Applications of Coupled Models for Renewable Energy Integration in Vermont

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Renewable Energy Integration in Vermont

- Renewable energy production and energy demand have significant sensitivity to local, short-term weather conditions
- In Vermont, there are additional challenges due to local variations in geography, meteorology and energy use
- Intermittency in renewable generation coupled with variation in demand can lead to congestion in the transmission system
- The uncertainty in the power generation and demand is typically poorly quantified
- As a result, conservative grid management leads to curtailment of renewable power (i.e., wind) production
An Additional Challenge – Recent Growth in Solar Power

Approximately 8000 PhotoVoltaic (PV) installations in Vermont (none are dispatchable)
- 27 utility-scale (> 1MW)
- 65 community-scale (150KW – 1MW)
- Remainder: residential-scale (< 150KW)

PV Capacity Growth (~7X in the last four years!)

PV Locations and Category
- Community
- Residential
- Utility

Conference on Weather, Climate, Water and the New Energy Economy: 5.3
The Vermont Electric Power Company (VELCO) operates an interconnected electric transmission grid

- 738 miles of transmission lines
- 13000 acres of rights-of-way
- 55 substations, switching stations and terminal facilities
- Equipment that enables interconnected operations with Hydro-Québec
- 1500 miles of fiber optic communication network, which helps to enable observations to lead the way
- 52-mile 450 kV direct current line owned by VETCO

VELCO has invested in enabling the Vermont Weather Analytics Center (VWAC)
"Observations Lead the Way": but more than just weather.

- Feedback from each model team used to determine requirements and metrics for each model for evaluation and improvements
- Integrated approach using a common platform, data model, visualization, etc.

Decision Support

Manage Demand
Maximize Supply
Maintain the Grid
VWAC Mesonet

We led the way with more weather observations...

28 Active Stations

- VELCO = 14 (additional sites planned for 2017)
- VEC = 5 (additional sites planned for 2017)
- UVM = 5
- LSC = 4

All data are publically available through MesoWest and MADIS
Weather: NWP Configuration (Deep Thunder)

- WRF-ARW, version 3.5.1
- 51 vertical levels, with increased resolution in the PBL (10s of meters near the surface)
- 00Z and 12Z forecasts, 72-hour duration (10-min output)
  - 72-hour, operational since November 2015
  - 48 hour, operational since April 2015
- Physics configuration for highly urbanized to rural domain as well as considerations for wind and solar farms
  - Thompson double-moment microphysics (includes explicit ice, snow and graupel)
  - Mellor-Yamada-Nakanishi-Niino (MYNN) PBL scheme with turbulent kinetic energy (TKE)-based local mixing and 2.5-order closure
  - NOAH land-surface modeling with soil temperature and moisture in four layers, fractional snow cover and frozen soil physics
  - Explicit cumulus physics for innermost nests, Grell-Freitas for outer nest
  - 3-category urban canopy model with surface effects for roofs, walls, and streets
  - RRTMG long- and short-wave radiation
Weather: Data Ingest (Deep Thunder)

- Data assimilation (3dVAR) of near-real-time surface and upper-air observations from Earth Networks WeatherBug, MADIS and private mesonets
  - Surface stations, radiosondes, aircraft, ship, profiles, satellite, ...
  - ~3000 stations (gray markers on map): 9km nest (~3000), 3km nest (~1200), 1km nest (~450) – varies for each forecast
  - Additional quality control

- NASA high-resolution (2km) sea surface temperatures (SST), which include Lake Surface Temperature (LST) analysis over the Great Lakes

- NASA high-resolution (90m) Shuttle Radar Topography Mission (SRTM) terrain elevation

- MODIS 1km 20-category land use data

- NASA 4km dynamic (daily) VIIRS Green Vegetation Fraction (GVF) data

- NASA 3km land surface fields for initialization

- NOAA/NCEP Rapid Refresh (RAP) 13km analysis for background fields

- NOAA/NCEP North American Model (NAM) 12km lateral boundary conditions

Map: Vermont

1071x1071 km, every 9 km
564x564 km, every 3 km
328x301 km, every 1 km

(Gray Dots Mark Locations of Sites for Data Assimilation)
Operational Precipitation Type Forecasts

