Grid Integration of Variable Generation Sources

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Conclusions

• There are no inherent technical limits to how much variable renewable generation can be placed on the grid.....
1. Variability and uncertainty of the resource
   - Need extra generation capacity to deal with ramp rates?
   - Increased operating reserves?
2. Supply/demand mismatch leads to curtailment and increased costs
3. True stability limits caused by decreased system inertia and primary frequency response
1) Variability and Uncertainty

- Hypothesis was that massive ramp rates and variability and uncertainty of the resource
  - Need extra generation capacity to deal with ramp rates?
  - Increased operating reserves?

- This is the major focus of many grid-integration studies of wind and solar
This is Scary!

Springerville AZ, One Day at 10 Second Resolution
Integration Studies

• Simulate system with and without solar and wind
  – Use unit commitment software includes existing generation mix, transmission system
  – Use lots of wind and solar simulations to consider spatial diversity
  – May involve substantial costs

• Evaluate impacts of forecast errors, resource variability, additional reserves, curtailment etc.

• Reduced form models have very limited use to understanding key integration issues
Integration Cost

Base Case Assumptions:
DA firmness (60%)
HA firmness (87%)
Added spin (2.4 MW)

<table>
<thead>
<tr>
<th>Wind Energy Penetration</th>
<th>1%</th>
<th>4%</th>
<th>7%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within-hour Regulating</td>
<td>$0.40</td>
<td>$0.41</td>
<td>$0.31</td>
<td>$0.37</td>
</tr>
<tr>
<td>Hour-ahead Uncertainty</td>
<td>$0.11</td>
<td>$1.88</td>
<td>$2.32</td>
<td>$2.65</td>
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<tr>
<td>Day-ahead Uncertainty</td>
<td>$0.39</td>
<td>$0.95</td>
<td>$0.93</td>
<td>$1.06</td>
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</table>
## Costs of Wind Integration

<table>
<thead>
<tr>
<th>Date</th>
<th>Study</th>
<th>Wind Capacity Penetration (%)</th>
<th>Regulation Cost ($/MWh)</th>
<th>Load-Following Cost ($/MWh)</th>
<th>Unit Commitment Cost ($/MWh)</th>
<th>Other Cost ($/MWh)</th>
<th>Total Oper. Cost Impact ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>Xcel-UWIG</td>
<td>3.5</td>
<td>0</td>
<td>0.41</td>
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<td>Na</td>
<td>1.85</td>
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<td>2003</td>
<td>WE Energies</td>
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<td>1.02</td>
<td>0.15</td>
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<td>Na</td>
<td>2.92</td>
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<td>Xcel-MNDOC</td>
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<td>Na</td>
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<td>2005</td>
<td>PacifiCorp-2004</td>
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<td>0</td>
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<td>Na</td>
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<td>Na</td>
<td>Na</td>
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<td>Na</td>
<td>Na</td>
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<td>na</td>
<td>na</td>
<td>na</td>
<td>Na</td>
<td>8.56</td>
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</tbody>
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a Regulation costs represent 3-year average.

b The Xcel/PSCO study also examine the cost of gas supply scheduling. Wind increases the uncertainty of gas requirements and may increase costs of gas supply contracts.

c Highest over 3-year evaluation period. 30.7% capacity penetration corresponding to 25% energy penetration.

d Unit commitment includes cost of wind forecast error.

e This integration cost reflects a $10/MMBtu natural gas scenario. This cost is much higher than the integration cost calculated for Xcel-PSCo in 2006, in large measure due to the higher natural gas price. Had the gas price from the 2006 study been used in the 2008 study, the integration cost would drop from $8.56/MWh to $5.13/MWh.
Conclusions of Wind Integration Studies
(up to about 30% Penetration)

• Integration costs are modest (typically less than $5/MWh)

• Increased variability can be accommodates by existing generator flexibility and other “low-cost” flexibility such as increased balancing area cooperation (balancing wind generation and load over larger areas to “share” the increased variability)

• Forecasting is improving.

• Spatial diversity smooth's aggregated wind output reducing short-term fluctuations to hour time scales

• Variability can be met with long-duration flexibility reserves compared to high-cost regulation reserves
Spatial diversity appears to address very short-term variability

- For solar in the bulk power system, short term variability and instantaneous ramp rates are largely mitigated by spatial diversity

Lew et al. 2013
2) Economic limits to VG Penetration - Curtailment

• At high penetration, economic limits will be due to curtailment
  – Limited coincidence of VG supply and normal demand
  – Minimum load constraints on thermal generators
  – Thermal generators kept online for operating reserves
  – Transmission constraints
Example Simulation - Solar PV in the Summer

