWS Truewind's Estimation of Plant Output

For each point, wind speed distribution created from from 12 years of weather simulations (*windTrends*)



Then gross turbine output calculated for a generic IEC Class 2 turbine power curve, corrected for air density

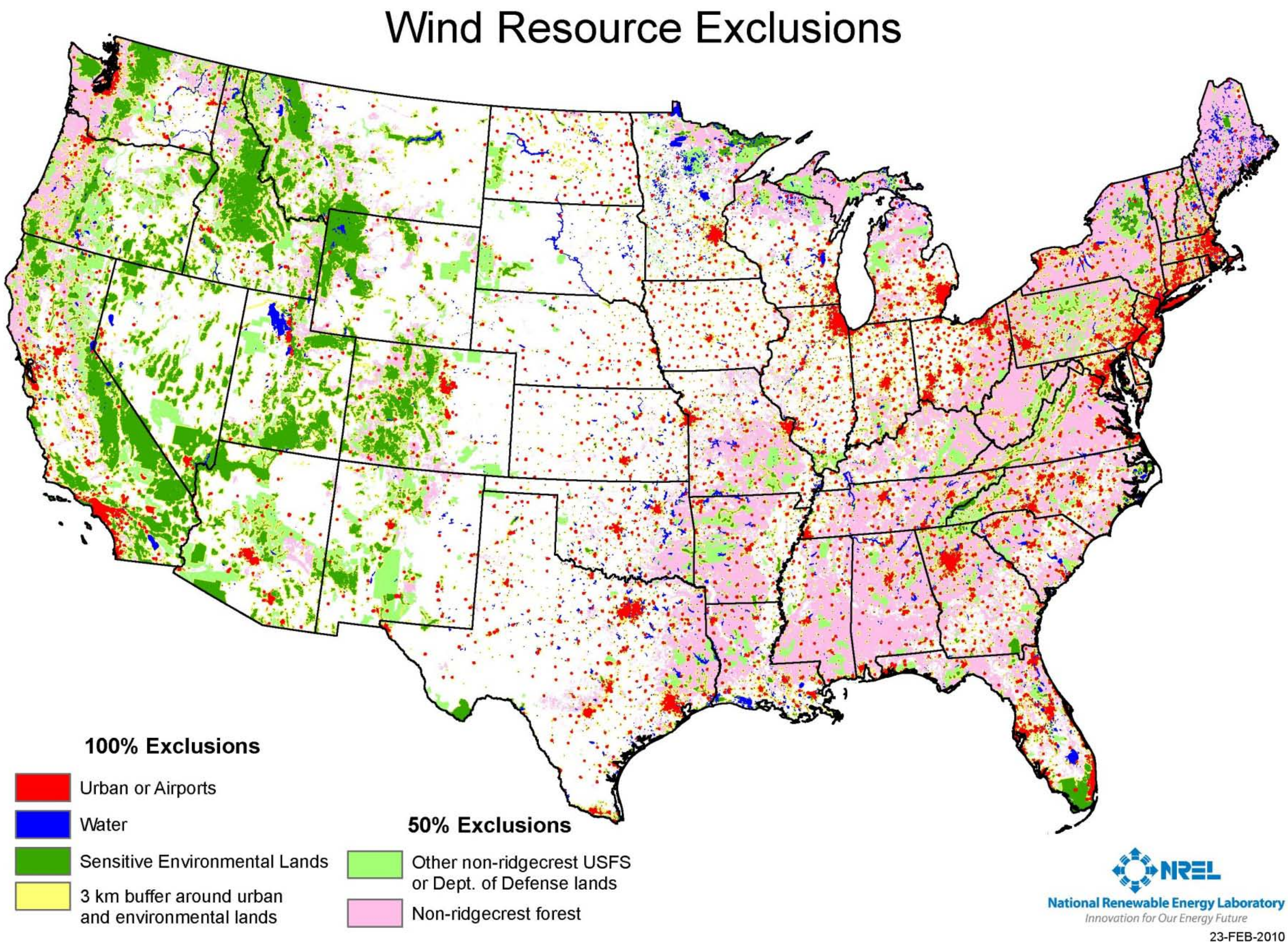


Development of Wind Potential Estimates

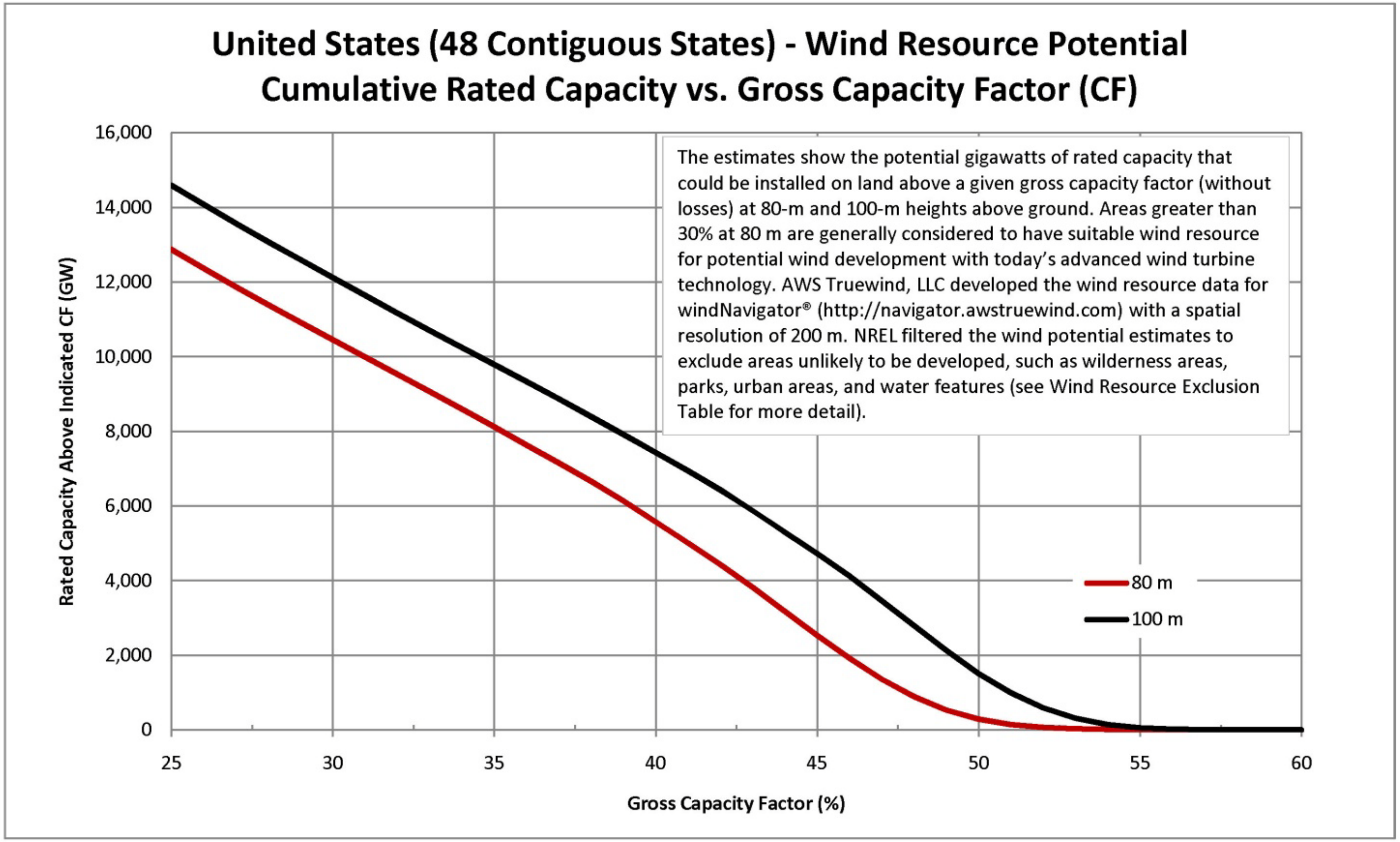
- AWS Truewind produced a national dataset of estimated gross **capacity factor** (not adjusted for losses)
  - **Spatial resolution of 200 m**
  - **Heights of 80 m and 100 m**
  - **Land-based areas only** (no offshore), 48 contiguous states

- NREL used the gross capacity factor (CF) data to estimate the land area and wind potential for each state
  - **Windy land defined as areas with >= 30% CF**, which are generally considered to be suitable for wind energy development
  - Areas with CF >=30% have mean annual wind speeds of about 6.4 m/s and greater
  - **Excluded sensitive environmental lands and incompatible land-use areas** (see map)
  - **For wind potential, assumed 5 MW/km^2** of installed nameplate capacity

