Overview

• Stand-alone vs. System performance
• Model intermittent energy resources and generating technologies
  – Model with equations and measured data
  – Model the uncertainty – next class
  – ‘appendix’ slides, for your reference
• Analyze integration of renewable energy technologies into the power system
  – System impact performance parameters

Discussion

• How do you characterize wind and solar energy?
• How would you model and analyze power generation and system integration of renewable energy technologies?
  – Be quantitative
• Data
  – What data is available or can be obtained?
  – What ideally would you like to have for data?
  – What do you expect the data to look like?

* Stand-Alone Performance *

a) Resource modeling
  – Geographic diversity = smoothing
b) Energy capture
  – Total GWh generated
c) Capacity factor – equivalent average capacity available from generator for a given time period
  – Used for all technologies
d) Cost of generating electricity
Solar Energy (Whr/m²/day)

NREL – EWITS: New England Wind Sites
(each pushpin could represent an entire, hypothetical windfarm)

Convert 10-minute Wind Speed Data to Wind Farm Power Output

- Select wind turbine
  - On-shore vs. off-shore turbines
  - Obtain the power curve for the turbine
- Account for geographic diversity \(\rightarrow\) leads to decreased variability
  - Within a single wind farm
  - Across multiple wind farms
Geographic Diversity

1. Adjust wind speed data to represent aggregated wind speed for entire wind farm area
2. Adjust the power curve to represent multiple, aggregated turbines
   - Multiple articles for parameter values

Geographic Diversity – Wind Speed

1. Algorithm for wind speed data includes:
   - Propagation time of wind through the wind farm – based on average windspeed and size of windfarm
   - Normalized standard deviation of the wind resource
     - As a function of turbulence intensity of wind and dimensions of the windfarm
   - Calculate a moving block average of original wind speed data and relate to Weibull parameters of original wind speed dataset
     - Weibull is a probability distribution, based on the normal distribution, that cannot be < 0

Computational Fluid Dynamics

Image from http://windinspire.jhu.edu/
Geographic Diversity – Nantucket Windspeed

Geographic Diversity – Distribution of Windspeed

* Analyze this Histogram *

Geographic Diversity – Power Curve

b. Algorithm for power curve includes:
- Adjust power curve to represent multiple wind turbines (≈ convolution with Normal distribution)
- Adjust resulting power curve for total energy capture to equal original power curve

• Final Calculation: Determine wind farm power generation by using adjusted wind speed data with adjusted turbine power curve

Windfarm = Single Power Curve?
**Geographic Diversity – Power Curve**

**What does this mean for power generation?**

- Power curve adjusted to represent a large, aggregated wind turbine

![Power Curve Diagram]

**NREL – NE Wind Sites Clustered**

(K-means clustering)

![NREL Image]

**Power Output: Geographic Diversity**

![Power Output Chart]

**Power Output: Geographic Diversity**

![Adjusted Data Chart]
**Stand-Alone Performance**

a) Resource modeling
   – Geographic diversity = smoothing

b) Energy capture
   – Total GWh generated

c) Capacity factor – equivalent average capacity available from generator for a given time period
   – Used for all technologies

d) Cost of generating electricity

---

### Capacity Factor Defined

- The ratio of (write out equation):
  - the net electricity generated, for the time considered,
  - to the energy that could have been generated at continuous full-power operation during the same period

- Or the actual energy generated in one year divided by the total, maximum energy generation possible in the year

- Precise for traditional technologies
- Variations in use for RETs
System Integration Parameters

i. Net load duration curve
   - (Effective load carrying capability)

ii. Capacity credit (capacity value, ELCC)
    - (Effective load carrying capability)

iii. Capacity displacement

iv. Emissions reductions

v. Cost of electricity
   - Net effect on system price (system lambda)
Analysis Questions

• How do we know if the energy generated by the RETs is useful to the system?
• These are variable resources that are most useful to the system if they are available during hours of peak demand...
  – Why?
• Need to know:
  – Expected (forecasted) generation in MW
  – Forecast error so the system is ready to respond to this deviation → next class

LDC Questions

• What if wind displaces 5% of baseload and 5% of intermediate generation, but does not generate at all during system peak load hours? (see next graph)
• Using the LDC
  – Which generators are ‘displaced’?
  – What is the change to system fossil fuel usage?
  – What is the change to total system energy demand?
  – What is the change to system capacity needs?

