Grid Effects of Cloud-Induced Variation in Solar Photovoltaic Generation

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- Modules: $4.08 / W
- Inverters: $0.715 / W

PV vs. demand

Full sun

load

solar

Load (MW)

Solar (MW)

Time Period (hour)

Wind vs. Demand

Sunlight varies

Operating Reserves

Typical capacity credits

- Coal, nuclear, natural gas, oil, hydro: 100%
- Solar 60-90%
- Geothermal 80-100%
- Wind 20-40%
Cloud Modeling
Statistical model, small cumulus clouds

Simulated cloud pattern for 50% shadow cover

Distributed PV Systems

Resulting Insolation

When a squall line moves across an area with PV, all PV generation is lost.

When clouds are moving over an area with PV, PV generation varies rapidly.

Maximum PV Variability (% per minute)

Service area (km$^2$)
When clouds are moving over an area with PV, PV generation varies rapidly.

Example:
- 1000 km² (about 400 mi²) service area
- 200 MW distributed PV
- 200 MW x 3%/minute = 6 MW/minute change

Power Flow Modeling
Public Service of Oklahoma (AEP) southeast Tulsa area
(450 square kilometers)

# Power Flow Results

Public Service of Oklahoma (AEP) southeast Tulsa area

**Spring, 15% Penetration**

Maximum change in Power Flow

(% of Nominal Power Flow in 1 Minute)

<table>
<thead>
<tr>
<th>Cumulus Clouds</th>
<th>Squall Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>4</td>
</tr>
<tr>
<td>Ties</td>
<td>5</td>
</tr>
<tr>
<td>Lines</td>
<td>22</td>
</tr>
</tbody>
</table>

**Spring, 30% Penetration**

Maximum change in Power Flow

(% of Nominal Power Flow in 1 Minute)

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<tr>
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<tr>
<td>Area</td>
<td>8</td>
</tr>
<tr>
<td>Ties</td>
<td>14</td>
</tr>
<tr>
<td>Lines</td>
<td>44</td>
</tr>
</tbody>
</table>

**Summer, 30% Penetration**

Maximum change in Power Flow

(% of Nominal Power Flow in 1 Minute)

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**Summer, 50% Penetration**

Maximum change in Power Flow

(% of Nominal Power Flow in 1 Minute)

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Power Flow Results
Public Service of Oklahoma (AEP) southeast Tulsa area

15 % distributed PV can cause:

• Transmission power flow reversal
• Transmission overloads

under certain conditions
Production Cost
Unit commitment and economic dispatch

For a system that is ramp-rate limited to 1% of load per minute:

One PV generator with capacity = 1.3% of load may exceed system ramp rate under certain cloud conditions.

Ramp rate limited system
1% of load per minute

Fluctuation in PV Output (% of installed PV capacity per minute)

PV Penetration (% of installed generation)

Marginal Prices at PV bus

- No PV
  - CO₂ $0/ton

- 300 MW (9%) PV
  - CO₂ $0/ton
  - CO₂ $50/ton
Changes in system operating cost

CO₂ $0/ton

CO₂ $50/ton

Changes in CO$_2$ emissions

Energy Storage to Relieve Congestion

Operations with storage

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