National Exclusion Map



Wind Resource Potential - United States



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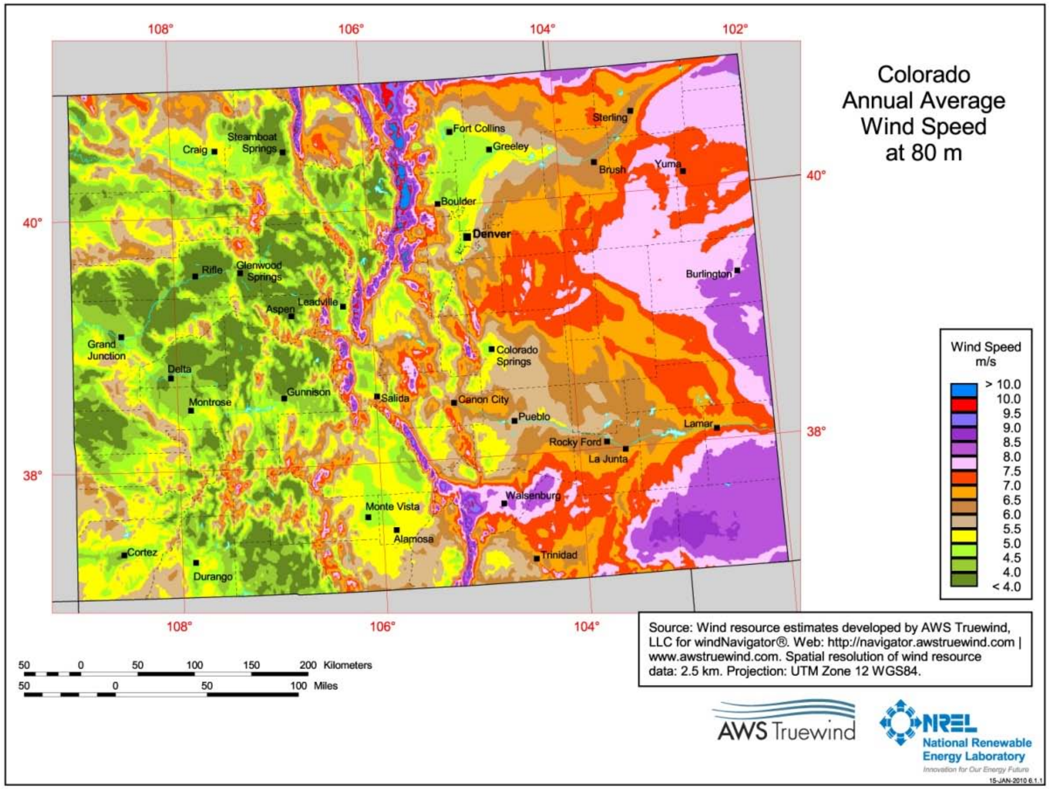
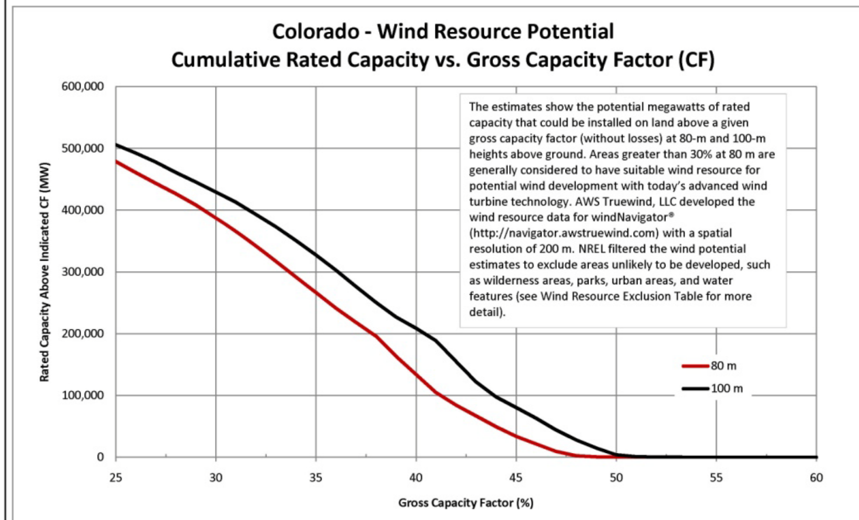
AWS Truewind

Capacity factor (CF) example: 1 MW turbine at 30% CF = 300 kW per year of output

Colorado Wind Map and Potential





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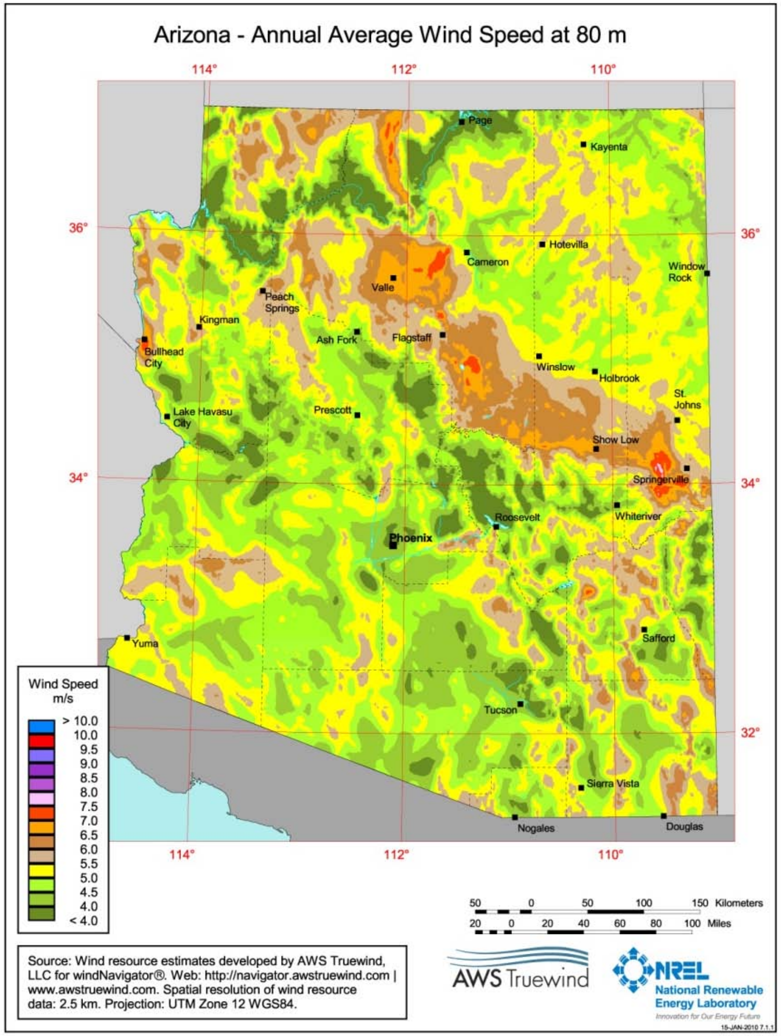
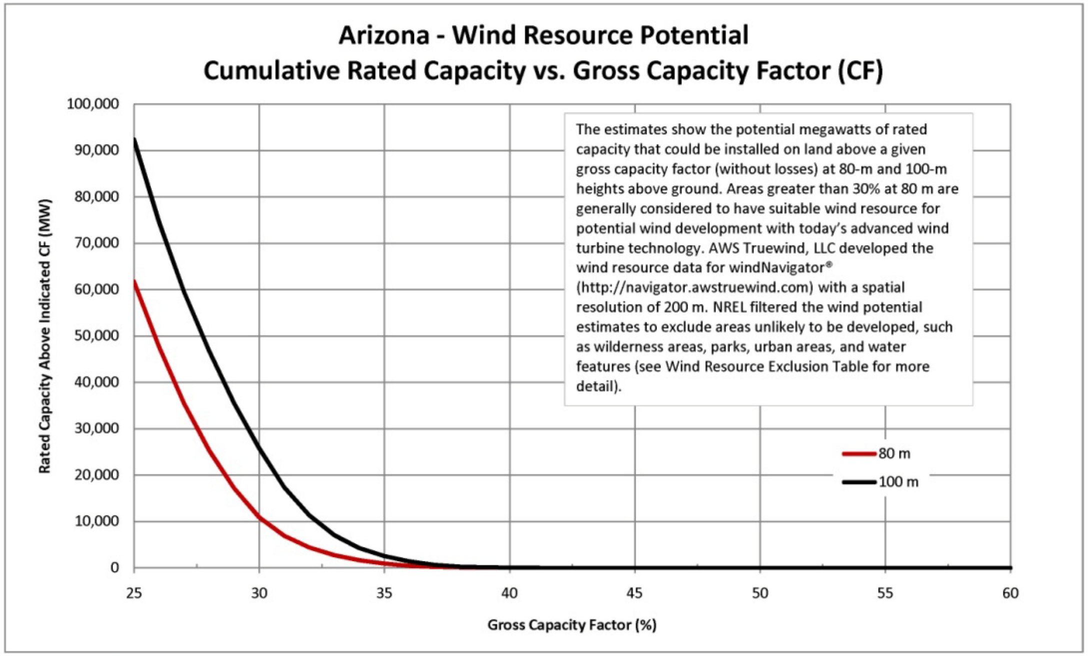
AWS Truewind

