Model Output Statistics (MOS)

- Statistical adjustment to NWP model predictions
  - Account for processes below the resolution of the NWP model
  - Correct for systematic errors caused by the model physics or initialization
- Requires a training sample of concurrent NWP data and measured values of the forecast variable
- Many statistical approaches can be used
  - Statistical models: linear regression, artificial neural networks etc.
  - Training sample strategies: fixed, rolling, regime-based etc.
NWP Ensembles

- Issue: Uncertainty present in any forecast method due to
  - Input data
  - Model type
  - Model configuration

- General Approach: Vary the sources of uncertainty within their range of uncertainty and generate a set (ensemble) of forecasts

- Benefits
  - Ensemble composite typically performs better than any individual forecast over a large sample
  - Ensemble spread provides case-specific measure of forecast uncertainty

- Typical Approach 1: Perturb input data, to produce set of forecasts
- Typical Approach 2: Use multiple models or model configurations to produce set of forecasts
Persistence and Time Series Methods

- Persistence: Current conditions = forecast
- Usually adjusted for daily solar cycle
- Useful benchmark for other types of forecasts
- Time series methods (e.g. ARIMA) can extend persistence concept by using recent and/or conditional climatological trends

Persistence Irradiance Forecast adjusted for time of day sun angle for 8:00 versus 8:05 AM
Forecasting Techniques - Hours Ahead

Cloud Advection Model

- Obtain initial position of clouds from satellite data
- Obtain wind field from another source (e.g. wind observations from profilers or Doppler radars or NWP model)
- Advect clouds to future positions using wind field
Forecasting Techniques - Hours Ahead

Cloud Vector Motion from Satellite

satellite images → cloud-index images → forecast of cloud-index images → forecast of global irradiance

Forecast:
- motion vector fields
- smoothing

Perez - SUNY method to convert sat cloud to irradiance
Heliosat
Forecasting Techniques – Minutes Ahead

SkyCam-Based Methods

• Cloud motion extrapolation techniques can be applied on minutes ahead time scale using skycam data in place of satellite image data
  - Need source of skycam data
  - Tracks and extrapolates motion of cloud elements
  - Few applications thus far; great potential for 0-1 hour forecasts
Forecasting Techniques - Hours Ahead

Rapid Update NWP

- Run NWP frequently and at high resolution
  - < 5 km
  - 2 hr or less cycle
- Improve cloud initialization
  - Estimate Cloud top height from infrared satellite imagery.
  - Estimate Cloud coverage from visible satellite imagery.
  - Estimate cloud base height from surface observations.
  - Moisten or dry atmosphere based on knowledge of cloud layers.
  - Locate regions of deep moist air with radar and moisten appropriately
- Improve representation of clouds in the NWP models
Integrated Solar Forecast System

- Combination of several methods and a variety of input data types
- Ideally: the system seamlessly switches from one technique to another as the look-ahead time increases
- Plant output model must consider the type of solar facility
  - PV, CSP etc
  - Could be a statistical or physics-based model
Types of Forecasts: Deterministic vs. Probabilistic

- **Deterministic**
  - Typically optimized to minimize a performance metric (e.g. RMSE)
  - Deterministic forecasts are simpler to interpret and use

- **Probabilistic**
  - More information than deterministic forecasts
  - The information difference is inversely related to forecast skill
    - At high skill, the difference is small
    - At lower skill levels the information difference is large
  - Studies have demonstrated that a trained user makes better application decisions when using a probabilistic forecast

- **Hybrid**
  - Deterministic time series (but with what performance criterion?)
  - Probabilistic confidence intervals

- **All of these could be in a time-series or event mode**
Solar Forecast Performance: Next Day
Evaluation Metrics

• **Deterministic**
  - Most widely used: Bias, MAE & RMSE
  - Forecast to observed correlation
  - Error distributions
    - Percentage of time that magnitude of error < threshold
  - Skill Score
    - Percentage improvement of a metric relative to a reference forecast
    - Persistence and climatology are typical reference forecasts
  - Many other possibilities
  - Ideally, metric should measure a user’s sensitivity to forecast error