IBM Deep Thunder for Vermont

24-Jan-2017 - 10:10 EST

Copyright IBM 2017
### Raw Weather Model Performance (4/20/2015 – 12/31/2016): 1km Nest

<table>
<thead>
<tr>
<th>Variable</th>
<th>Bias</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2m T (°F)</td>
<td>-0.35</td>
<td>3.47</td>
</tr>
<tr>
<td>2m DP (°F)</td>
<td>0.27</td>
<td>3.34</td>
</tr>
<tr>
<td>10m Wind Speed (m/sec)</td>
<td>1.01</td>
<td>3.03</td>
</tr>
<tr>
<td>10m Wind Direction (°)</td>
<td>2.74</td>
<td>19.7</td>
</tr>
</tbody>
</table>

### Precipitation Score Results

<table>
<thead>
<tr>
<th>Precipitation Score</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>0.96</td>
</tr>
<tr>
<td>CSI</td>
<td>0.43</td>
</tr>
<tr>
<td>POD</td>
<td>0.66</td>
</tr>
<tr>
<td>Odds Ratio</td>
<td>81.6</td>
</tr>
</tbody>
</table>
Electricity Demand Forecasting

- Statistical modeling (e.g., regression, generalized non-linear additive) demand at multiple aggregation levels:
  - Vermont state level
  - Distribution units service territories (eight), towns (200) and counties (14)
  - Subtransmission and distribution (>100) substations
  - Distributed renewables “behind the meter”

- Factoring in heterogeneous inputs:
  - Weekday, time of day, time of year
  - Spatio-temporal weather features
  - Impact events (heat waves, snow storms)

- Integrating various data sources:
  - Telemetry (SCADA)
  - Physical network models
  - Smart meters
  - Weather forecasts and observations

\[ y_k = \sum_{d \in D} 1(x_{k}^{\text{DayType}} = d) f^{\text{TimeOfDay}}(x_k) + f^{\text{Temperature}}(x_k) + f^{\text{Irradiance}}(x_k) + \ldots \]

Generalized Additive Model:

- Time of day, day type (Mon, Tue-Thu, Fri, Sat, Sun), time of year, special days (holidays, Super Bowl, ...)
- Dry bulb temperature: current value, mean/max of previous day, etc.
- Dew point, irradiance
- Real-time demand information: Mean, min and max of previous day and minimum of current day
State-wide Electricity Demand Example

72-hour demand forecast is normalized to illustrate temporal and spatial detail
Electricity Demand for Making Snow – Distribution Substation

Probabilistic forecasts
- **Blue** line is most likely
- **Orange** line is actual
- Shading is uncertainty
Electricity Demand Web Portal

Probabilistic forecasts
• Blue line is most likely
• Shading is uncertainty

Distributed PV Solar Power Production: Substation Level
## State-Wide Electricity Demand Forecasting Performance (2016)

<table>
<thead>
<tr>
<th>Month</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>2.12</td>
</tr>
<tr>
<td>September</td>
<td>3.28</td>
</tr>
<tr>
<td>October</td>
<td>2.59</td>
</tr>
<tr>
<td>November</td>
<td>3.43</td>
</tr>
<tr>
<td>December</td>
<td>3.22</td>
</tr>
</tbody>
</table>
Data for Wind Farms

- NWP-derived, \([u, v, w]\) across the blade extent, temperature and moisture
- Wind and temperature measurements from turbines and met tower
- Turbine nacelle direction
- Generated power at each turbine and accumulated power, including availability and operational mode
- Engineering characteristics of the turbines (e.g., specifications, power curves, etc.)