Arizona – Wind Map and Potential





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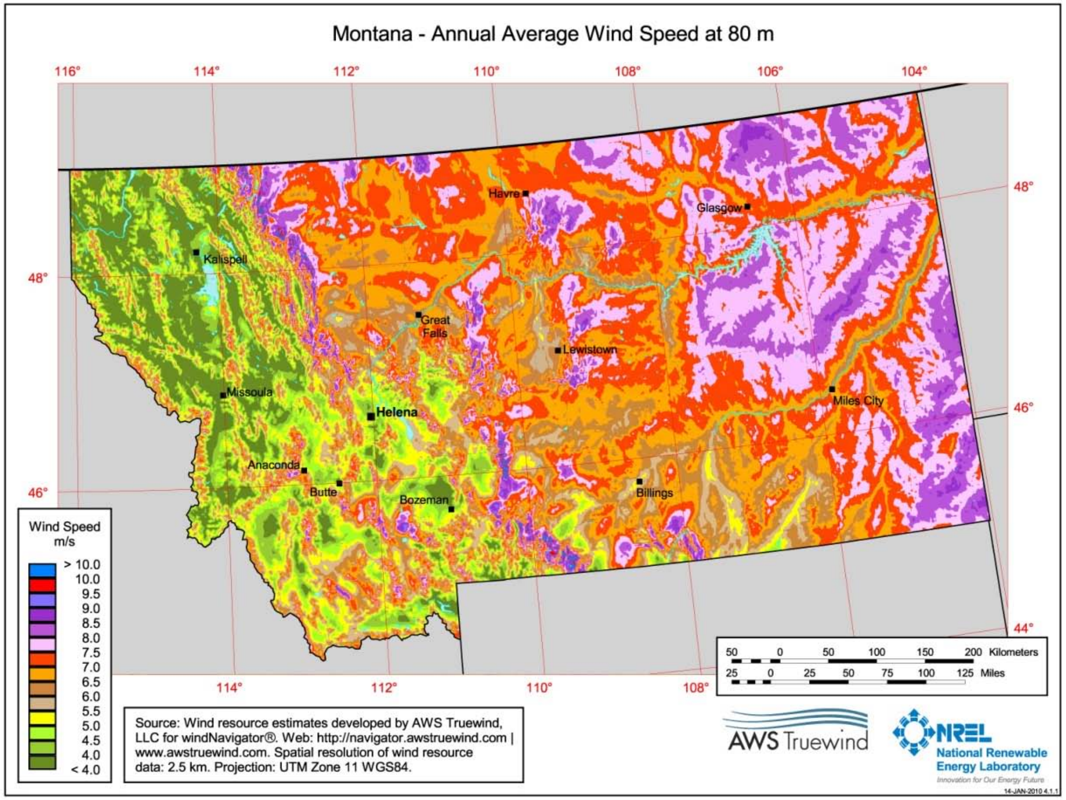
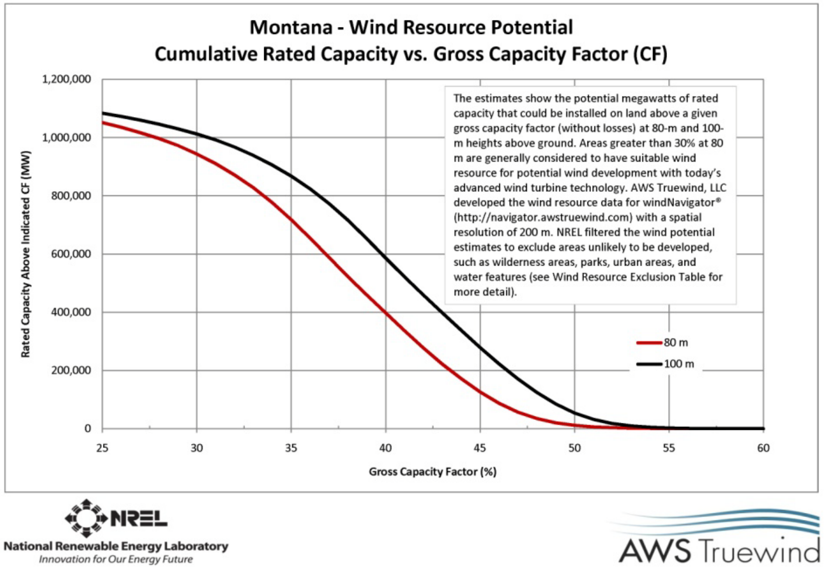
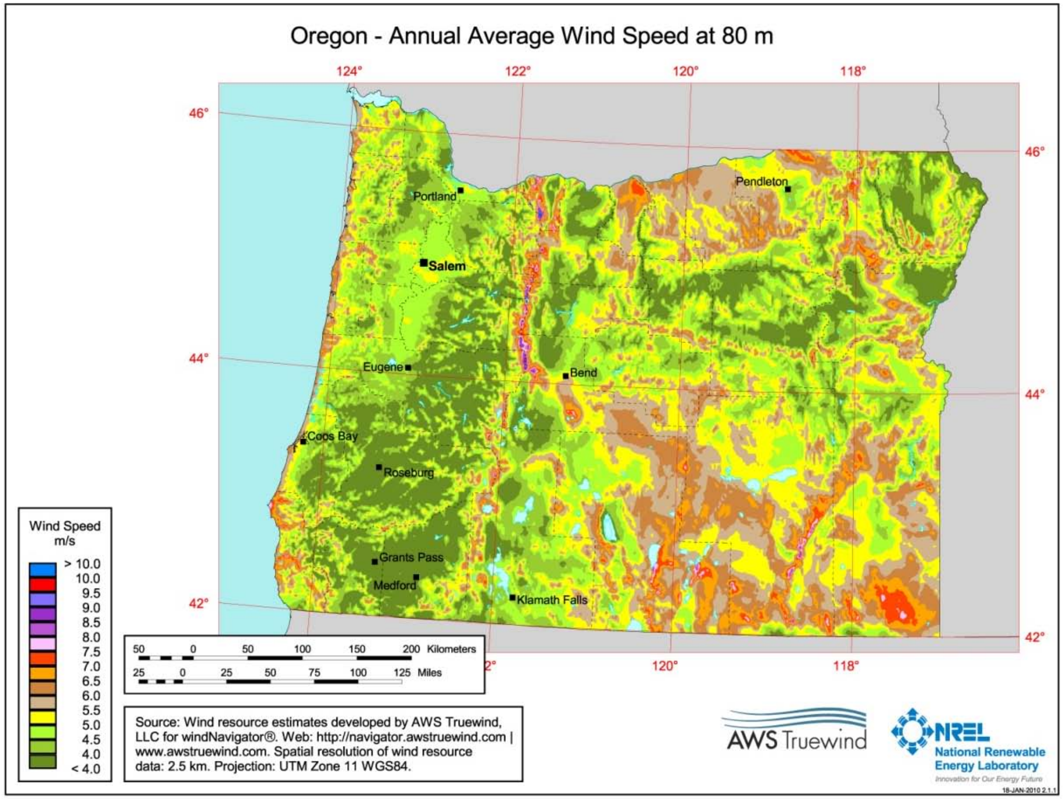
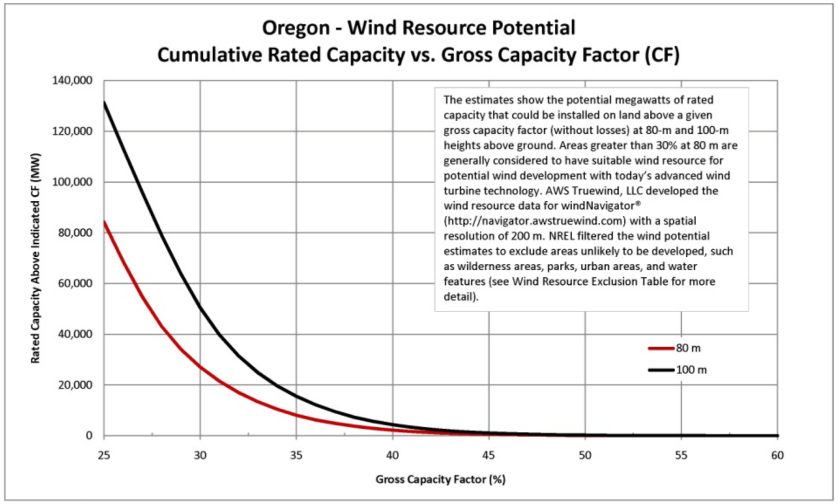
Montana – Wind Map and Potential





Oregon Wind Map and Potential





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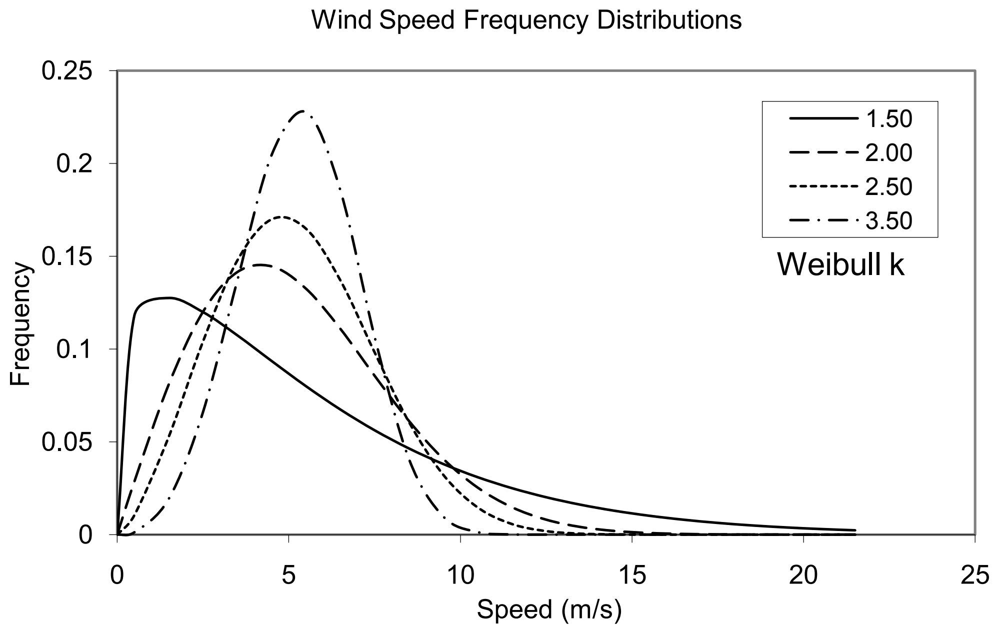
AWS Truewind

Capacity Factor vs Wind Speed and Power

Mean Wind Speed (WS) and Wind Power Density (WPD)
as functions of Capacity Factor and Weibull k

	WS	Weibull k			
		1.5	2	2.5	3
Capacity Factor	25%	5.65	5.82	5.98	6.11
	30%	6.28	6.34	6.44	6.55
	35%	6.96	6.87	6.92	6.97
	40%	7.71	7.43	7.39	7.41
	45%	8.56	8.03	7.89	7.85
	50%	9.57	8.69	8.42	8.32

	WPD	Weibull k			
		1.5	2	2.5	3
Capacity Factor	25%	300	231	207	197
	30%	412	298	259	242
	35%	561	379	320	292
	40%	763	480	391	349
	45%	1044	605	475	417
	50%	1460	769	578	496



Variation of Wind Power Class and Capacity Factor

Mean wind speed = 7.0 m/s but different Weibull k

California wind corridor
- Weibull k = 1.5, Power Class = 5, Capacity Factor = 35%

Eastern U.S.
- Weibull k = 2, Power Class = 4, Capacity Factor = 36%

Midwest U.S.
- Weibull k = 2.5, Power Class = 3, Capacity Factor = 36%

Specific areas
- Weibull k = 3, Power Class = 2, Capacity Factor = 35%

Note: Capacity factors are rounded to the nearest whole percent

Wind Monitoring Equipment and Measurement Programs

What do we monitor?

- Wind speed (average and gusts)
- Wind Direction
- Temperature

How often do we record it?

- 10 minute average is standard practice
- 1-second sampling (to evaluate turbulence intensity)

For how long?

