MARK AHLSTROM, CEO, WINDLOGICS INC.

WIND & SOLAR ENERGY
FORECASTING & INTEGRATING VARIABLE GENERATION

TWIN CITIES METRO
NOVEMBER 22, 2013
WindLogics Background

Founded in 1989
Assessment, forecasting & integration of renewable energy
- 65 people
- 50% Meteorology
- 25% Math, Statistics, CompSci
Became a NextEra Energy company in 2006

*Forecasting & optimization solutions that enable low cost, reliable & sustainable power systems*
Example - Patterns over the Day
Atmospheric Complexity

- Solar Radiation
- Moisture Fluxes
- Turbulence
- Evaporation
- Convection
- Condensation
- Surface Heat
- Surface Heat
Start with Current Conditions
Meteorological Models - Physics Simulation
Models - Various Uses & Sources

Operational Models
  – Days ahead
  – Next few hours

Custom “Meso” Models
  – High resolution
  – For areas of interest

Long-term Datasets
  – Reanalysis products
  – Satellite solar products

National models
  – NOAA/NCEP in the US
  – ECWMF consortium in Europe
  – Many national models from Canada and Europe (some global models)

Private sector models
  – Private companies, or contracted from government labs
Instruments for Wind Project Sites

Meteorological towers

Remote sensing devices
  – Sodar (sound-based)
  – Lidar (laser-based)
Instruments for Solar Project Sites

- **Photodiode-based instruments**
- **Shadow-band Radiometer (right)**
  - Measures both global horizontal irradiance (for photovoltaic panels) and direct normal irradiance (for concentrating solar)
- **Pyrheliometer (below)**
  - More accurately measures direct normal irradiance (for concentrating solar technologies)

Directly measures global horizontal irradiance (GHI) and diffuse horizontal (DHI) and derives direct normal (DNI) via the following relationship:

\[ \text{GHI} = \text{DHI} + \text{DNI} \times \cos(\Phi) \]

\( \Phi = \) solar zenith angle

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Climate
Weather versus Climate

*Climate is what you expect*
- Long-term normals
- Smoothed, averaged value of what is normal for a location at this time of year

*Weather is what you get*
- The normal variability of weather is high, and the “noise” can overwhelm the climate signals in the short term
Storms follow the jet streams, so they are also called storm tracks.

During El Niño, warmer sea surface temperatures over the tropical Pacific Ocean prompt the development of circulations that affect the position of the jet streams.

One example shown here: El Niño’s impact on the southern branch storm track.
Storm Tracks Typically Cross the U.S.

Southern storm track is most favorable for Texas and Midwest wind resource
During El Niño, a “Split Flow” Pattern Predominates

Storm track configuration is generally applicable for late fall, winter and early spring

reduced wind resource as weather systems steered around this area by split flow

Northern Jet Stream

Southern Jet Stream
Both Wind and Solar Have Long-Term Variability

(Annual Energy - 1972-2002)
The P50 (long-term average) and the P99 (one year in 100)
Variable Generation - Wind and Solar
The Challenge of Variable Generation

All power plants and fuel supplies have operational characteristics and integration issues

Variability and uncertainty are intrinsic to weather, and therefore to wind and solar energy

- Understand weather-driven variability and risk
- Understand impacts on the power system and power markets
- Engineer systems to operate and optimize the new system
The Physics of the Power Curve Drives Technology Development

“Motherhood and Apple-Pie” Truths about Wind Technology

- Power in the wind is proportional to wind speed cubed
- At best, we can capture 59% (the Betz limit)
- “Rated Power” governs size and cost of the turbine infrastructure
- Energy is power multiplied by the amount of time spent at that power level
- Capacity Factor is average output divided by the Rated Power
- Wind shear puts higher winds at greater elevation
Location & terrain make big difference

Power in the wind is proportional to the cube of wind speed, so must optimize location, layout & height

A constantly changing fuel supply
- Horizontal variation (patterns of wind flow)
- Shear (wind speed increases with height)
- Diurnal & seasonal fluctuations
- Long-term inter-annual variability