Wind Power Forecasts

- Per farm (4)
- Per turbine for three of the farms
- 1 to 3 day-ahead focus
- Multiple statistical ensemble (e.g., CHAID Tree, Neural Network, and Classification and Regression Tree, Support Vector Machine, Convex Optimization)
Probabilistic forecasts:
- **Blue** line is most likely
- **Green** line is actual
- Shading is uncertainty
# Farm-Level Wind Power Forecasting Performance Summary (2016)

<table>
<thead>
<tr>
<th>Farm Name/Forecasting Time</th>
<th>Mean Absolute Error (KW)</th>
<th>Mean Absolute Error / Name Plate Capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KCW: Hours 0-24 (63 MW capacity)</td>
<td>6605</td>
<td>10.5</td>
</tr>
<tr>
<td>KCW: Hours 24-48</td>
<td>7380</td>
<td>11.7</td>
</tr>
<tr>
<td>KCW: Hours 48-72</td>
<td>7680</td>
<td>12.2</td>
</tr>
<tr>
<td>Sheffield: Hours 0-24 (40 MW capacity)</td>
<td>3892</td>
<td>9.7</td>
</tr>
<tr>
<td>Sheffield: Hours 24-48</td>
<td>4020</td>
<td>10.1</td>
</tr>
<tr>
<td>Sheffield: Hours 48-72</td>
<td>4486</td>
<td>11.2</td>
</tr>
<tr>
<td>GMW: Hours 0-24 (10 MW capacity)</td>
<td>1501</td>
<td>13.2</td>
</tr>
<tr>
<td>GMW: Hours 24-48</td>
<td>1581</td>
<td>13.8</td>
</tr>
<tr>
<td>GMW: Hours 48-72</td>
<td>1760</td>
<td>15.4</td>
</tr>
</tbody>
</table>
Predictive Statistical Models Built from Historical Weather Forecasts and Observations, Power and Other Data

Data for Solar Farms

- Weather model-derived near-surface GHI, DNI, GNI, wind speed & direction, temperature, pressure and moisture
- Irradiance, wind and temperature measurements at the farm, if available
- Generated power at each farm and accumulated power, including availability and farm operational mode
- Engineering characteristics of the PV panels (e.g., specifications, power curves, etc.)

Solar Power Forecasts

- Per farm (21 with > 1 MW capacity)
- 1 to 3 day-ahead focus
- Physical irradiance to power model
- Multiple statistical ensemble
- Cloud cover categorization
Probabilistic forecasts

- Blue line is most likely
- Green line is actual
- Shading is uncertainty
### Solar Power Forecasting Performance Summary (2016)

<table>
<thead>
<tr>
<th>Forecasting Cycles</th>
<th>Mean Absolute Error (KW)</th>
<th>Mean Absolute Error / Name Plate Capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 UTC: Hours 0 - 24</td>
<td>2687</td>
<td>7.1</td>
</tr>
<tr>
<td>0 UTC: Hours 24 - 48</td>
<td>2742</td>
<td>7.2</td>
</tr>
<tr>
<td>0 UTC: Hours 48 - 72</td>
<td>3065</td>
<td>8.1</td>
</tr>
</tbody>
</table>

~50MW capacity
Enabled an operational capability for all coupled modelling components with over 150 users

Availability of high-quality observations to enable operational updates is an ongoing challenge

Collaborative and diverse team (users, researchers, developers, industry experts) critical to success

- Need to build trust with diverse users and incorporate their feedback
- Deliver complex information succinctly
- Must be integrated with utility company procedures
Next Steps

- Continuing to improve calibration of all models for new use cases, and characterization of uncertainties, including further development of verification methods, and for longer lead times
  - Operational statistics for evaluation
  - Retrospective analysis and tuning using new events that have impact especially for determining periods of congestion
  - Developed capability to prospect for new utility-scale solar farms
  - Adding support for additional utility-scale solar farms (over 18MW of capacity)
  - Assessed peak load information and surveyed state’s Distributed Energy Resources (DER) for forecast adjustment

- Developing additional specialized visualizations and methods of dissemination
Related Presentations