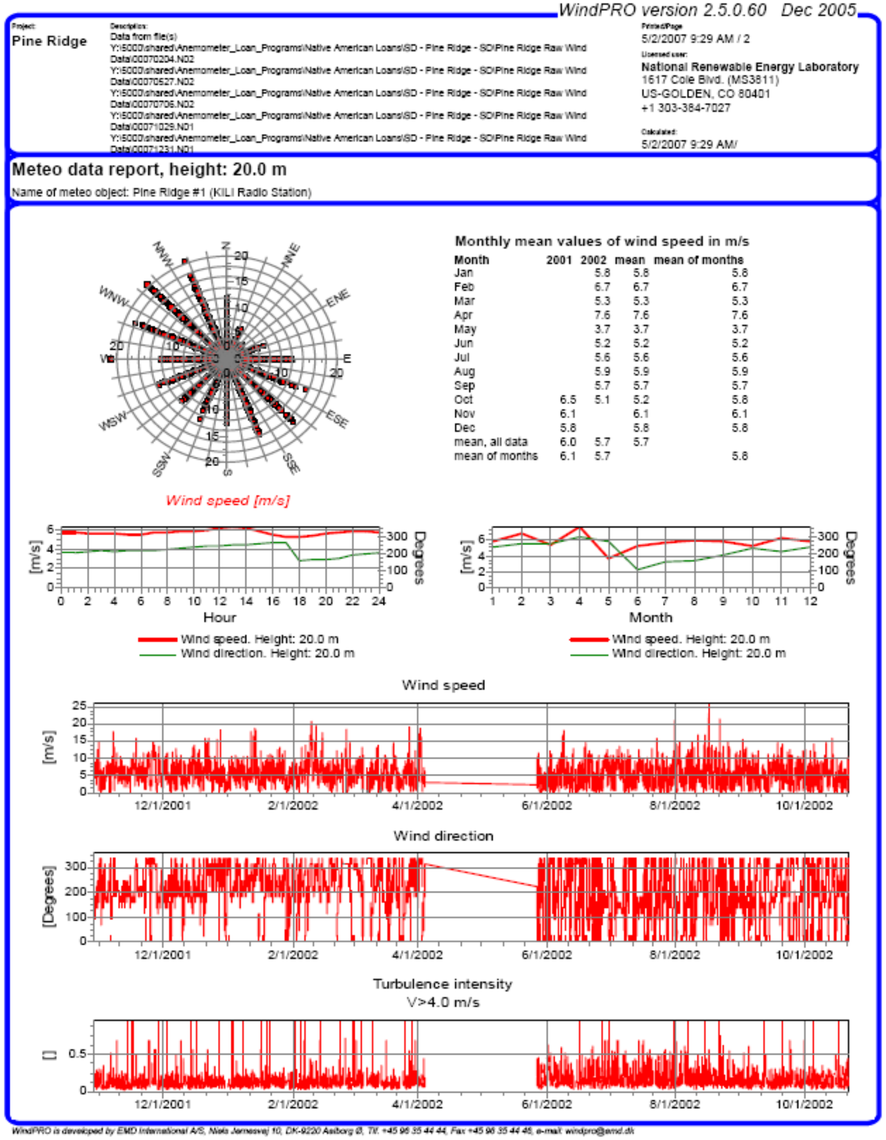
- 2 years is good
- 1 year is a minimum

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.)

Statistics
- Average wind speed and wind power density
- Seasonal and diurnal variations
- Variation with height above ground
- Turbulence intensity
- Frequencies of wind direction and wind speed
- Many others

Sample data report for wind measurement site



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

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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

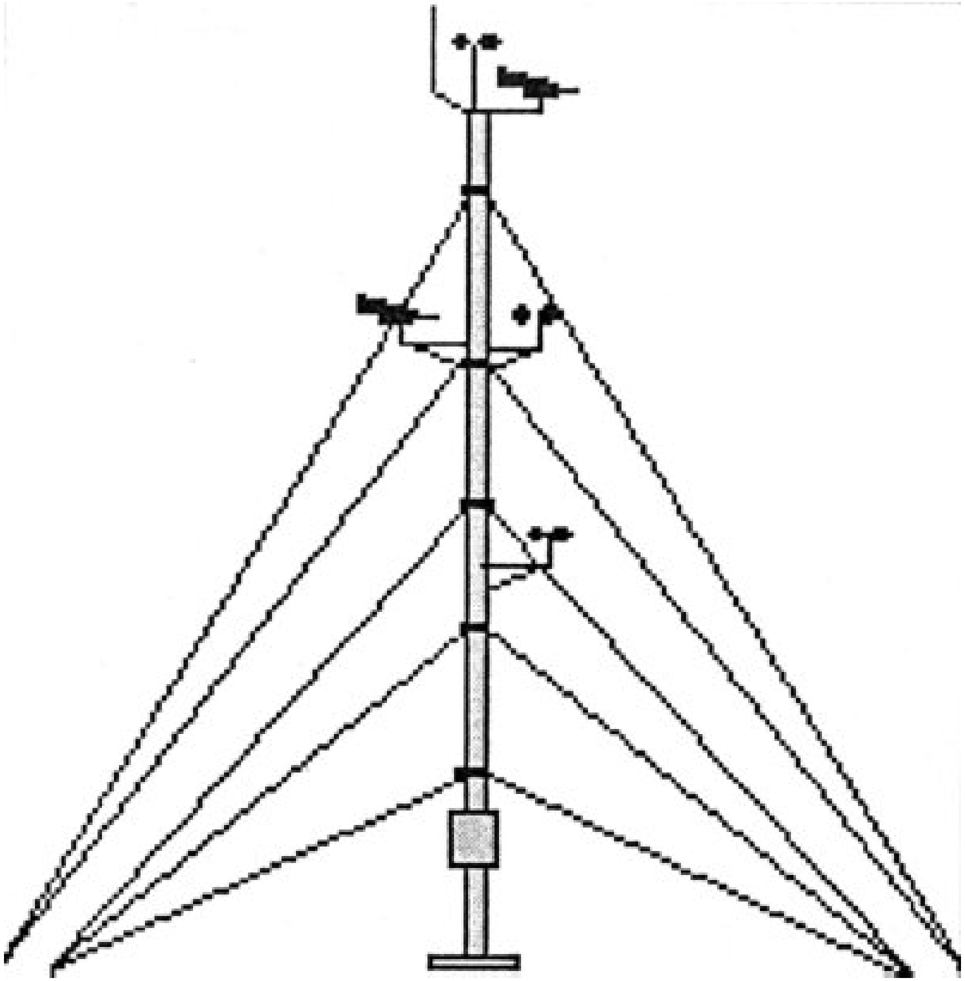
Month	2001	2002	mean	mean of months
Jan		5.8	5.8	5.8
Feb		6.7	6.7	6.7
Mar		5.3	5.3	5.3
Apr		7.6	7.6	7.6
May		3.7	3.7	3.7
Jun		5.2	5.2	5.2
Jul		5.6	5.6	5.6
Aug		5.9	5.9	5.9
Sep		5.7	5.7	5.7
Oct	6.5	5.1	5.2	5.8
Nov	6.1		6.1	6.1
Dec	5.8		5.8	5.8
mean, all data	6.0	5.7	5.7	
mean of months	6.1	5.7		5.8

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

Wind Monitoring Equipment

- Sensors (Speed, Direction, Temperature)
- Data Loggers
- Towers

Tower with Logger and Sensors



Anemometer & Wind Vane

Standard anemometer (SecondWind C3) $115

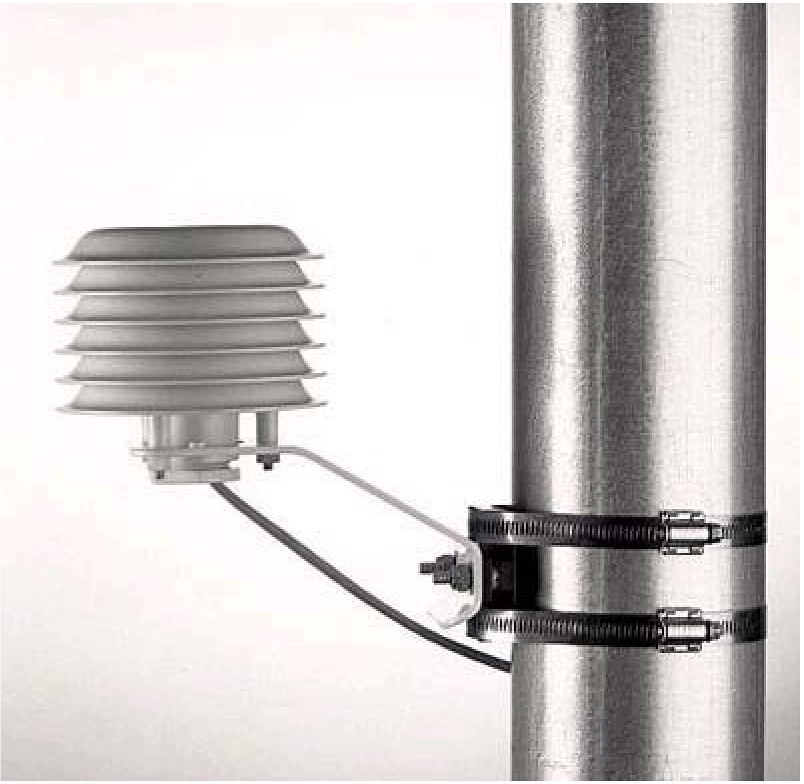
Calibrated anemometer (NRG Max40 or SecondWind C3) $295

Heated anemometers and vanes for very cold climates $970 each!