Planning, financing & operating issues
- Large capital investment with a long timeline
- Variability on all spatial & temporal scales
- Implications for utility operations
Traditional Method: Measure-Correlate-Predict (MCP)

**Measure** on-site data
- Usually done with a 60 meter meteorological tower (met tower)
- Typically requires at least a year of data

**Correlate** to another longer-term measurement
- Extend on-site data by correlating to another source
- An airport or other weather station is usually used

**Predict** long-term project energy output
- Predict long-term values from relatively short-term measurements
- Predict hub height wind speeds from lower measurements
Can’t afford a full gridded array of met towers – one or two will have to suffice.

Anemometers are never perfect...

Data Gaps, Icing, Calibration, Spares...

Measuring above 60 meters is too expensive.

Can’t wait forever – one or two years measurement will have to suffice.

Diurnal patterns don’t match hub height.

Airport Anemometers are too low, blocked by trees and vegetation...

Airport Anemometers are too far away...

7 or 8 years is NOT long-term data...

Challenges of distance, height, time & space
Integrated Wind Understanding

Take advantage of all the available data

1. Collect and manage high-quality met tower data and other on-site measurements (Sodar, Lidar...)
2. Use the best available gridded archives of weather data from government agencies
   - Actual recorded weather data from many sources
   - Typically used to initialize weather forecast models
3. Add the best available high-resolution topography and land cover information
4. Apply numerical weather models and local wind field models - integrating data over space and time
5. Analyze long-term variation and the financial impact on your specific situation
6. Use wind forecasting and operational assessment to minimize cost and operating impacts while maximizing revenues

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Optimize for Turbine, Blade Size, Height, Spacing, etc.

50m Height
Production estimate in GWh per year at multiple heights

80m Height
Gross Capacity Factor (GCF) & Net Capacity Factor (NCF)

Gross Capacity Factor (GCF) is based on wind resource and a “theoretical” turbine

Losses reflect deductions in energy production in a real world wind power plant
- Wake and array losses: 3-7% typical, depends on density and size
- Turbine availability: 3% typical, negotiable in turbine agreement
- Turbine power curve: 2% typical, negotiable in turbine agreement
- Electrical losses: 2-3% typical, based on design & current levels
- Icing, bugs, dirt, etc.: 1-2% typical, site & turbine dependent

Net Capacity Factor (NCF) is the estimate of actual energy production that should be available at the meter
Site Assessment Results (Prior to Construction)

Understanding the resource, variability & risk

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Wind Forecasting
Multiple Weather Models are Available
Power Forecast - Type 1

**Offline**: Statistically correlate observed & forecast wind

- Archive of Forecast Data
- Months of Wind Data from Site
- Wind / Forecast Model Relationship

\[ u = f(x, y) \]

**Real-time**: Create the Power Forecast

- Current Weather Forecast
- Apply Forecast/Wind Relationship
- Forecast Wind Speed
- Turbine Power Curve
- Power Forecast

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Power Forecast - Type 2

Offline: Train the Power Forecast

- Archives of Forecast Data
- Months of Power Data from Site

\[ u = f(v, x, y, z) \]

Real-time: Create the Power Forecast

- Current Weather Forecasts
- Apply Forecast/Power Relationship

\[ u = f(v, x, y, z) \]

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Forecast versus Reality?

A given forecast model provides a “reality” based on its input data and physics formulations

– Useful if you can learn the trends and biases of the model
– Useful for filling gaps in space and time, as for creating a time-synchronized historical dataset

Can we learn trends & biases?

