Wind & Solar Energy Prediction: Challenges of Opportunities

Mr. William P. Mahoney III
Deputy Director, Research Applications Laboratory
National Center for Atmospheric Research, Boulder, Colorado, USA

Source: AMEC
Mother Nature Is Not Always Kind
Setting the Context - Scale

Source: Terra Magnetica
Weather & Solar Energy Related Industry Issues

- Wind energy resource estimates at wind farm sites are over-estimated on average
- Wind turbines are failing faster than predicted (up to 40% earlier)
- Wind & solar power variability complicate power integration and load balancing across the grid – requires reserves
- Wind energy prediction has typical errors of 10-15% (flat terrain) to 15-25% (complex terrain)
- Wind turbines are not designed to handle extreme weather conditions (shear, ice, snow, high wind, etc.). More representative weather datasets are needed for turbine design
Overarching Wind Energy Science Challenges

- Boundary layer meteorology (0 to 200 m above ground) is not well understood nor is this layer well measured.
- The wind energy industry greatly under appreciates the complexity of the airflow in this layer.
- The wind industry has historically assumed less turbulence and more wind with height above the ground.

Image source: Wind Measure International
Overarching Solar Energy Science Challenge

Improve prediction needed of:

- Cloud lifecycle
- Aerosols
- Jet Contrails
- Surface conditions (snow/ice melt on solar devices)

- Cloud and precipitation processes are highly complex and operate on very small scales (10s to 100s of meters)
- Weather models greatly over simplify cloud physics properties and precipitation processes.
- Jet contrails can spread into a cirrus deck and are not predicted by any models
Current Meteorological Shortfalls for Wind Energy

- Lack of wind, temperature, and stability measurements between 10 and 200 m above ground
- Weather models not optimized for wind energy prediction and modeling across scales
- Need improved data assimilation techniques to take advantage of wind farm and other local observations
- Dearth of vertical observations offshore
- Lack of understanding of complex flows near the Earth’s surface
- Ice and snow accretion and deposition prediction
Current Meteorological Shortfalls for Solar Energy

- Lack of surface irradiance measurement covering a wide range of climates
- Lack of global water vapor measurements at high resolution (horizontal and vertical)
- Weather models not optimized for solar energy prediction; modeling across scales (synoptic to cloud scale)
- Inadequate data assimilation techniques to take advantage of solar farm solar and other local cloud observations
- Lack of full understanding of cloud physics and precipitation processes
Examples of Complexity
Predicting Inversions – Wind Decoupling

Nocturnal inversion – Denver 19 September 2010
15 degree C difference over ~1500 ft

observatio

Warmer Air
Cold Air

60-80 m
10 m
Low-Level Jets of High Wind (U.S. Midwest)

Lidar (laser radar) measured wind velocity toward lidar

Low-level jet streams can damage wind generators

10 ms\(^{-1}\) ribbon of high speed air

Courtesy, Robert Banta, NOAA
Wind Variability at Turbine Height Can be Substantial

Streamwise Velocity (m s⁻¹)

Copyright Ned Patton, NCAR
Influence of Stability on Low-Level Flow

Horizontal slices of vertical velocity

Near neutral

Strongly unstable

Courtesy Ned Patton, NCAR
Turbine wakes result in power loss, turbulence, wind shear and overall wear and tear on the turbines drive trains.

Courtesy Branko Kosovic, NCAR
Wind Shear vs. Turbine Efficiency

Knowledge of the wind profile is important for wind to power conversion – Shear across blades can reduce efficiency by up to 20%!

(Lundquist and Wharton, 2009)

(T. Aguilar, 2010)
Wind Energy Ramps – Colliding Gust Fronts

Colliding thunderstorm gust fronts in Texas

RADIAL VELOCITIES (m/s)

Mahoney 1988
Wind Energy Ramp Events

8/03/09 771mw up-ramp from 20:10 - 22:10 followed by a 738mw down-ramp from 22:40 - 00:50

800 MW in < 2 hrs.
cold front
small thunderstorms

MW

TIME

800
700
600
500
400
300
200
100
0
16:50
17:10
17:30
17:50
18:10
18:30
18:50
19:10
19:30
19:50
20:10
20:30
20:50
21:10
21:30
21:50
22:10
22:30
22:50
23:10
23:30
23:50
0:10
0:30
0:50
1:10
1:30
1:50

Wind Energy Ramp Nowcasting

Predicting wind energy ramp events using a rapid cycle, high-resolution weather model and Doppler radar data.