Temperature Sensor

$195

Helps determine periods of icing



Towers for Wind Resource Assessment

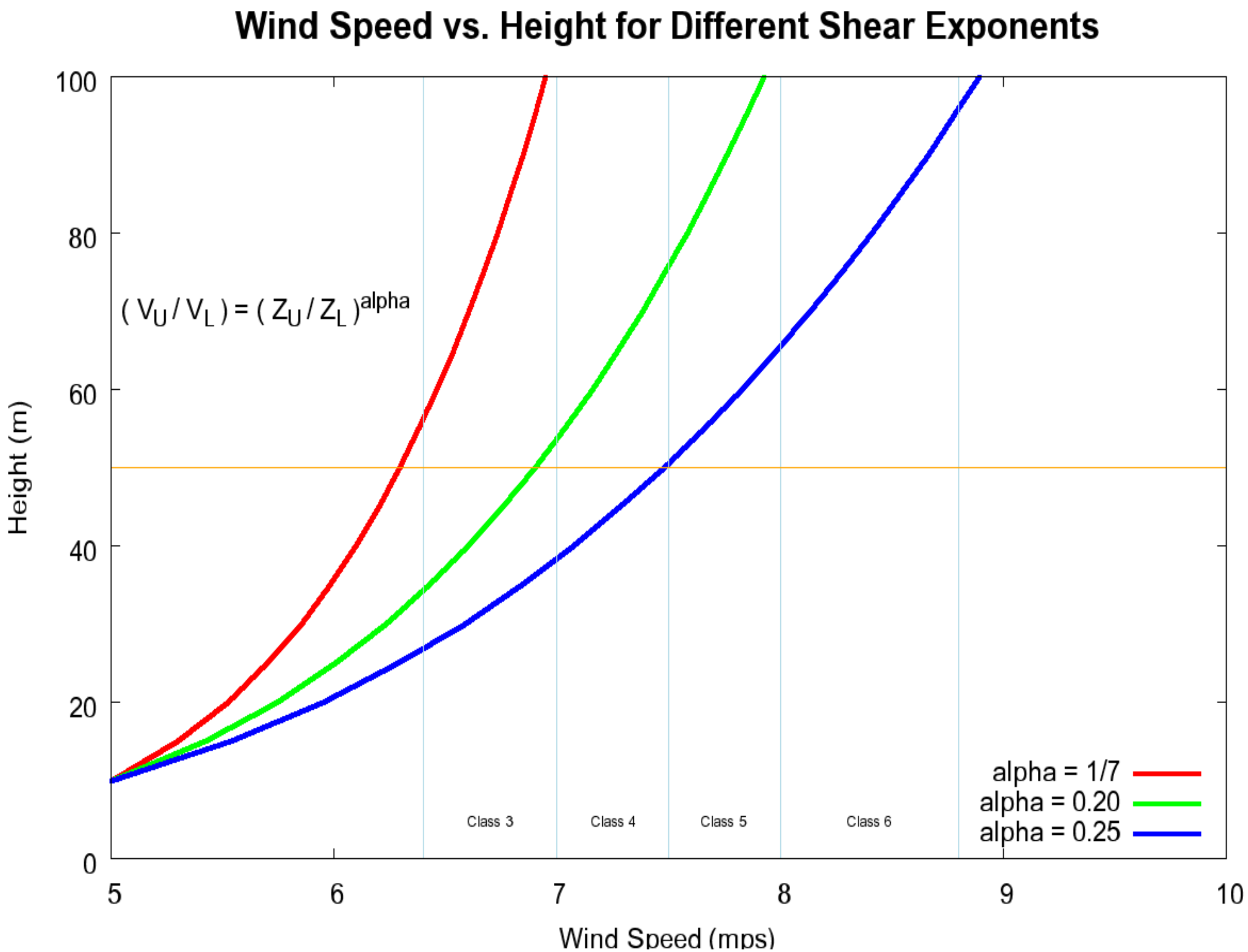
- Tubular Towers
  - Most common for wind evaluation
  - Tilt-up
  - Up to 60m (or even 80m)
  - 20m = $1000, 60m = $10000-12000
- Booms hold sensors away from tower

Lattice Towers

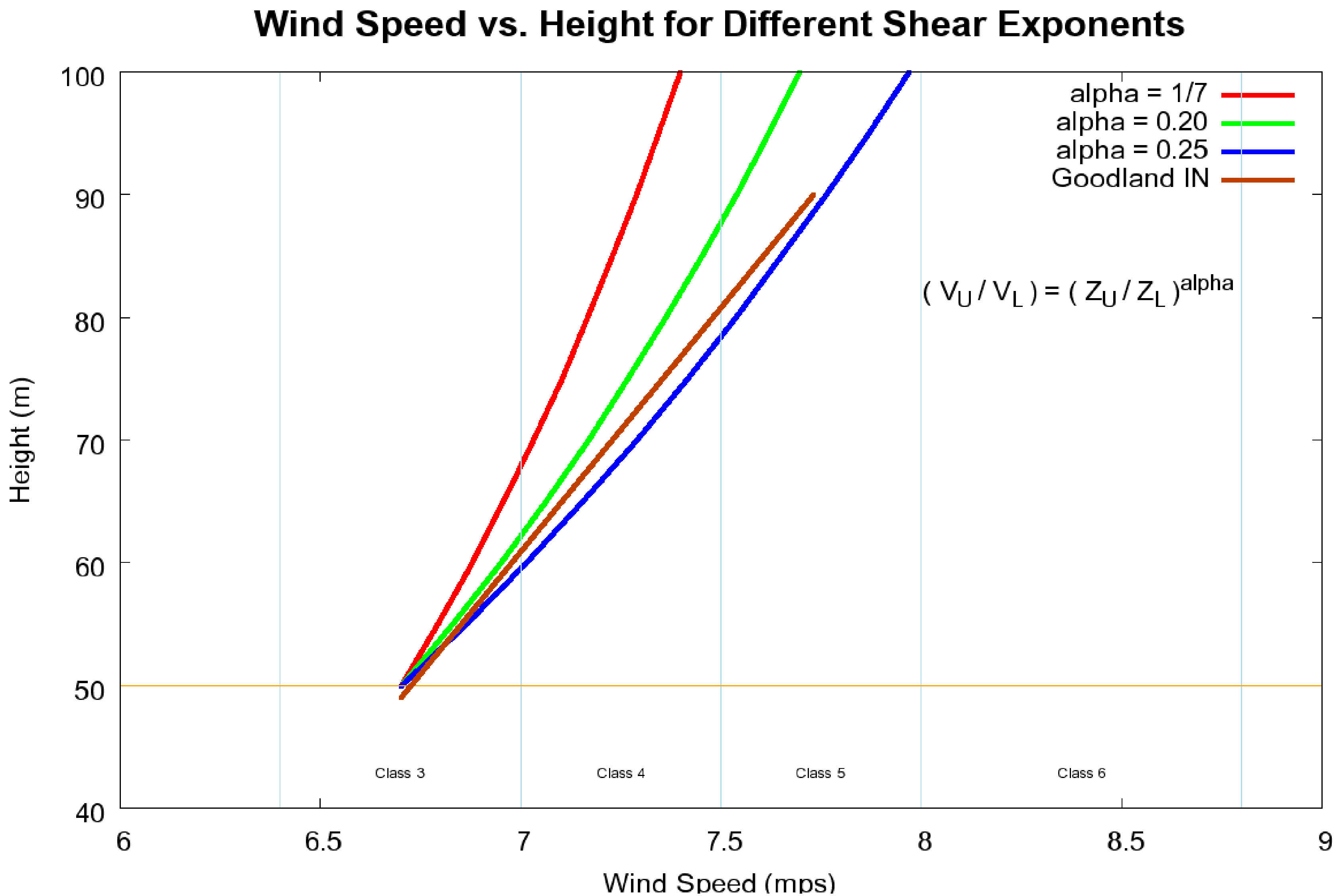
- Existing communications towers (broadcast, cell phone, etc.)
- Up to 120m
- Need permission from owner

Tall towers and remote sensing measurements

- Tall towers and remote sensing measurements are needed to validate model data at 80-100m and produce high-confidence wind resource data
- Tall towers (100 m + in height)
  - New towers ($100K/tower for 3 years data)
  - Existing towers ($50K/tower for 3 years data)
- Remote sensing instruments
  - Sodar
  - Lidar
  - Radar

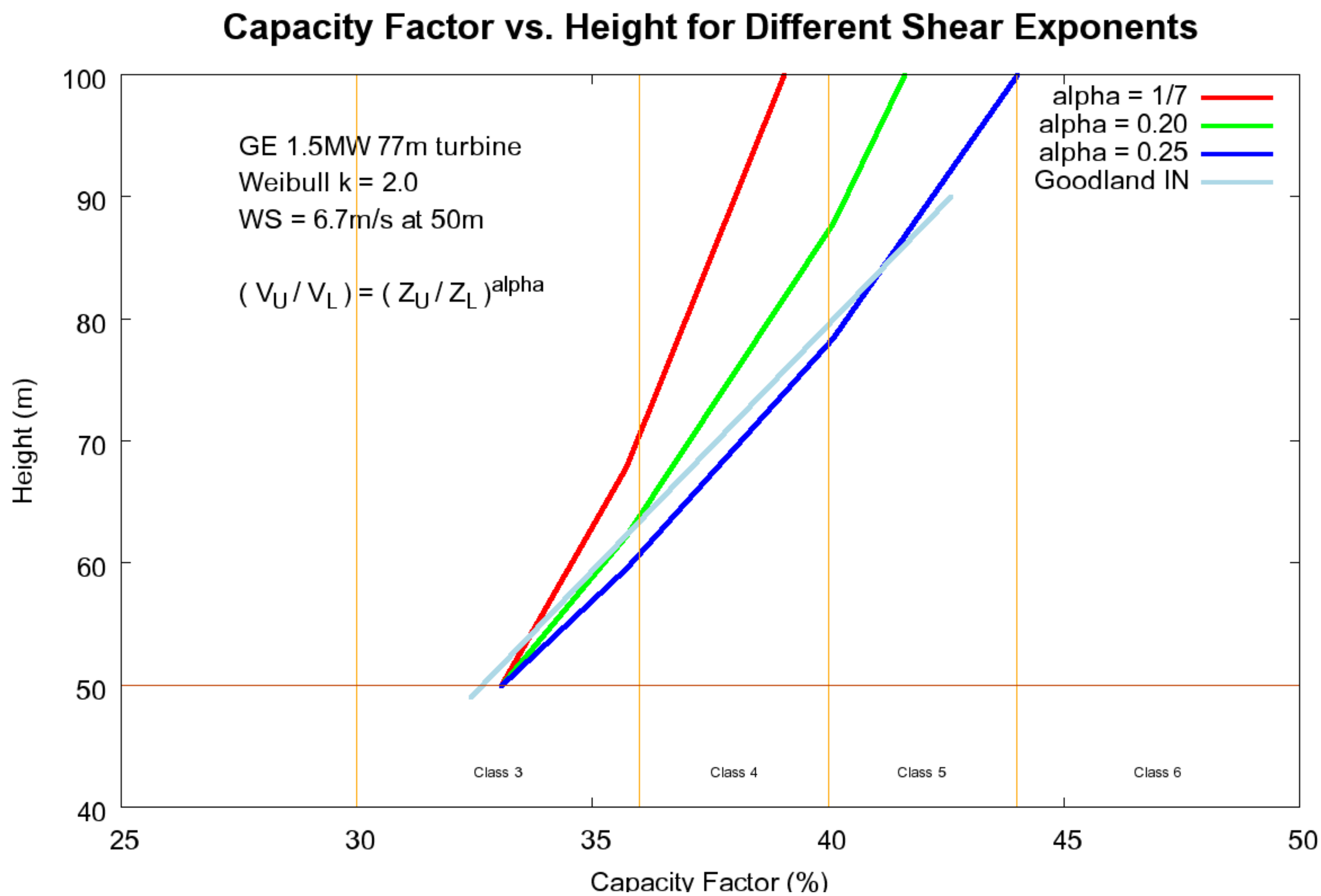


Annual average shear exponents can vary from 1/7 to 0.25, causing considerable uncertainty in vertical extrapolations of wind resource



