Changes in the Economic Value of Variable Generation with Increasing Penetration Levels:
A Pilot Study of California

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Overview and motivation

- Resource procurement and investment decisions are made more difficult by the variable and unpredictable nature of variable generation (VG)
  - Simple comparisons of the levelized cost of energy (LCOE) between new generation options, for example, are insufficient to show relative economic attractiveness
  - Part of what is missing from simple comparisons is an evaluation of the economic value of the energy generated
- Use a long-run modeling framework to evaluate economic benefits of several different VG technologies:
  - Wind, single-axis tracking photovoltaics (PV), and concentrating solar power (CSP) with and without six hours of thermal energy storage (CSP\textsubscript{6} and CSP\textsubscript{0}, respectively)
  - Include high time resolution (hourly over a full year) and incorporate operational constraints into long run valuation framework
Long run investment framework

**SHORT-RUN PROFIT**

- Economic value of resources

**PRICES**

- Integration
  - Operations
  - Short Run
  - Variable Costs
  - Security

- Valuation
  - Planning
  - Long Run
  - Fixed Costs
  - Adequacy

**RESOURCES**

- Mix of resources available to balance supply and demand

Adapted from Stoft (2002)
Long run investment framework

**SHORT-RUN PROFIT**
- Day-ahead schedules with real-time deviations

**INVESTMENT**
- Compare to value of annual flat block of power
- Decompose value components
- Vary fixed cost of new CTs
- Annualized fixed cost of:
  - Coal
  - Nuclear
  - CCGTs
  - CTs
  - Storage

**RESOURCES**
- 2030 Loads
- Incumbent generation

**PRICES**
- Hourly prices for day-ahead using forecasts, real-time with actual
- Minimum generation
- Ramping constraints
- Operating reserves
- Part-load inefficiencies

Add increasing wind, PV, or CSP
- Use all existing gen. or retire after technical life
Pilot California case study: data and assumptions

• **Resources:**
  - Focus on California, 2030 hourly loads (2004 load shapes)
  - Solar PV and wind hourly actual and day-ahead forecast from WWSIS (2004 shapes)
  - Incumbent generation: retirement after technical life of 30 yr for CT/CCGT, 50 yr steam, 60 yr nuclear

• **Prices:**
  - Simplified commitment and dispatch based on 19 thermal plant vintages: linear on-line constraints rather than integer commitment.; forecasts are deterministic (not stochastic)
  - CSP commitment and dispatch is similar simplification of approach used by Sioshansi and Denholm (2010)
  - Hourly energy prices for day-ahead (DA) based on forecasts, real-time (RT) based on actual
  - Hourly ancillary services prices for regulation, spinning and non-spinning reserves
  - Reserve quantities based on rules-of-thumb developed in the WWSIS
  - “Energy only” market, meaning that capacity costs are covered through scarcity prices in energy market rather than side capacity payment

• **Short-run profits:**
  - Revenues based on DA schedule at DA prices, deviations at RT prices, and ancillary services costs/revenues
  - Short-run profit of generation reflects the marginal economic value of adding an additional unit of energy with the same production profile
Primary caveats

• Narrow definition of economic value:
  • Avoided capital investment cost and variable fuel and O&M costs from other power plants in CA

• Focus on California without evaluation of transmission:
  • Renewable electricity only used to meet CA demand
  • Incumbent generation only includes generation in the CA NERC sub-region

• Marginal economic value instead of average value:
  • Only indicates value of next increment of VG

• Simplified commitment and dispatch decisions:
  • Vintages rather than individual unit commitment
In long run equilibrium, short-run profit of new plants equals annualized fixed costs.

Investment model iterates through several candidate portfolios of generation capacity.

Total annualized fixed cost of a new combined cycle plant is assumed to be $203/kW-yr.

Since new CCGTs are included in final iteration: short-run profit of CCGTs equals annualized fixed cost of CCGTs.
Investment and dispatch decisions with increasing PV penetration

<table>
<thead>
<tr>
<th>PV Penetration</th>
<th>Incremental Reduction in Non-PV Capacity (GW)</th>
<th>Incremental Increase in Nameplate PV (GW)</th>
<th>Effective Marginal Capacity Credit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% -&gt; 5%</td>
<td>2.8</td>
<td>5.8</td>
<td>48%</td>
</tr>
<tr>
<td>15% -&gt; 20%</td>
<td>0.4</td>
<td>5.9</td>
<td>7%</td>
</tr>
</tbody>
</table>
Summary of investment and dispatch decisions with increasing VG penetration

- Total nameplate capacity of VG and non-VG resources increases with increasing VG penetration
  - Implied capacity credit is less than that of a conventional plant for all VG
  - Capacity credit is highest for CSP$_6$ at both low and high penetration levels and for PV and CSP$_0$ at low penetration

