Operational Numerical Weather Prediction (NWP) of Hub-height Winds for Mountainous British Columbia

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Topics:

1. Terrain Issues
2. Power curves, heterogeneity, convolution, farm-average power
3. Need for extensive upwind modeling
4. Sensitivities, partially addressed via ensemble NWP
5. Operational hub-height forecasts made by UBC
6. Current research and a renewable-energy meteorology course
Background: Wind farms in BC

WFRT member Bryan Jansens provides hub-height wind forecasts for all wind farms in BC except Grouse Mtn.

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Brand/Model</th>
<th>Year Built</th>
<th>Hub Height (m agl)</th>
<th>Rotor Diam. (m)</th>
<th># of turb.</th>
<th>Power (MW)</th>
<th>Map Location</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Terrain elevation (m)</th>
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</table>

Figure 4. Map of wind-farm regions in British Columbia.
Source: Google Map, annotated by R. Stull.
Utility of Accurate Hub-height Wind Forecasts

• utility companies (e.g., BC Hydro) can better manage the mix of non-dispatchable wind power with dispatchable hydro power to provide reliable service to their customers

• energy traders (e.g., PowerEx) can optimize the buying and selling of power cross-border to reduce overall electric cost to customers

• independent power producers (e.g., wind-farm operators) can better anticipate and mitigate extreme events, and can plan for routine maintenance when conditions will be favorable

https://www.windpowerengineering.com/awea-new-type-wind-power-customer-factor-transmission-planning/
1. Canadian Terrain Cross Section

- West-East terrain cross section through Whistler (50.12°N)
Turbines at a Wind Farm have a Variety of Locations relative to Terrain

What is the relationship between power curves for individual turbines and the whole wind farm?
2. Power curves, heterogeneity, farm-average output

a. Idealized Power Curves

- Let:
  - $M_{in}$ = cut-in speed
  - $M_R$ = rated-power wind speed
  - $M_{out}$ = cut-out speed

- Power ($P$) is:
  - for $M_{in} \leq M \leq M_R$:
    \[ P = P_R \left( \frac{M - M_{in}}{M_R - M_{in}} \right)^b \]
  - for $M_R \leq M \leq M_{out}$:
    \[ P = P_R \]
  - $P = 0$ elsewhere

![Diagram of idealized power curve](image)

**Fig. 1.1.** Idealized curve of output power $P$ vs. wind speed $M$ for a single hypothetical wind turbine with maximum rated power of 1 MW.
b. Variability

- Let $M_s$ be a specified wind, forecasted to be representative of whole farm.
- Let $M$ be the actual wind speed at any one turbine.

$M$ can vary from $M_s$ because of:
- turbines at different locations in wind farm
  - topographic effects
  - synoptic & mesoscale variability
  - interference from upstream turbines
- turbines with different models or efficiencies
- different turbulence gusts at different turbines

$M_s$ can vary because NWP forecasts have spread

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*Fig. 1.2. Example of Gaussian variability (illustrated with $\sigma = 2 \text{ m/s}$) of wind speed $M$ about the specified wind-farm average $M_s$.***
b. Variability

Sort the winds anomalies into discrete bins.
Assume the wind variability is Gaussian:

Let the discrete farm-average speed be $M_i$, on which the Gaussian curve is centered.

Let $j$ be a bin-offset index (relative to $i$) for the actual winds $M_j$, for $-J \leq j \leq J$.
$J$ is finite but large, such as $J = 30$ bins.

Let $\tilde{G}_{i,j}$ be the un-normalized Gaussian shape.

Let $G_{i,j}$ be the normalized Gaussian shape.

$$G_{i,j} = \frac{\tilde{G}_{i,j}}{\sum_{j=-J}^{J} \tilde{G}_{i,j}}$$
For any one turbine, its wind speed determines its power output (using the idealized power curve).

But different turbines with different speeds are at different locations on the power curve.

Thus, the farm-average power is the sum of all points on the power curve, weighted by the number of turbines producing that power.

Mathematically, this weighted average is a convolution.
d. Application

**We know:**
- The theoretical (design) power curve for individual turbines

**We don’t know:**
- Any inefficiencies that have developed in the turbines
- Which turbines are down for maintenance
- What is the measured wind speed at each turbine
- How the empirical power curve varies with season, synoptic regime, location in the farm, etc.
- Whether the distribution is Gaussian
- How sigma varies with wind speed

**We DO know:**
- The empirical wind-farm total power curve for past times, for each wind farm.
Approach:
- Use power curve from past, with NWP forecast winds, to make power forecasts.
- Find a model to empirically fit the past power curve.