•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

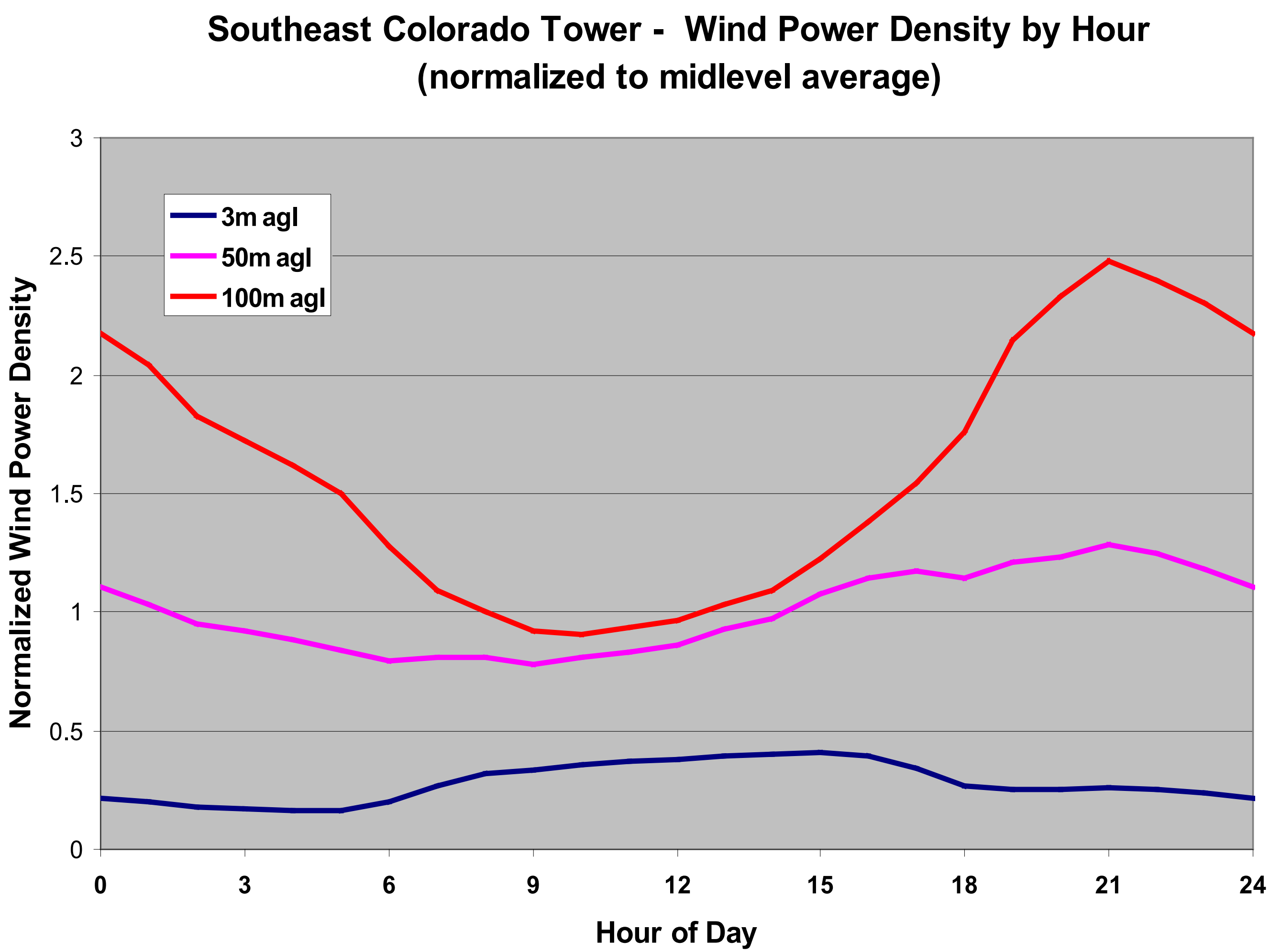
•Measured shear exponent at Goodland is 0.235, with much higher wind resource at 90 m than estimated by 1/7 shear estimate



- 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 gross 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

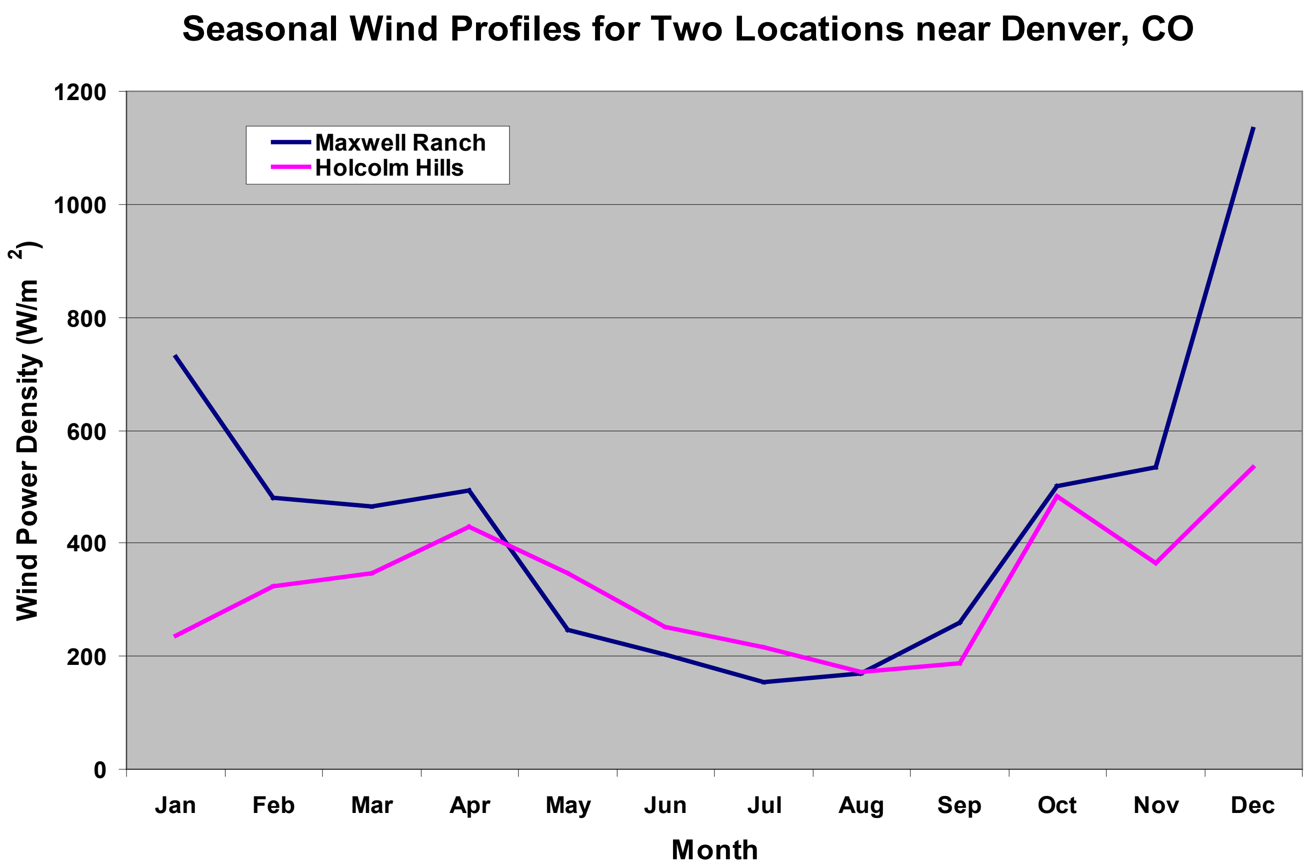
Diurnal Wind Profiles vs Height

- Diurnal wind profiles can change dramatically with height above ground
- Without adequate data, hub-height profile estimate is uncertain