Capacity Displacement

![Chart showing load versus hour with different colors representing various types of generation]

Capacity Credit?

• Dispatchable capacity rendered unnecessary
• Time series data versus LDC representation – different uses & benefits

![Chart showing capacity credit over time with different types of generation]
Capacity Credit

- What are the pros and cons of using the LDC versus time series data to determine capacity credit?

UK data: [http://www.windbyte.co.uk/windpower.html](http://www.windbyte.co.uk/windpower.html)
Struggling with Intermittent Resources

- Chronological (time series) data is deterministic
- Wind and solar data are inherently probabilistic … stochastic

* Capacity Credit *

- Alternative terms
  - Capacity credit
  - Capacity value
  - Effective load carrying capability
    - This also uses the concept of ‘loss of load probability’ or LOLP
    - The probability that regional electrical demand will not be served – traditional goal could be for no more than 1 hour of outage every 10 years
- Read at least one posted article!
Emissions Reductions

• Discuss – how can these be analyzed and quantified?
• Deterministic or probabilistic?

Cost of Electricity

• Discuss – how can this be analyzed and quantified?
• Deterministic or probabilistic?

Summary of RET Analysis

1. Modeling RETs and quantifying their stand-alone performance
2. Modeling RETs as part of the power system and quantifying impacts in terms of system performance

Appendix
Solar Energy

- National resource map
- Characterize the solar resource
  - Hourly data graphs
  - Mathematical modeling
- Note
  - Solar Power Density = Solar Insolation
  - W/m²

Solar Power Density ↔ Insolation

\[ \rho = \rho_o \cos \xi (\alpha_{dt} - \beta_{wa}) \alpha_p \]

- \( \rho \): solar power density on earth in kW/m²
- \( \rho_o \): extraterrestrial power density, the solar constant (1.353 kW/m²)
- \( \xi \): zenith angle (angle from the outward normal on the earth surface to the center of the sun)
- \( \alpha_{dt} \): direct transmittance of gases except for water (the fraction of radiant energy that is not absorbed by gases)
- \( \beta_{wa} \): water vapor absorptions of radiation
- \( \alpha_p \): is the transmittance of aerosol

Solar Efficiency (\( \eta \))

\[ \eta_s = \cos \xi (\alpha_{dt} - \beta_{wa}) \alpha_p = 5 - 70\% \]

- Ranges of values for solar efficiency??
- Where/when is solar efficiency maximum?
Daily Solar Power Density

\[ \rho = \rho_{\max} e^{-\frac{(t-t_o)^2}{2\sigma^2}} \]

- \( t \): hour of the day using the 24 hr clock
- \( \rho_{\max} \): the maximum solar power density
- \( t_o \): time at \( \rho_{\max} \) (noon time in the equator)
- \( \sigma \): standard deviation

Components of Solar Insolation

Solar Energy in Boston: Averages

Hourly Solar Data

- Adjusting solar data if you do not have data for the desired location...
- Combine the patterns shown in hourly data with
- Statistics such as max, average and standard deviation from parameter values
Wind Resource

• Characterize the wind resource
  – 10-minute data, hourly data & probabilities (variability)
• Forecast
  – Statistical and probabilistic modeling
  – Significance of forecast error (uncertainty)

Kinetic Energy of Air

\[ KE = \frac{1}{2} \ m \ v^2 \]

- \( m \): mass of air
- \( v \): speed of wind

\[ m = \text{volume} \times \delta = A \ v t \delta \]

- \( A \): sweep area
- \( \delta \): air density (kg/m\(^3\))
- \( t \): time

Air Power Density (\( \rho \)) in W/m\(^2\)

\[ KE = \frac{1}{2} \ m \ v^2 = \frac{1}{2} A \delta t \ v^3 \]
\[ P = \frac{KE}{t} = \frac{1}{2} A \delta \ v^3 \]

\[ \rho = \frac{P}{A} = \frac{1}{2} \delta \ v^3 \]

\[ \rho \sim V^3 \]
Hourly Wind Data Availability

NREL: http://www.nrel.gov/wind/systemsintegration/ewits.html


Europe: http://www.knmi.nl/samenw/hydra/register/

Wind Power Studies

- AWS Truewind, LLC., Troy, NY. www.awstruewind.com