Advantages of the Convolution Model (over curve fitting):
- Based on (simplified) physical attributes
- Best-fit parameters fit the physically anticipated signal and not the noise.
- Physical changes (adding/removing turbines) can be incorporated by modifying the single-turbine curve.

Dis-Advantages of the Convolution Model:
- Curve fitting (polynomial or spline) is easier, and works just as well.
e. The empirical power curves for 4 wind farms in BC, all normalized to 100 MW.

None of the curves exhibit a cubic power-law! Instead, powers are: $b = 1.0, 1.6, 1.6, 1.8$
3. Need for forecast domain to extend upwind

Not appropriate to use Local Models of Terrain near the Wind Farm, because Upwind Terrain has a Significant Influence

Namely, the flow at A affects the hub-height winds at B.
Nonlocal Flow Effects

Numerical Simulations of Idealized Terrain

for a wind-ramp event at a wind farm:

- Rocky Mountains (add / remove)
- Coast Range (add / remove)

Enables discovery of alternative / better forecast methods

Simulations by Jesse Mason

photo credit: Jesse Mason
Nonlocal Flow Effects

Simulations by Jesse Mason

Enables discovery of alternative / better forecast methods

Idealized Rockies Only

Both Coast & Rocky Mtns.

Inference: need sufficiently large NWP forecast domain to capture upwind effects.
4. Numerical Weather Prediction

- NWP is a physics-based approach. The atmosphere is divided into a 3-D grid of cells, and the approximate equations of dynamics and thermodynamics are solved at each grid cell. The cells interact with neighboring cells as the solution takes many small time steps to reach the desired forecast horizon.
- The winds are just one portion of the total weather that is forecast.
- Output of the NWP is not perfect, and can be improved with statistical / AI approaches, in a step called “post-processing”.
4. Sensitivities and how to mitigate them with ensemble NWP forecasts

1) Local flows that affect any individual wind turbine are sensitive to the wind direction relative to the terrain.

2) Wind directions from Numerical Weather Prediction (NWP) are sensitively dependent on initial conditions (which for BC, is the poorly observed air over the Pacific Ocean).

One way to compensate is to make an ensemble of many NWP forecasts for each wind farm for each hour, each with slight different wind forecasts.
The Weather Forecast Research Team at UBC runs an ensemble of 51 NWP forecasts every day initialized from 00 UTC. These are:

- multi model (WRF-ARW, WRF-NMM, MM5, MPAS)
- multi Initial Condition (from gov’t centers in Canada, USA, France, Germany)
- multi-physics parameterizations
- multi-grid spacings

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<th>Model:</th>
<th>MM5</th>
<th>MM5</th>
<th>WRF (ARW)</th>
<th>WRF (ARW)</th>
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</table>
Example spaghetti diagram of ensemble of wind forecasts

Raw forecasts for a wind farm.
Bias-corrected forecasts for a wind farm.
Create a best-guess:
Deterministic forecast (= ensemble average), &
Probabilistic forecast (based on spread)
Calibrate the Probabilistic Forecast based on past Observations from the wind farm, to improve statistical reliability.
Verify over Seasons

Absolute error from each model is accumulated over every hour for 3 months.

Smaller error is better.
6. Current Research

- more ensemble members (Tim Chui, Henryk Modzelewski, & Roland Schigas)
- weighted ensembles (Reagan McKinney)
- longer-range (out to 2 weeks) forecasts (Jill Psotka)
- post-processing with machine learning (Bryan Jansens)
- improved forecasts with AI (Nina Effenberger)

Course: ATSC 313: Renewable Energy Meteorology (3 cr. online)

www.eoas.ubc.ca/courses/atsc313/

Taught by Doug McCollor

Welcome to this online course.

Syllabus:

**For New & Prospective Students:**
- **Welcome** - Glad you are interested. (dm)
- **Course Info** - Whom this course is for. (dm)
- **Syllabus Overview** - Main topics in this course. (dm)
- **Course Goals** - What you will be able to do. (dm)
- **Sample** (pdf) - Showing all 9 steps within a learning module.
Conclusions

- Complex terrain compounds NWP forecast errors
- Wind distribution among multiple turbines can be accounted for via convolution
- Need for NWP models to extend extensively upwind
- Sensitivities can be partially addressed via ensemble NWP in operational forecasts
- Research plans and a renewable-energy meteorology course

Thanks to our sponsors:
BC Hydro, MITACS, NSERC, and several wind farms in BC

Any Questions?