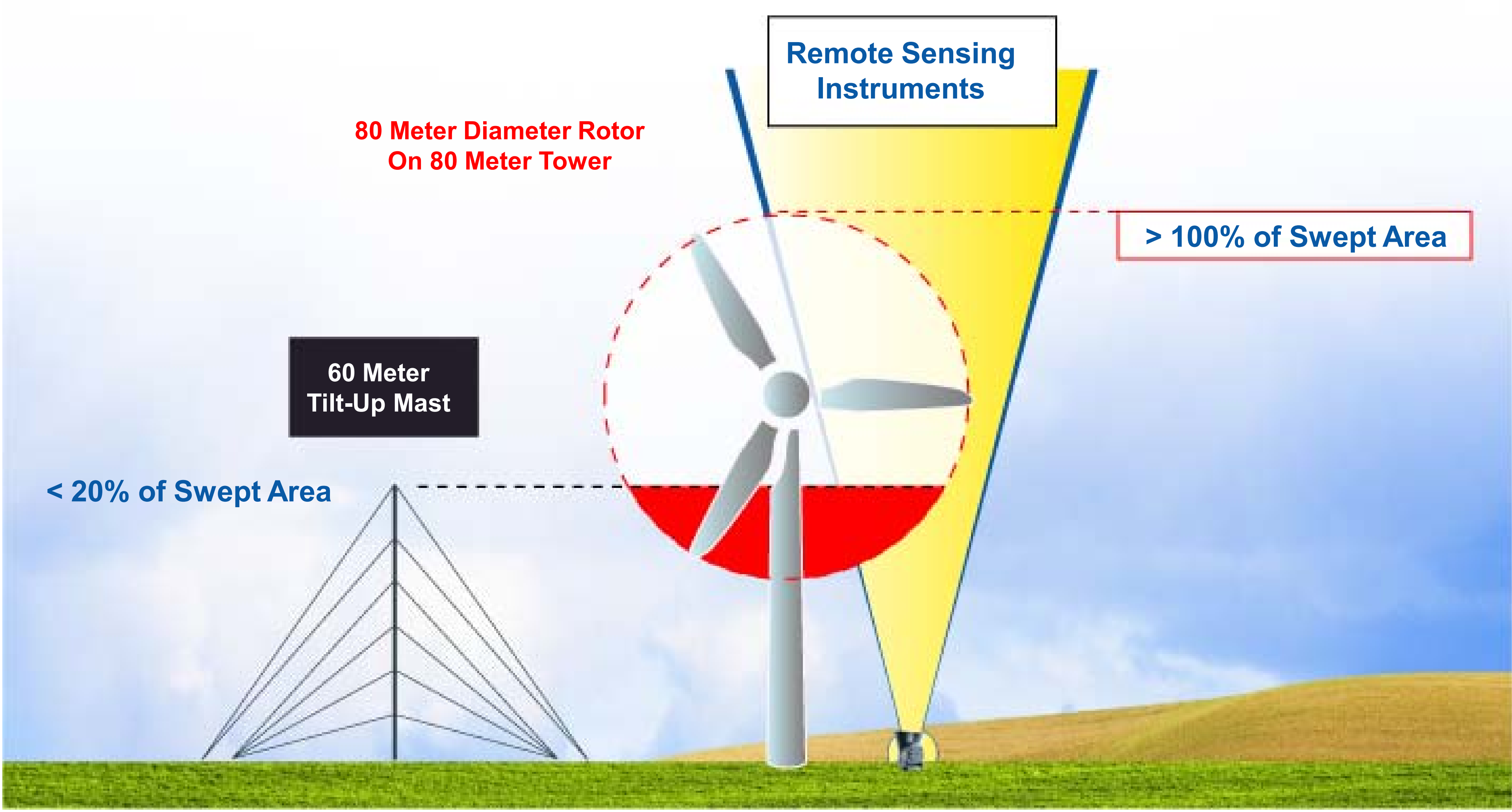


Seasonal Wind Profiles – Geographic Variations

- Seasonal wind profiles can change over short distances depending geography and terrain
- Without adequate data, estimates of seasonal profiles may be uncertain

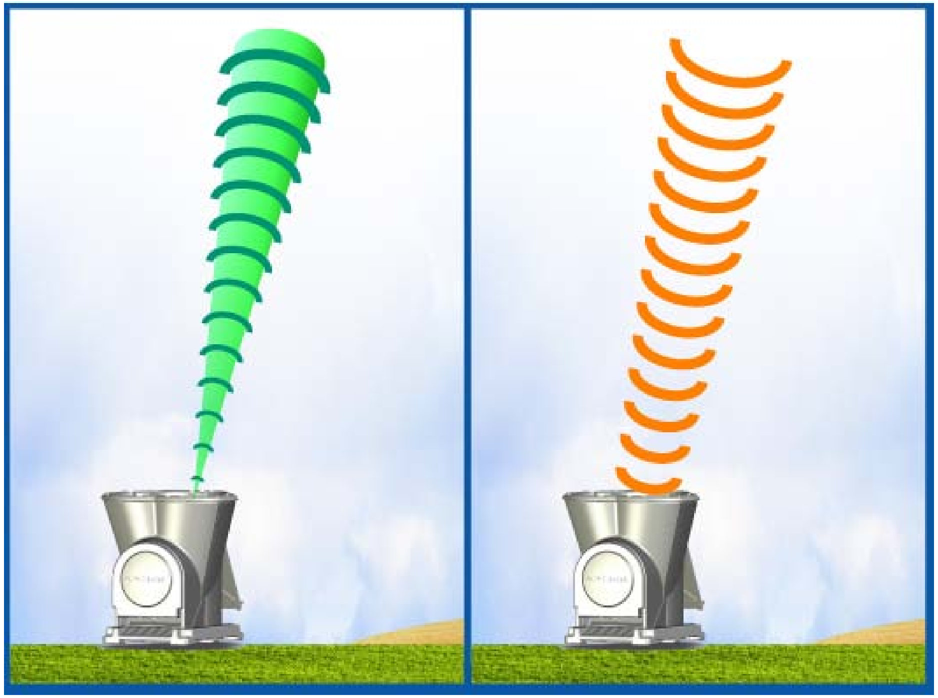


Why Remote Sensing?



What is Sodar?

- **<u>So</u>**nic **<u>d</u>**etection **<u>a</u>**nd **<u>r</u>**anging
- Audible Chirp
- Sends a sound signal into the air
- Upon return of signal, record changes and calculates wind speed, direction, shear



Sodar

- Operates by detecting back-scattered sound (4 to 6 kHz)
- Range 15 m to 200 m above ground (with 5 to 10m resolution)
- Can measure wind at greater levels than tall towers but needs consistent oversight
- Power requirements 10 – 60 Watts

Commercially-Available Sodars

Representative Examples of Mini-Sodars

Second Wind
Triton

ASC
4000

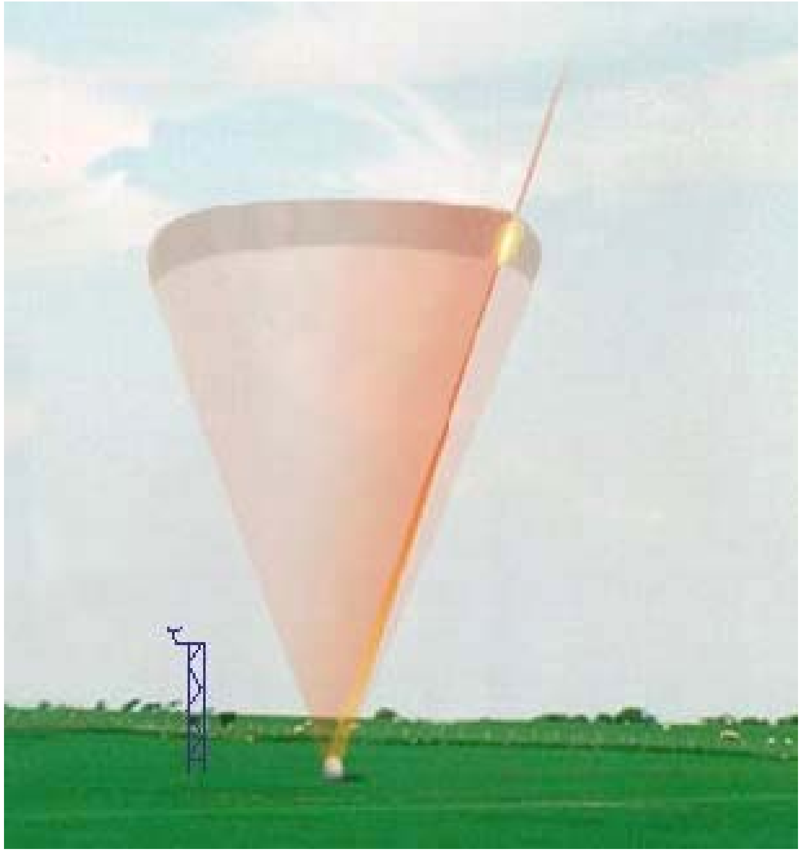
ART
VT-1

Scintec
SFAS

	Mini-Sodars	Mid-Range Sodars
Nominal operating frequency	4500 Hz	2000 Hz
Measurement range	15-200 m	30-1000 m
Minimum vertical resolution	5-10 m	20 m
Averaging times	2 to 60 minutes	2 to 60 minutes
Claimed accuracy	0.3 to 0.5 m/s	0.3 to 0.5 m/s

What is Lidar?

- **L**aser **d**etection **a**nd **r**anging
- Infrared laser
- Send a pulsed / swept signal into the air
- Upon return of signal, record changes and calculates wind speed, direction, shear



Lidar

- •Range 10m to150m above ground
- •Operates by detecting back-scattered light
- •Similar to sodar, lidar can measure wind at greater heights than towers but needs consistent oversight
- •Power requirements >100 Watts