- Energy from VG primarily displaces energy from CCGTs
  - Leads to large reduction in capacity factor of CCGTs
  - Load factor of CCGTs also decreases, but decrease is moderated by fact that CCGTs can be brought offline
  - Overall only a modest reduction in CCGT efficiency with increasing wind, PV and CSP$_0$ penetration
Marginal value of variable generation varies with technology and penetration
Decomposition of marginal economic value into additive components

- **Capacity value ($/MWh):**
  - Portion of short-run profit earned during hours with scarcity prices (defined to be greater than $500/MWh)

- **Energy value ($/MWh):**
  - Portion of short-run profit earned in hours without scarcity prices if DA forecast exactly matches RT generation

- **DA Forecast Error Cost ($/MWh):**
  - The net earnings from RT deviations from the DA schedule

- **Ancillary Services Cost ($/MWh):**
  - The net earnings from selling AS and/or paying for increased AS in the case of variable generation
Marginal value of a flat block of power changes only at very high penetration

<table>
<thead>
<tr>
<th>Component ($/MWh)</th>
<th>0% Flat</th>
<th>5% Flat</th>
<th>10% Flat</th>
<th>15% Flat</th>
<th>20% Flat</th>
<th>30% Flat</th>
<th>40% Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Capacity Value</td>
<td>+20</td>
<td>+20</td>
<td>+20</td>
<td>+20</td>
<td>+20</td>
<td>+20</td>
<td>+16</td>
</tr>
<tr>
<td>(Capacity Value in $/kW-yr)</td>
<td>(170)</td>
<td>(180)</td>
<td>(170)</td>
<td>(180)</td>
<td>(180)</td>
<td>(180)</td>
<td>(140)</td>
</tr>
<tr>
<td>+ Energy Value</td>
<td>+50</td>
<td>+50</td>
<td>+50</td>
<td>+50</td>
<td>+50</td>
<td>+50</td>
<td>+49</td>
</tr>
<tr>
<td>+ DA Forecast Error</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>+ Ancillary Services</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>= Marginal Economic Value</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>65</td>
</tr>
</tbody>
</table>
Marginal value of wind is largely driven by energy value

<table>
<thead>
<tr>
<th>Component ($/MWh)</th>
<th>0% Wind</th>
<th>5% Wind</th>
<th>10% Wind</th>
<th>15% Wind</th>
<th>20% Wind</th>
<th>30% Wind</th>
<th>40% Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Capacity Value</td>
<td>+17</td>
<td>+12</td>
<td>+10</td>
<td>+10</td>
<td>+9</td>
<td>+8</td>
<td>+8</td>
</tr>
<tr>
<td>+ Energy Value</td>
<td>+50</td>
<td>+49</td>
<td>+48</td>
<td>+48</td>
<td>+48</td>
<td>+46</td>
<td>+39</td>
</tr>
<tr>
<td>+ DA Forecast Error</td>
<td>-0.2</td>
<td>-3</td>
<td>-4</td>
<td>-2</td>
<td>-2</td>
<td>-3</td>
<td>-6</td>
</tr>
<tr>
<td>+ Ancillary Services</td>
<td>-0.4</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>= Marginal Economic Value</td>
<td>67</td>
<td>57</td>
<td>54</td>
<td>55</td>
<td>54</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>
Marginal value of PV is high at low penetration due to high capacity value

<table>
<thead>
<tr>
<th>Component ($/MWh)</th>
<th>0% PV</th>
<th>2.5% PV</th>
<th>5% PV</th>
<th>10% PV</th>
<th>15% PV</th>
<th>20% PV</th>
<th>30% PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Capacity Value</td>
<td>+37</td>
<td>+34</td>
<td>+27</td>
<td>+13</td>
<td>+8</td>
<td>+4</td>
<td>+1</td>
</tr>
<tr>
<td>(Capacity Value in $/kW-yr)</td>
<td>(120)</td>
<td>(110)</td>
<td>(82)</td>
<td>(39)</td>
<td>(24)</td>
<td>(11)</td>
<td>(4)</td>
</tr>
<tr>
<td>+ Energy Value</td>
<td>+54</td>
<td>+53</td>
<td>+52</td>
<td>+49</td>
<td>+45</td>
<td>+41</td>
<td>+27</td>
</tr>
<tr>
<td>+ DA Forecast Error</td>
<td>-0.4</td>
<td>-5</td>
<td>-4</td>
<td>-6</td>
<td>-5</td>
<td>-4</td>
<td>-3</td>
</tr>
<tr>
<td>+ Ancillary Services</td>
<td>-0.9</td>
<td>-0.8</td>
<td>-0.7</td>
<td>-0.4</td>
<td>-0.2</td>
<td>-0.1</td>
<td>-0.0</td>
</tr>
<tr>
<td>= Marginal Economic Value</td>
<td>90</td>
<td>81</td>
<td>73</td>
<td>55</td>
<td>47</td>
<td>41</td>
<td>25</td>
</tr>
</tbody>
</table>