• **Probabilistic**
  – Three key attributes
    • Reliability (most commonly evaluated)
    • Sharpness
    • Resolution
  – Need a measure of all three factors
    • Brier score, Ranked Probability Score (RPSS), etc.
IEA Day-Ahead Forecast Performance Benchmark

• **Background:** Investigation performed in conjunction with the International Energy Agency (IEA) Task 36 NWP Project directed by Richard Perez of the State University of NY at Albany.
  – **Objective:** compare performance of solar irradiance forecasts from different NWP modeling systems
  – Several participants: ECMWF, Environment Canada, SARC, AWST, etc.

• **AWST’s Sub-project:** Examine performance of solar irradiance forecasts from several mesoscale models and MOS algorithms

• **Evaluation Period:** May 2009 to April 2010

• **Evaluation Approach:** Examine performance statistics (MAE etc.) and analyze specific cases to understand error patterns
IEA Evaluation Locations: SURFRAD Sites

- Fort Peck, MT
- Sioux Falls, SD
- Boulder, CO
- Bondville, IL
- Desert Rock, NV
- ARM SGP
- Goodwin Creek, MS
- Penn State, PA
Forecast Performance – Days Ahead

AWST’s IEA Project Day-Ahead Experiments

• Three NWP Model Forecasts
  – **MASS**: commercial model (MESO)
  – **WRF**: open source community model
  – **ARPS**: developed at University of Oklahoma
  – Nested grid with 5 km resolution inner grid
  – NOAA’s Global Forecast System (GFS) for initial and boundary conditions
  – Forecasts initialized at 0000 UTC each day

• MOS Adjustment for Each Model
  – Screening multiple linear regression
  – Rolling 60-day unstratified sample
  – Predictors are selected output variables interpolated to the forecast location
  – Applied separately to each model’s output

*Example Image: Downward Short Wave Flux at Ground Surface (W m^-2)*

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Day Ahead Forecast Example: Clear Day

RAW

MOS

April 29 2010 12:30 PM EDT (1630 UTC)
Day-Ahead Forecast Example: Cloudy Morning

RAW

MOS

April 30 2010 11:57 AM EDT (1557 UTC)
Day-Ahead Forecast Example: Partly Cloudy Afternoon

April 30 2010 4:59 PM EDT (2059 UTC)
12-Month Bias, MAE and RMSE for Desert Rock Day-ahead Forecasts

12-Month Bias of GHI Forecasts for Desert Rock

12-Month MAE of GHI Forecasts for Desert Rock

12-Month RMSE of GHI Forecasts for Desert Rock
12-Month Bias, MAE and RMSE for Penn State Day-ahead Forecasts

12-Month Bias of GHI Forecasts for Penn State

12-Month MAE of GHI Forecasts for Penn State

12-Month RMSE of GHI Forecasts for Penn State
12-Month Bias, MAE and RMSE for Goodwin Creek (Raw and MOS)

12-Month Bias of GHI Forecasts for Goodwin Creek

12-Month MAE of GHI Forecasts for Goodwin Creek

12-Month RMSE of GHI Forecasts for Goodwin Creek
## 12-Month Day-Ahead GHI Forecast Performance Statistics

### Performance Statistics

<table>
<thead>
<tr>
<th></th>
<th>RAW NWP</th>
<th>MOS-ADJUSTED NWP</th>
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<tbody>
<tr>
<td><strong>Bias</strong></td>
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<tr>
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</table>

**Best Performance**
Estimated Solar Power Forecast Performance

- Output model (from AWST data)
- Output model applied to measured and forecasted GHI values
- MAE for all hours of the day with non-zero measured average GHI (daylight)
Solar Forecast Performance: Hours Ahead
Short-term GHI Forecast Benchmark (U Albany)

