How much of U.S. power did wind provide in 2009?

A. 0.9 %
B. 1.8 %
C. 2.7%
D. 3.6 %
Why are meteorological observations taken at wind farms?

A. **Resource assessment** to quantify project viability

B. **Power performance** verification of turbines

C. Atmospheric science **research**

D. Assimilation into numerical models for wind and power **forecasting**

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**Today’s discussion**

- Current observational standards
- Research suggesting an expansion of those standards
To finance a wind farm, bankers require adherence to accepted standards codified in guidelines

- International Energy Agency (IEA)
- International Electrotechnical Commission (IEC)

These standards specify:

- How met towers may be installed
- Which type of terrain over which they are considered representative
- What measurements should be taken with which instruments: cup anemometers shall be used to measured wind speed and atmospheric turbulence (turbulence intensity)
  - Later investigations specify what kind of cup anemometers may be used, due to issues of angular response, dynamic effects and bearing friction characteristics
- Little comment on measurements other than wind
Subsequent Risø report delineates “classes” of cup anemometers based on wind tunnel tests of cup anemometers

Deviations arise from:
• turbulence intensity,
• turbulence structure,
• air temperature,
• air density, and
• flow inclination angle

Figure 3-7  A typical setup of the anemometer and the four propeller anemometers in the LT5 wind tunnel. The wind is blowing from right to left. The upper propellers are labelled p2 and p3 from left to right and the lower propellers are labelled p4 and p5 from left to right.

Subsequent Riso report delineates “classes” of cup anemometers based on wind tunnel tests of anemometers

Figure 2-2. IEC61490-12-1 classification class index examples
Assuming $U=(u,v,w)$, should the cup measure:

A. The horizontal wind speed vector

$$U_{\text{hor}} = \frac{1}{T} \int_t \sqrt{u^2 + v^2} \, dt$$

B. The total wind speed vector

$$U_{\text{vec}} = \frac{1}{T} \int_t \sqrt{u^2 + v^2 + w^2} \, dt$$

What about the atmosphere and the terrain surrounding the cup?

- Class A: “ideal” terrain: flat, little atmospheric turbulence or density variations; flow inclination angle +/- 3 degrees
- Class B: “complex” terrain; flow inclination angle +/- 15 degrees
What do you think is missing from the standard?

- Brainstorming time!

Modern wind turbines span heights ~ 200m, penetrating a complex atmosphere
The diurnal cycle of atmospheric stability strongly influences winds in the turbine rotor disk

Radiosonde profiles demonstrate that the cooling of the surface overnight is accompanied by dramatic accelerations in the winds.

How do meteorologists quantify atmospheric stability?

- Compare buoyancy forces to shear/mechanical forces
- Richardson Number:
  \[ Ri_{bulk} = \frac{g\Delta \theta_v \Delta z}{\theta_v \left( \Delta U^2 + \Delta V^2 \right)} \]
- Monin-Obukhov Length
  \[ L = \frac{-\theta_v u^3}{kg \left( w' \theta_v' \right)} \]
Today’s discussion

- Current observational standards
- Research suggesting an expansion of those standards

Thinking outside of the cup: turbine response modeling studies indicate the entire rotor disk is critical

- Antoniou et al., EWEC 2007: “Influence of wind characteristics on turbine performance”
Thinking outside of the cup:
Accurate resource assessment (and power performance evaluation) should probably include more atmospheric consideration

- Lundquist and Wharton, 2009, IEA Experts Meeting on SODAR and LIDAR;
- Wharton, Lundquist, Sharp, Crescenti, and Zulauf, 2009, AGU Fall Meeting;
- Wharton and Lundquist, 2010, in preparation for Wind Energy

Widespread impression of wind farm underperformance

- “20% by 2030” depends on sufficient capacity factor, not just installations
- Impression that many US parks underperforming can undermine public perception, financing, etc.
- With support from IRI, we investigate the role of atmospheric variability in one wind farm’s performance
This wind farm provides a unique and valuable dataset

**Characteristics:**

- Presence of both marine and terrestrial BL over hilly terrain
- Little directional wind shear
- Strongly channeled flow

**Large dataset:**

- On-site met towers + SODAR
- Turbine power and nacelle wind speeds available
- Four seasons of data; strong seasonality and diurnal signal

The data surpass those typically available at wind farms

**Meteorological data:**

- 2 met towers w/ cup anemometers \((u, v)\) at 5 heights (30, 40, 50, 60, 80 m), 10 min. avgs; \((T, p)\) measurements unusable
- SODAR observations \((u, v, w)\) for 19 heights (20 m to 200 m, 10 m resolution), 10 min. avgs.
- Nearby research station with a sonic anemometer \((u, v, w, \bar{w'\bar{u'}})\), 30 min. avgs.

**Turbine data:**

- Leading edge turbines: nacelle U and power 10 min. avgs, 80m hubs
Wind speeds vary with seasons; summer winds exhibit strong wind shear

Wind speeds exhibit a strong daily cycle in spring and summer
Seasonal variability in winds is reflected in turbine capacity factor: most power generated on summer/spring nights.

How to estimate stability? An off-site research measurement is compared with 3 on-site estimates.