Single-axis PV and CSP without TES have similar relative magnitude of different components and similar changes in value of components with increasing penetration.
Marginal value of CSP with TES retains high level with higher penetration

<table>
<thead>
<tr>
<th>Component ($/MWh)</th>
<th>0% CSP&lt;sub&gt;6&lt;/sub&gt;</th>
<th>2.5% CSP&lt;sub&gt;6&lt;/sub&gt;</th>
<th>5% CSP&lt;sub&gt;6&lt;/sub&gt;</th>
<th>10% CSP&lt;sub&gt;6&lt;/sub&gt;</th>
<th>15% CSP&lt;sub&gt;6&lt;/sub&gt;</th>
<th>20% CSP&lt;sub&gt;6&lt;/sub&gt;</th>
<th>30% CSP&lt;sub&gt;6&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Capacity Value</td>
<td>+37 (150)</td>
<td>+37 (160)</td>
<td>+37 (150)</td>
<td>+35 (150)</td>
<td>+24 (100)</td>
<td>+20 (85)</td>
<td>+15 (61)</td>
</tr>
<tr>
<td>(Capacity Value in $/kW-yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Energy Value</td>
<td>+55</td>
<td>+55</td>
<td>+55</td>
<td>+55</td>
<td>+58</td>
<td>+53</td>
<td>+52</td>
</tr>
<tr>
<td>+ DA Forecast Error</td>
<td>-0.1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>+ Ancillary Services</td>
<td>+1.4</td>
<td>+1.4</td>
<td>+1.3</td>
<td>+1.2</td>
<td>+1.0</td>
<td>+0.7</td>
<td>+0.1</td>
</tr>
<tr>
<td>= Marginal Economic Value</td>
<td>94</td>
<td>93</td>
<td>92</td>
<td>90</td>
<td>83</td>
<td>71</td>
<td>64</td>
</tr>
</tbody>
</table>
Times with high net load and high prices shift to early evening with increasing PV

Highest load hours are occur in late afternoon.

With high PV penetration, highest net-load hours occur in the early evening.

PV does not generate in early evening hours

High price periods shift from times with high load to times with high net-load

Contribution of high price hours to marginal economic value of PV declines with high PV penetration
Times with high net load remain similar with modest penetration of CSP6

Highest load hours are occur in late afternoon.

With CSP₆, highest net-load hours remain in the late afternoon.

CSP₆ extracts energy from thermal storage starting in the early evening.

High price periods remain in the late afternoon even with increasing CSP₆ penetration

Contribution of high price hours to marginal economic value of CSP₆ remains relatively high even at 15% penetration
Sensitivity scenarios demonstrate marginal value depends on assumptions

• Remove major operational constraints in dispatch model:
  • Energy value of PV and CSP0 particularly increase at high penetration relative to reference scenario

• Increase cost of energy with a $32/tonne CO₂ price:
  • Energy value of all VG resources increases by $10-13/MWh up to 20% penetration

• Reduce the cost of capacity from conventional plants:
  • Lowers the capacity value but increases the energy value due to new CTs displacing more-efficient new CCGTs

• Assume no existing plants retire for technical reasons:
  • Increases amount of low-efficiency natural gas plants, decreases capacity value and increases energy value
Conclusions

• **Solar has high value at low penetration levels**
  • The high value is largely due to the high capacity value at low penetration

• **There is little apparent value to thermal storage for CSP plants at low penetration levels**

• **The value of PV and CSP without thermal storage drop considerably with increasing penetration levels**
  • Main driver is change in capacity value and energy value with increasing penetration
  • Day ahead forecast error and ancillary service costs do not change nearly as much with increasing penetration
Conclusions (con’t)

• At medium to high penetration CSP with thermal storage is considerably more valuable relative to PV and CSP without thermal storage

• The value of wind is largely driven by energy value and is lower than solar at low penetration
  • Largely because the capacity value of wind is lower than that of solar at low penetration

• At high penetration, the value of wind can exceed the value of PV and CSP without thermal storage
  • The capacity value is relatively stable and the energy value does not drop as fast as the energy value of PV and CSP without thermal storage
Recommended Further Research

• Impact of mitigation strategies on the value of variable generation at high penetration levels
  • Combinations of VG, flexible conventional generation, demand response, low-cost bulk power storage, etc.

• Capacity credit of solar at low penetration; how capacity credit changes with increasing penetration
  • Capacity credit of CSP with thermal storage may need to be based on methods suited to evaluating adequacy in energy-constrained systems

• Variation in value for different regional characteristics:
  • Demand profile, incumbent generation, renewable resource options
For More Information

Download the full report:

http://eetd.lbl.gov/ea/EMS/re-pubs.html

Listen to a webinar presentation:

http://westgov.adobeconnect.com/p2bc7cavm3e/

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