- Period: August 23, 2008 to January 31, 2009 (drier season)
- Composite RMSE for 6 sites
  - Fort Peck, MT, Boulder, CO, Sioux Falls, SD, Bondville, IL, Goodwin Creek, MS, State College, PA
- 5 forecast methods
  - NDFD (NWP-based), persistence satellite, persistence measured, cloud vector motion, cloud vector motion smooth
Forecast Performance: Solar vs. Wind
Solar vs. Wind Forecasting

- **Location Attributes**
  - Utility-scale solar plants are sited in sunny areas
    - Less variable than an average site
  - Wind plants are sited in windy areas
    - More variable than an average site

- **Power System Attributes**
  - Solar generation has a quasi-linear relationship to irradiance
  - Wind generation is a function of wind speed cubed between start-up speed and rated capacity

- **Forecast Input Data**
  - Dominant factor is cloud coverage and density which can be spatially observed via satellite and sky-cams
  - Wind speeds patterns can’t be as easily observed
Solar vs. Wind Forecasting Performance: An Arbitrary Real Word Comparative Example

- Wind: ~ 80 MW facility in the ERCOT control area
- Solar: ~ 5 MW facility in central California
- Monthly MAE (% of capacity)
  - Wind: 11.8% (all hours)
  - Solar:
    - For a relatively cloudy time of year
      - 3.1% (all hours)
      - 6.9% (daylight hours)
      - 10.7% (10 AM – 3 PM)
Solar Forecast Performance: Impact of Aggregation

- Impact of aggregation on solar forecast performance has not been thoroughly analyzed
  - Penetration of solar power production is low in most areas
  - Limited data available
- Impact of aggregation is substantial for wind
- What will be the impact of aggregated wind and solar on forecasts of combined generation?

Impact of aggregation on day-ahead wind forecast MAE
The Road to Increased Forecast Value
Future Prospects:
How can forecast value be increased?

- Improve forecast performance
  - Days ahead
    - Gradual improvement in global/regional NWP model performance due to additional global data, data assimilation system improvements and refinements to NWP models
    - Further near-term improvement due to more sophisticated correction of NWP’s systematic errors and statistical weighting of NWP ensemble members – probably diminishing returns soon
  - Hours and minutes ahead
    - Use of customized rapid update NWP
      - Improve cloud initialization and cloud submodels
    - Refinement of satellite-based cloud element tracking methods
      - Techniques to account for cloud development and dissipation
      - Higher resolution satellite-image data
    - Application of skycam-based cloud tracking for 0-1 hr ahead forecasts
    - More sophisticated time series forecasting techniques with off-site data
Future Prospects:
How can forecast value be increased?

• Develop Distributed Solar Generation Forecast Tools
  - Inventory of solar generation sites
    • System attributes
    • Operating condition
  - Data from the sites?
  - NWP and satellite-based methods can be easily adapted for this application
  - Statistical schemes need site data (power output or irradiance)

• Make more effective use of forecast information
  - Use of probabilistic forecasts
    • Substantial amount of information is discarded when ONLY deterministic information is provided
    • Research studies in other (non-energy) applications have indicated that trained users make better application decisions when using a probabilistic forecast
  - Better forecast integration with decision-maker’s procedures
Summary

• State-of-the-art forecasts are generated with a combination of statistical, pattern-recognition and physics-based forecast tools and a variety of input data types

• Relative performance of the forecasting tools varies with look-ahead time – best current tool for each look-ahead range:
  – Weeks / months ahead: statistical links to global indices (e.g. El Nino)
  – 6 hours – 10 days ahead: Statically adjusted ensemble of NWP
  – 1 – 6 hours ahead: Satellite-based cloud motion extrapolation
  – 0 – 1 hour ahead: Sky-cam based cloud motion extrapolation

• “Typical” day-ahead forecast errors for an individual facility:
  – GHI: 75 watts/m² to 175 watts/m²
  – PV plant power output: 8-13% of capacity during peak generation hours
  – Overall performance is better for sunnier sites

• Potential for improvement in the near-term is highest for minutes and hours ahead forecasts