Simulated Dispatch in California for a Summer Day with PV Penetration from 0-10%
Simulated Dispatch in California for a Spring Day with PV Penetration from 0-10%
Plant operators would rather sell energy at a loss than incur a costly shutdown. Wind and solar may be curtailed under these conditions.
Extreme Case - Zero Value (Curtailed) PV

20% Contribution from PV

Denholm and Mehos. 2011
PV Curtailment

Fraction of Energy From PV

Denholm and Mehos 2011
PV Curtailment Cost Impact

Fraction of Energy From PV

Effective SunShot LCOE

PV Levelized Cost Multiplier

Marginal

Average

Denholm and Mehos 2011
Wind Cost of Curtailment

Fraction of Energy From Wind and Solar

Relative Cost of VG (Average)

- 21 GW Min Load (65% FF)
- 12 GW Min Load (80% FF)
- 6 GW Min Load (90% FF)

Denholm et al. 2010
Wind Marginal Curtailment Rates

Marginal VG Curtailment

Fraction of Energy From RE

- 21 GW Min Load (65% FF)
- 12 GW Min Load (80% FF)
- 6 GW Min Load (90% FF)

FF = Flexibility Factor

Denholm et al. 2010
Increasing PV Value and Avoiding Curtailment

Denholm et al. 2010
Flexibility Supply Curve Concept

Denholm et al. 2010
Mitigation Options

Options need to:
1. Increase the coincidence of PV supply and energy demand
2. Decrease uncertainty that requires holding operating reserves
3. Decrease variability that requires holding operating reserves

Options Include:
1. System flexibility
2. Better forecasting
3. Spatial diversity
4. Energy storage
Increased Generator Flexibility - PV

“Nuclear baseload”
“Average Mix”
“Perfect”

Denholm and Margolis 2007
Spatial Diversity

Very small BA with a single wind resource. This is an example of how NOT to evaluate the impact of wind (or pick chart colors) (Denholm 2004)
Increased Flexibility - Wind

Fraction of System Electricity from Wind

- 80% flexibility (12 GW min load)
- 90% flexibility (6 GW min load)
- 100% flexibility (0 min load)

Denholm & Hand 2011
Different RE Mixes Improves Supply/Demand Coincidence

Solar / Wind Mix
- 0/100
- 20/80
- 30/70
- 40/60
- 60/40
- 80/20

Fraction of System Electricity from Solar and Wind

Fraction of VG Curtailed

Denholm & Hand 2011
Energy Storage Can Reduce VG Curtailment

![Graph showing the impact of energy storage on reducing VG curtailment.](image)

- **Fraction of System Electricity from Wind & Solar**
- **Fraction of VG Curtailed**

Lines represent different storage durations:
- **No Storage**
- **4 hours**
- **8 hours**
- **12 hours**
- **24 hours**

Denholm & Hand 2011
3) Grid Stability including Inertia and Primary Frequency Response

What we have now
Wind and PV Do Not Provide Traditional Inertia

What we will have in the future?
Frequency in WECC after a N-2 Fault

Solvable problem?

Ela et al 2014
Instead of Conclusions, My Opinions

• Old rules of 10-20% limits are not based on real science
• The scary problems of ramp rates, uncertainty and variability are on their way to being solved problems
• The limits to RE deployment are based on the economics of curtailment driven by system flexibility and supply demand coincidence
• There are many sources of flexibility which will be deployed, many (most?) of which are cheaper than energy storage
• At ultra-high penetration of VG, storage will likely be important
• For 100% RE scenarios I don’t know how to solve the seasonality problem without fuels production
Flexibility Supply Curve Concept

<30%?  30-40%?  40-80%?

Denholm et al. 2010

The relative order of these is conceptual only.
Questions?

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Backup – How we got to 80% in REF
1) Cycle Generators

Baseline scenario

80% RE-ITI scenario

Coal

Gas CC

Gas CT

Power (GW)
2) Build New Transmission

![Map showing transmission infrastructure with inter-PCA and intra-PCA data](image)

**Inter-PCA (MW)**
- < 1,000
- 1,000 - 2,500
- 2,500 - 5,000
- 5,000 - 10,000
- 10,000 - 15,000
- > 15,000

**Intra-PCA (Million MW-Miles)**
- < 0.05
- 0.05 - 0.1
- 0.1 - 0.5
- 0.5 - 1
- 1 - 3
- > 3

**Graphs**
- Hours on the x-axis
- CO to KS
- MT to ND

**Legend**
- Blue line: CO to KS
- Red line: MT to ND
3) Deploy Dispatchable Renewables

Source: Denholm et al (2012)
4) Harness Responsive Demand (smart grid?)
5) Accept inevitable curtailment in the spring.

8-10% of wind, solar, hydropower curtailed in 2050 under 80% RE scenarios
6) And develop new storage

Installed capacity is sufficient to meet summer afternoon peak demand from diverse reserves supplying firm capacity.
References