Commercially-Available Lidars for Wind Energy Applications

Examples

Pulsed Coherent Lidars

Continuous Wave (CW) Lidar

Natural Power ZephIR

Wind Profiling Lidar

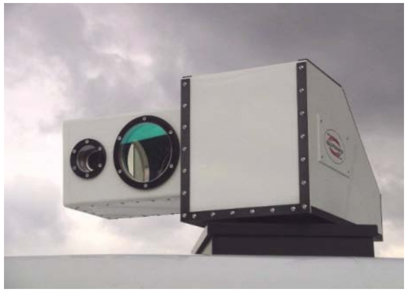
NRG Systems/Leosphere WindCube

Scanning Lidars

Lockheed-Martin WindTracer

Catch the Wind Vindicator

HALO Photonics

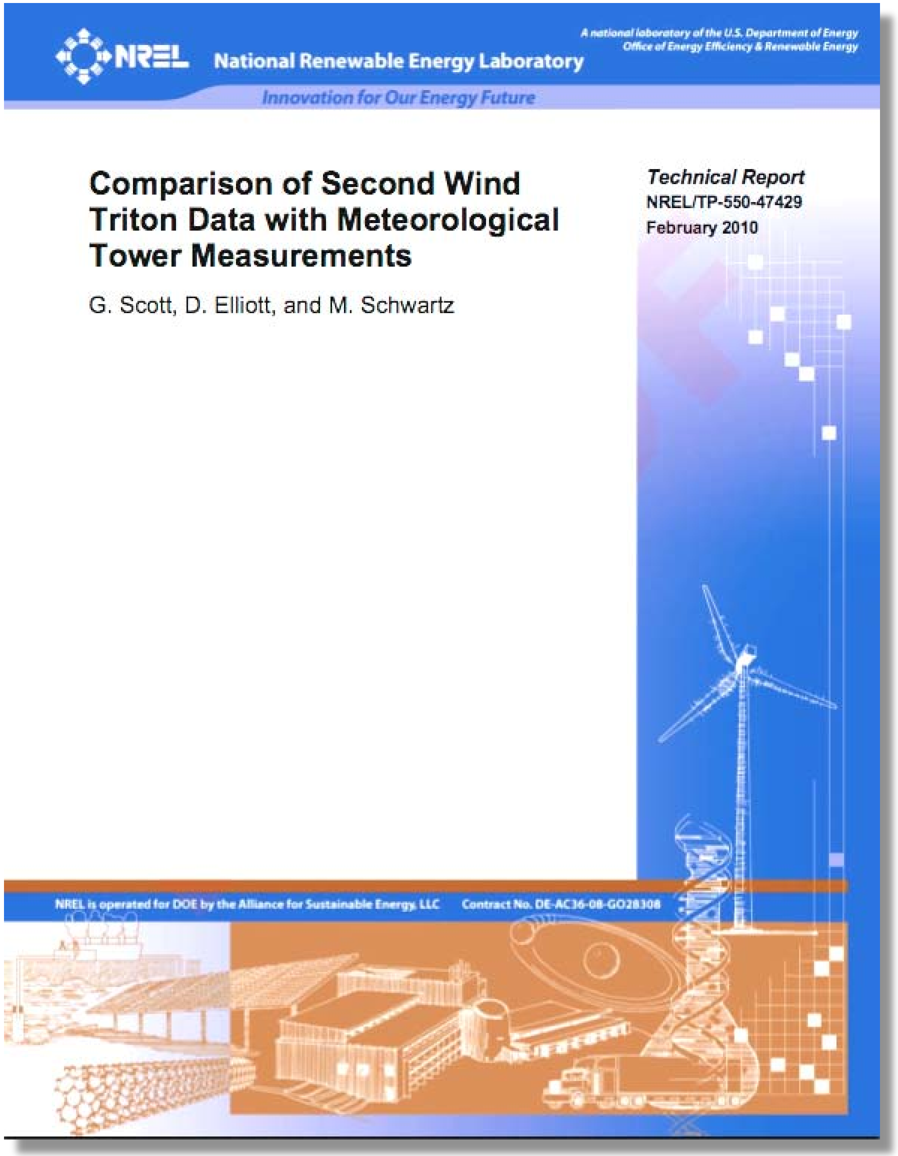


Remote Sensing / Tall Tower Data Analysis

Example of Technical Assistance:
Cooperative Research and Development Agreement (CRADA) between NREL and Second Wind (a private U.S. company)

NREL analyzed almost 7 months of wind measurement data from a sodar unit and compared these data to measurements from a tall (80-m) meteorological tower.

Results: Generally good agreement between sodar and tower measurements.

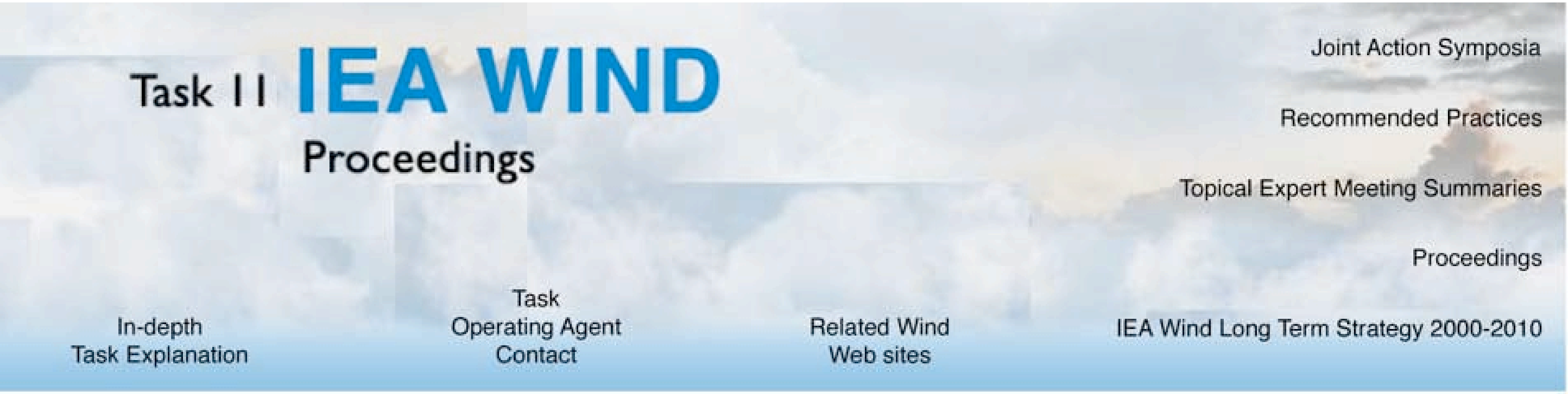


International Collaboration on Remote Sensing Techniques for Wind Resource Assessment

Technical Assistance

Hosted International Energy Agency Task 11
Base Technology Information Exchange
Topical Experts Meeting at NREL
Remote Wind Speed Sensing Techniques using SODAR and LIDAR
October 15 & 16, 2009

31 Participants from 11 Countries



IEA Meeting on Remote Sensing Using Sodar and Lidar

The IEA Topical Expert Meeting on Remote Sensing at NREL in October 2009 recommended:

- Need for more experience from remote sensing
  - To increase the accuracy and the repeatability of measurements
  - Especially comparing the performance of Sodar and Lidar with tower measurements
- Development of IEA Recommended Practices for Sodar and Lidar
  - Two ad-hoc groups were formed to put together proposals for the proper operation of Sodar and Lidar
  - Draft documents are in preparation
- Arrange a new expert meeting to discuss pertinent issues and new research on this topic

Opportunities for Wind Energy Industry

How and when remote sensing is being used?

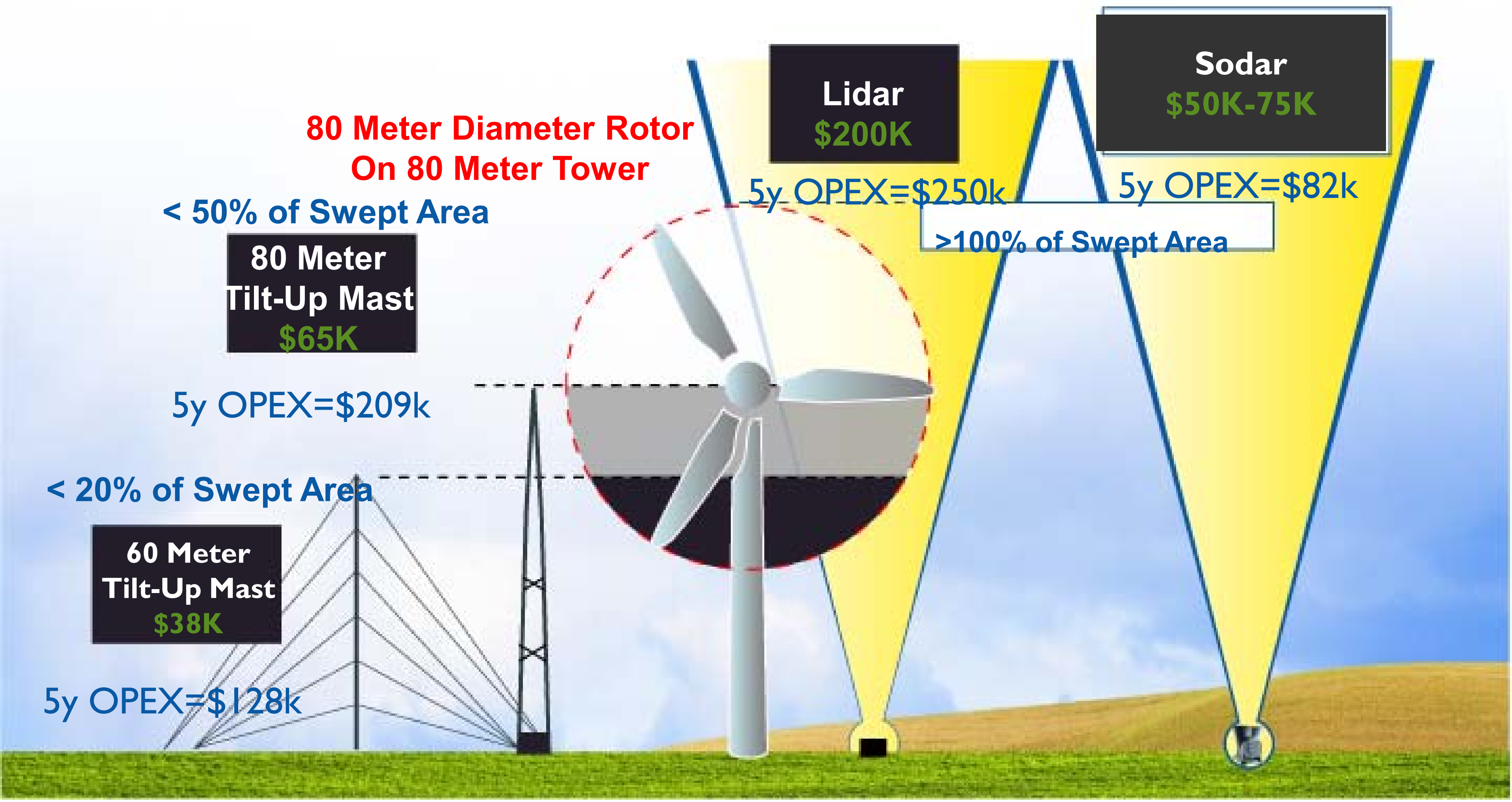
- Fields of application
  - Wind Resource Assessment ➔ Prelim. siting / Reduce bias-uncertainty
  - Site Suitability ➔ Curtailment issues
  - Project Performance ➔ Understand underperformance
  - Offshore ➔ Reduce cost of WRAP

- Fields of research
  - Wind shear
  - Wind veer
  - Turbulence intensity
  - Flow angle
  - Wake

} Effect on AEP
Effect on aeroelastic loading
Design improvement
Control algorithm
Simulation refinement
Standard update
(power curve/site suitability)

How and when should remote sensing be used ?

Met Tower vs. Remote Sensing
$$$



Thank you