**Eighth Conference on Weather, Climate, and the New Energy Economy**
- J7.3 Coupled NWP and Adaptive Machine Learning to Improve Solar and Wind Energy Forecasting for the State of Vermont (Thursday, 26 January: 4:00 PM)

**33rd Conference on Environmental Information Processing Technologies**
- J8.5 Containerization of Weather Forecasting Platforms: Benefits and Challenges (Wednesday, 25 January: 9:30 AM)
- J9.6 The Vermont Weather Analytics Center — Platform and Architecture (Wednesday, 25 January: 9:45 AM)

**Eighth Conference on the Meteorological Application of Lightning Data**
- 5.5 Use of High-Resolution Lightning Potential Forecasts for Vermont Utility Applications (Wednesday, 25 January: 9:30 AM)

**Eighth Conference on Environment and Health**
- 870 Weather Driven Psyllid Movement Within and Between Citrus Orchards (Tuesday, 24 January)

**Town Hall Meeting: The Weather Value Chain of the Future: From IoT to Artificial Intelligence** (Wednesday, 25 January: 12:15 PM-1:15 PM)

**13th Symposium of the Urban Environment**
- 5.5 Impact of Cool Roofs on Urban Energy Utilization in a Future Warm Climate (Tuesday, 24 January: 11:30 AM)

**31st Conference on Hydrology**
- 470 A Comparison Study of the Noah and Noah-MP Land Surface Models (Tuesday, 24 January)
- 6A.2 The Sensitivity of a Coupled Atmosphere-Hydrology Model at Lake George, NY to Changes in Land Surface Model Configuration and Stream Celerity (Tuesday, 24 January: 1:45 PM)

**28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction**
- 106 Assessment of Post-Processing Methods for Daily High and Low Temperature Prediction (Monday, 23 January)
- 575 Is There Value in Very High Resolution Weather Forecasts? Experiences from The Jefferson Project at Lake George (Tuesday, 24 January)

**29th Conference on Climate Variability and Change**
- 1150 Numerical Simulation of Indian Summer Monsoon Using MPAS-A: A Sensitivity Study (Wednesday, 25 January)

Conference on Weather, Climate, Water and the New Energy Economy:  5.3
Deep Thunder Web Portal

72-Hour Wind Speed and Direction Forecasts for Vermont
72-Hour Solar Irradiance Forecasts for Vermont
Deep Thunder Web Portal

72-Hour Forecasts for Vermont

IBM Deep Thunder for Vermont
Surface Total Precipitation and Winds
Cloud Water Density at 1.0e-04 kg/kg

Valid for 04/29/2015 2000 EDT through 04/30/2015 2000 EDT
Next Forecast Will be Available Between 04/30/2015 0000 EDT and 04/30/2015 1700 EDT
# 72-Hour Site-Specific Summary Forecast for Vermont

## Summary:

<table>
<thead>
<tr>
<th>Service</th>
<th>Monday - Wednesday</th>
<th>Full Day</th>
<th>0700 - 1500</th>
<th>1500 - 2300</th>
<th>2300 - 0700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation amount (in)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Peak Precipitation Rate (mph)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Accumulated Snowfall (in)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Snowfall (in)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Wind Chill (F)</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
</tr>
<tr>
<td>High Temp (F)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Low Temp (F)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Heat Index (F)</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
</tr>
</tbody>
</table>

## Specific Forecast Data:

- **Precipitation Amount**: 0.00 in.
- **Peak Precipitation Rate**: 0.00 mph.
- **Accumulated Snowfall**: 0.00 in.
- **Snowfall**: 0.00 in.
- **Wind Chill**: 00°F
- **High Temp**: 20°F
- **Low Temp**: 10°F
- **Heat Index**: 00°F

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**Note**: For more detailed forecast and current weather information, please refer to the Deep Thunder Web Portal.
Probabilistic forecasts

- **Blue line is most likely**
- **Orange line is actual**
- **Shading is uncertainty**
State-wide Distributed Solar Power Example

72-hour distributed PV power forecast is normalized to illustrate temporal and spatial detail.