What if we have multiple models, with different physics or inputs, that disagree on the forecast?
Ensembles of Multiple Forecasts

Forecast 1  Forecast 2  Forecast 3  Forecast ‘N’

Minimize error  Preserve distribution

Observations  Forecast

Machine Learning Methods
Confidence, Predictive Intervals and Certainty
Modern Wind Power Forecasting Technology

Advanced physical and “learning system” methods

**Multiple forecast models**
Ensemble methods for both accuracy and uncertainty

**Computational Learning System**
Adaptive adjustment based on actual wind plant performance

**Smart persistence**
Takes advantage of current conditions approaching real time

These systems remove forecast model bias, identify the variables and models that work best under certain conditions, and get better over time.
Typical Wind Power Forecasting Results

Results for a single typical wind plant
- Day-ahead hourly power: *12-20% MAE of rated capacity*
- Next day total energy: *~ 20% of energy delivered for the day*

Results for a region or system have lower error
- Often 30-50% better depending on geographic dispersion
- “Portfolio effects” become important & help operations
- MISO reports day-ahead wind forecast error of 6%

Additional features are in R&D
- Ramp forecasting, situational awareness, etc.
- Improving over persistence for very short term (5-15 minutes)
- Tighter integration into tools and operations
Energy Markets and Dispatching Wind
Independent Systems Operators (ISOs) run energy markets

Both regulated utilities and other “independent power producer” companies can generate, sell and trade energy

Day-ahead market with hourly schedules

Real-time market with five minute schedules

Ancillary products
Variable Generation and Energy Markets

Large regional energy markets make it easier to integrate higher amounts of variable generation

Energy markets
  – Day-ahead energy market with hourly schedules
  – Fast real-time energy market
Larger balancing area
Deep dispatch stack
Economic ancillary services
Midcontinent ISO (MISO) Market

MISO runs a fairly standard “Day Two” market system:

– Submit day-ahead offer

– Some ability to adjust day-ahead offers until 4 hours ahead

– Submit real time offer
  – Submitted 30 minutes in advance of each operating hour

– Follow five-minute dispatch signal from MISO (+/- 8% band)

Dispatch & curtailment are based on offer prices (offers “set price”) and reliability needs (security constrained economic dispatch)
MISO Dispatchable Intermittent Resource Tariff

MISO runs a fairly standard “Day Two” market system:

– Submit day-ahead offer

– Some ability to adjust day-ahead offers until 4 hours ahead

– Submit real time offer
  – Wind provides a rolling five-minute forecast for the next hour
  – The 10-minute-ahead forecast value is used for each 5-minute dispatch

– Follow five-minute dispatch signal from MISO (+/- 8% band)

Dispatch & curtailment are based on offer prices (offers “set price”) and reliability needs (security constrained economic dispatch)
The Short Term Wind Forecast Error Curve

AESO Shortterm Forecast Mean Absolute Error August 2012

Forecast
Persistence

Forecast Horizon [hours]

From: Jacques Duchesne, AESO
The Short Term Wind Forecast Error Curve

System-wide Error (% MAE)
Dispatching Wind Changes the Perception of the Problem

“Variability” is the change or error within the dispatch period
   Uses some regulation, but not much given geographic aggregation

“Uncertainty” is mostly the error from the day-ahead forecast
   Largely handled through the real time dispatch stack
   Uses some non-spin reserve for extreme situations

Is there a ramping or flexibility problem?
   With a deep and robust real time dispatch... not really
   Wind ramping up - you have dispatch control of wind if needed
   Wind ramping down - units backed down and have room to move up

Without a deep and robust real time dispatch stack, integrating wind is more challenging... but the most effective action is to get one!
Wind as a Full Market Participant

Wind in dispatch  *(real time operations)*
  Must be based on a 0-10 minute-ahead forecast!
  A robust real time market encourages wind to offer day ahead!

Wind in day-ahead market  *(day-ahead unit commitment)*
  Ongoing importance of better day-ahead forecasts
  Value to both system operator and market participants

Wind forecast changes within the day
  Ramping and reducing day-ahead forecast error
  Value to system operators for rolling commitment decisions
Solar Energy
Direct Normal Irradiance (DNI) and Global Horizontal Irradiance (GHI)

- Direct Normal Irradiance (DNI)
  - Accepts only direct irradiance
  - Solar Thermal

- Global Horizontal Irradiance (GHI)
  - Accepts all solar irradiance
  - Photovoltaic
Clouds are the Largest Driver of Solar Variability

Cloud shadows on the DeSoto field during construction
Solar variability is influenced by cloud type, size and speed.
Visual Solar Energy Forecasting
(for next few minutes)

Yankee Environmental Systems
Total Sky Imager (TSI-880)

http://www.nrel.gov/midc/srrl_bms
Satellite-based Solar Energy Forecasting
(for next few hours)

Clouds moving from the west (~ 45 m/s)

Forecast would have been for a significant ramp to hit DeSoto at ~ 1440 LST (not bad!)