(1) Wind shear exponent, \( \alpha \)

\[ U(z) = U_R \left( \frac{z}{z_R} \right)^\alpha \]

\( U \): mean horz. wind speed at height \( z \) or \( z_R \)

(2) Turbulence intensity, \( I_U \)

\[ I_U = \frac{\sigma_U}{\bar{U}(z)} \]

\( \sigma_U \): standard dev. of mean horz. wind speed (\( \bar{U} \)) at 80 m

(3) Turbulence kinetic energy, \( TKE \)

\[ TKE = 0.5 \overline{(u'^2 + v'^2 + w'^2)} \]

\( u'^2 \): variance of wind speed

Obukhov length, \( L \) (off-site)

\[ L = \frac{\theta' v \cdot u'^3}{k \cdot g \cdot \bar{w} \theta'} \]

\( \theta' \): virtual potential temperature

\( k \): von Karman constant

\( g \): gravity

\( \bar{w} \theta' \): sensible heat flux

\( u' \): friction velocity = \( \left( \overline{u'^2 + v'^2 + w'^2} \right)^{1/4} \)
Which quantity exhibited poor agreement with the surface flux \((z/L)\) stability estimate?

A. Cup anemometer \(I_u\)
B. Sodar \(I_u\)
C. Sodar \(\alpha\)
D. Sodar \(TKE\)

Which quantity is routinely available at most wind farms?

A. Cup anemometer \(I_u\)
B. Sodar \(I_u\)
C. Sodar \(\alpha\)
D. Sodar \(TKE\)
Estimates of stability from a typical cup anemometer fail to agree with more sophisticated measures

The cup anemometer tends to underestimate highly turbulent convective conditions.

Percentage of summer-time stable, neutral and convective conditions

Stability classes segregate the rotor wind profile

- **Stable conditions**: high wind shear, low turbulence, and possible nocturnal low-level jets
- **Neutral conditions**: minimal wind shear
- **Convective conditions**: have lowest wind speeds, very little wind shear in swept-area, and are highly turbulent.
Hub-height wind speed often fails to represent momentum experienced by the entire rotor disk.

- **Stable** $U_{\text{equivTI}} > U_{80m}$
- **Neutral** $U_{\text{equivTI}} = U_{80m}$
- **Convective** $U_{\text{equivTI}} < U_{80m}$

Hub-height winds are often maximum winds across the rotor disk.

We calculate an “equivalent” wind speed to integrate across rotor disk, because hub-height often fails to indicate the true rotor wind speed.

**Equivalent wind speed, $U_{\text{equivTI}}$**

$$U_{\text{equivTI}} = \frac{2}{A} \int_{H-r}^{H} U_{\text{eff}}(z) \left( r^2 - H^2 + 2Hz - z^2 \right)^{1/2} dz$$

- $A$ : rotor area, $U_{\text{eff}}(z)$ : mean wind speed at height $z$, $r$ : radius of rotor area, $H$ : hub-height

$U_{\text{eff}}(z)$ calculated for each height within the rotor disk:

$$U_{\text{eff}}(z) = \frac{3}{2} \sqrt[3]{U(z)^3 (1 + 3I_{U}^2)}$$

accounting for the additional energy (turbulence) in the instantaneous wind speed (following Wagner et al. 2009)
A typical summer power curve based on equivalent wind speed still exhibits significant variability

Capacity factor, $CF$ (%)

$$CF = \frac{P_{\text{actual}}}{P_{\text{rated}}} \times 100$$

$P_{\text{actual}}$: actual power yield of the individual turbine

$P_{\text{rated}}$: maximum power yield of the turbine as determined by the manufacturer

At 8 m s$^{-1}$ the CF ranges from 35% to 70%!

Stratification of power curves reveal stability-related influences on power output
Even stronger variation seen in another leading-edge turbine

In fact, all leading edge turbines show that power generated is dependent on stability
In summary:

- Atmospheric stability, through the mechanisms of turbulence and wind shear, governs the generation of power at these tall turbines.

- Power varied by over 20% due to atmospheric stability.

- “Deficits” in production are actually inaccurate assessments of the available wind speed due to failure to account for variable of wind across rotor disk due to atmospheric stability variations.

Wind farm “underperformance” can in part be explained due to incomplete resource assessment

- Resource assessment instrumentation should be upgraded:
  - SODAR stability parameters segregate wind farm data into stable, neutral and convective periods in agreement with research-grade observations
  - Cup anemometer data inaccurately estimate stability regimes
  - SODAR performs poorly during precipitation, however – role for LIDAR?

- Because of complex wind profile shapes, power curves should be a function of wind speed and turbulence over entire rotor disk ($U_{equivTI}$) (as in Wagner et al., 2009)

- Power output correlates well with atmospheric stability:
  - Enhanced turbine performance during stable conditions
  - Reduced turbine performance during convective conditions
Ongoing research activities towards expanding observations at/near wind farms

- IEA Remote Sensing Experts meeting in Oct 2009 at NREL
- SODAR recommended practices document in preparation (contact Kathleen Moore at iedat.com)
- LIDAR recommended practices document in preparation (contact Dan Jaynes of Garrad Hassan America)
- DOE/NOAA collaboration on “Short-term Forecasting” (DE-FOA-0000343) to demonstrate value of additional atmospheric observations toward improving wind plant power forecast accuracy; observations to begin in early 2011
- Others that you know of?

Questions?

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