Animation of the Variational Doppler Radar Analysis System (VDRAS) covering eastern Colorado wind farms. Wind vectors and Doppler radar reflectivity are shown.
Complex Flows – Offshore Wind

For offshore applications it is important to capture wind and wave interactions.

Moving waves

Waves generate their own wind field that persists to hub height.
Hurricane Flow Characterization Complexities

WRF Hurricane Simulation
Large-Eddy Simulation (LES)
190 ft (62 m) resolution

Resolving turbulence scales

How do wind turbines respond to hurricanes, typhoons and USA Nor’easter?
Icing Accretion and Snow Deposition

Icing prediction and its impact on turbine performance is a critical research topic.

4D aviation icing product, NCAR
Wind Energy Prediction – Data Flow

Predict wind speed at turbine height

Predict wind energy of each turbine using manufacturer or empirical power curve algorithms

Predict electrical connection node power by adding up generation capacity of each turbine using power curve data
Each technology has its own ‘sweet spot’ with respect to prediction skill.
Research in Complex Flows

Grid Cell Size [m]
Domain Size [m]

$10^4$  $10^7$  $10^3$  $10^6$

Adopted from Mike Robinson (DOE/NREL)
Research in Complex Flows

Grid Cell Size [m]  \[10^4\]  \[10^3\]  \[10^1\]  \[10^4\]
Domain Size [m]  \[10^7\]  \[10^6\]

Adopted from Mike Robinson (DOE/NREL)
Research in Complex Flows

Grid Cell Size [m]
- $10^4$
- $10^7$

Domain Size [m]
- $10^0$
- $10^3$

- Global
- Regional
- Local
- Turbine
- Blade

Adopted from Mike Robinson (DOE/NREL)
Fully-Coupled CFD/CSD for Turbine/Platform Interaction with the Atmosphere and Ocean

Objective: To create a state-of-the-art High-Performance Computing “Cyber Wind Facility” for the renewable energy industry and researchers.

Mesoscale Weather Data

Cyber Wind Facility
- highly resolved 4-D cyber data
- coupled atmospheric turbulence - blade loadings - shaft torque data
- coupled wave structure - platform motion - turbine loadings data
- experiment design, test-bed, turbine design, controls concepts
- advanced correlations for BEM and other advanced design tools

Mesoscale Weather Data

*Courtesy Jim Brasseur, Penn State
Atmospheric Science Research to Support Wind and Solar Energy

- Multi-year field experiments (on and off-shore)
- Boundary layer meteorology (complex flow)
- Cloud physics & precipitation processes (icing, snow, etc.)
- Turbulence characteristics and prediction
- Computational science (improve efficiency)
- Land surface condition prediction
- Ocean dynamics (waves, currents)
- Aerodynamic studies related to turbine design
- Multi-scale modeling (global to millimeter scales)
- Future climate modeling (effects on wind/solar resources)
Thank You

mahoney@ucar.edu
Wind Energy Prediction – User Interface
Xcel Energy Wind Energy Prediction System
Hardware – Deterministic Modeling System

- Four Dell 2950 servers: 2 CPUs (8 cores) at 2.66GHz, 8-16GB RAM, 2-4TB RAID5

- Sixty-one Dell 1950 servers: 2 CPUs (8 cores) at 2.66GHz, 4or8GB RAM, 250GB, Myrinet card

- One 64 port gigabit switch for network access to storage and user access to cluster

- One 64 port Myrinet switch for high speed MPI

- Network attached, 8-10TB of storage for model processing and output.

- Installed within 2 or 3 new Dell full height (42U) racks, with peripherals such as:
  - 8 port KVM switch, Dell 15” LCD console panel, power distribution units, UPS 3000, all associated cabling.
Xcel Energy Wind Energy Prediction System

Hardware – Ensemble Modeling System

Three Dell 2950 servers: 2 CPUs (8 cores) at 2.66GHz, 16GB RAM, 2-4TB RAID5

- Forty-two Dell 1950 servers: 2 CPUs (8 cores) at 2.66GHz, 4or8GB RAM, 250GB

- One 64 port gigabit switch for network access to storage and user access to cluster

- Network attached, 12-16TB of storage, with potential ability to scale to 40TB

- Installed within 2 new Dell full height (42U) racks, with peripherals such as:
  - 8 port KVM switch, Dell 15” LCD console panel, power distribution units, UPS 3000, all associated cabling.