Short term solar power forecasts can use geostationary satellite data, but this is not a total forecasting solution
Weather Model-based Forecasting (hours and days ahead)

Depending on the time horizon of interest, merging of forecasts from models, satellites and ground-based imagers may be required.

The NOAA HRRR is a 3-km resolution, hourly updated, cloud-resolving atmospheric model.

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Solar Power Variability & Forecasting

Clouds are largest influence on variability and forecasting
- Can see coherent patterns of motion for "stable" clouds
- Convective events ("unstable" clouds) are more challenging to predict, although as with wind, we can predict the risk
- Newer, higher resolution weather models show promise

Satellite-based cloud resources are available to guide short term solar forecasts (an advantage over wind forecasting)

Aerosols and haze also impact energy production, particularly for concentrating solar technologies
Distributed Solar
Centralized versus Distributed?
Centralized versus Distributed?

Centralized offers...

Visibility
Control
Economies of scale

In other words, it looks more like a conventional power plant
Centralized versus Distributed?

Distributed offers...

- Non-utility ownership
- More widely distribute
- Ability to offset power at retail rates or “value-of-solar” rates

But the distribution system (local lines and transformers) were generally not designed to have power flow back upstream, so local reliability impacts must be considered.
Distributed Solar and “Value of Solar” Tariffs
Net Energy Metering - Concept and Utility Concerns

Net metering has been in state policy since 1983 and is now used in 40 states, but has characteristics that are becoming a concern to utilities.

Concept: Energy generated at the point of consumption is worth more than energy at a remote power plant.

- Popular with regulators and public to support distributed solar
- Netting at the retail meter and retail rate is easy to do

Some concerns with net metering:

- Electric service is more than just energy… the cost of reliability
- No provision for ensuring that the utility recovers the full cost of serving the solar customer
- Complications with tiered rate structures
- Tends to encourage on-peak consumption to coincide with solar energy
Value of Solar Approach

1. Separately meter consumption & production
2. Calculate savings from PV production
3. Bill consumption using existing tariffs
4. Credit production using Value of Solar
Austin Energy - Value of Solar Based on Nodal Price Analysis

![Bar chart showing PV system value broken down by different factors.](image-url)
Minnesota’s 2013 Solar Energy Legislation

**Solar Energy Standard (for investor-owned utilities)**
- 1.5% of retail electricity sales from solar by 2020 (~450 MW)
- 10% of this must be from projects under 20 kW
- Goal of 10% of electricity sales from solar energy

**Solar Incentives and Solar Gardens**
- Xcel production-based incentive for projects under 20 kW
- “Made in Minnesota” incentive for projects up to 40 kW
- Subscriptions to community solar gardens up to 1 MW in size

**Net Metering Cap Raised from 40 kW to 1 MW**
- Net excess paid at retail rate for up to 40 kW
- Net excess for larger projects paid at avoided cost

**First State to Implement a Value of Solar Tariff**
- Will likely replace net metering for new projects under 1 MW
- Tariff rate likely to be higher than retail rate
A Model Program for Distributed Solar?

Minnesota could set a very important precedent for the nation

Latest developments from November 19 - Value of Solar Methodology

How to support distributed solar in a fair and sustainable way?

Provide long-term fixed-price contracts
Avoid cannibalizing energy charges and cost recovery of system investments
Pay based on a defensible “Value of Solar” for distributed generation
Discussion

Mark Ahlstrom
mark@WindLogics.com
651-556-4262