Economic dispatch for DC-connected battery systems on large PV plants

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May 3, 2018
Overview

- Falling costs of battery energy storage, combined with an increasing need to mitigate variable generation is leading to more PV projects that include batteries.
- Large PV plants face challenges optimizing the value of the power they produce, particularly when the batteries are DC-coupled and otherwise clipped power is available.
- NREL and Southern Company have developed a heuristic algorithm in SAM to inform plant operation under this scenario.
System Configuration

- DC-Coupled battery shares the PV inverter
- PV power can charge the battery without going through the inverter
Why DC-Connected?

- When the PV DC power output exceeds the inverter DC power input, excess power is clipped.
- In an AC connected system, even if PV power is dumped to the battery, it doesn’t reduce clipping, since PV power must still pass through the inverter before going to the battery.
- In a DC connected system, PV power can be dumped to the battery before passing through the inverter.
Controller development

• Develop a controller that at every time, looks ahead 18 hours and decides:
  o Whether to charge from the grid
  o Whether to charge from PV
  o Whether to charge from PV power which would otherwise be clipped.
  o Whether to discharge

• Factor in the PV production forecast, the PPA time-of-delivery factors, and estimated wear cost of the battery
Controller Development

- PV and clipping forecast
- PPA sell-rate forecast, utility buy-rate
- Battery wear costs ($/cycle)

Battery Controller

Battery power charge and discharge signal, including whether is from the grid or PV
• Always charge from PV if clipping occurs
• Charge from PV if it is more valuable to sell the PV power later
  • But, reserve energy for future clipped power
• Also charge from the grid if the energy charge is less than a future PPA price, accounting for charge and discharge efficiencies.
• Discharge if in a high PPA price period, and have inverter and battery capacity.
Evaluate installing PV with a DC-coupled battery system for time-of-use optimization and capturing otherwise clipped power.

- Base PPA rate: $0.10/kWh (with time-of-delivery factors)
- Buy rate = sell rate
- Default SAM financial assumptions, tax rate set to new corporate tax rate of 21%
- Perfect forecast on PV production
A time-of-delivery factor is a multiplier on the PPA price. Time-of-day variability in the PPA price is a strong driver in the controller.

Evaluated a highly variable PPA option available in SAM: SDG&E 2015 Full Capacity Deliverability Local. In summer months, peak PPA rate is almost three times greater than off-peak.
Resulting monthly system operation

- January
- February
- March
- April
- May
- June
- July
- August
- September
- October
- November
- December

Power (kW)

Time of Day (hours)
Example peak summer day operation

Battery charges from PV minimally during peak operation to reduce clipping, otherwise charges mostly from grid.
## Results Summary

- **PV is cost effective, and installing a battery slightly reduces this value**
- **DC-connected battery reduces clipping by 75%.**
- **In this case, the battery mostly charges from the grid to take advantage of the difference in buy rate vs. sell rate**

<table>
<thead>
<tr>
<th>Variable</th>
<th>PV Only</th>
<th>DC-Connected Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Energy (year 1)</td>
<td>1,912 MWh</td>
<td>1929 MWh</td>
</tr>
<tr>
<td>Year 1 Energy Clipped</td>
<td>44.0 MWh</td>
<td>11.2 MWh</td>
</tr>
<tr>
<td>Year 1 Battery Energy Charged</td>
<td>0 kWh</td>
<td>107 MWh</td>
</tr>
<tr>
<td>Year 1 Battery Energy Charged from PV</td>
<td>0 MWh</td>
<td>35 MWh</td>
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<tr>
<td>Year 1 Battery Energy Charged from Grid</td>
<td>0 MWh</td>
<td>72 MWh</td>
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<tr>
<td>Year 1 Battery Energy Discharged</td>
<td>0 kWh</td>
<td>92 MWh</td>
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<tr>
<td>Net Present Value</td>
<td>$118,080</td>
<td>$107,570</td>
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</tbody>
</table>
Effect of sensitivities on project economics

Battery Bank Replacement Criteria

- Choosing when to replace the battery bank plays a large role in the total project economics.
- In this scenario, project economics are maximized when the battery bank is replaced after degrading to 50% or less of its original capacity.

PPA Price

- The PPA price determines how much the project owner is compensated for selling electricity to the grid.
- Even with low system costs, project does not become economically viable until PPA price is $0.10/kWh
Effect of DC to AC ratio on project economics

- Battery utilization from PV increases as DC to AC ratio increases.
- At high ratios, battery power and capacity limits are overwhelmed and cannot capture all of the clipped power.
- NPV decreases at higher ratios due to a severe decrease in annual AC energy produced.
Effect of time step on project economics

5-minute weather data

Annual energy clipped without battery: 61.2 MWh

Hourly weather data

Annual energy clipped without battery: 44.0 MWh

<table>
<thead>
<tr>
<th>Variable</th>
<th>5-minute weather with DC battery</th>
<th>Hourly weather with DC battery</th>
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<tbody>
<tr>
<td>Annual Energy (year 1)</td>
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<td>1929 MWh</td>
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<tr>
<td>Year 1 Energy Clipped</td>
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<tr>
<td>Net Present Value</td>
<td>$93,084</td>
<td>$107,570</td>
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</tbody>
</table>
Effect of forecast on project economics

- Initially assumed perfect forecast on PV clipping.
- Consider worst case, using yesterday's clipping.

Effect of forecast on project economics

<table>
<thead>
<tr>
<th>Variable</th>
<th>PV only</th>
<th>Perfect Look-ahead Forecast</th>
<th>Look-behind forecast</th>
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</thead>
<tbody>
<tr>
<td>Annual Energy (year 1)</td>
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<tr>
<td>Year 1 Energy Clipped</td>
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<td>11.2 MWh</td>
<td>15.1 MWh</td>
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<tr>
<td>Net Present Value</td>
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<td>$107,570</td>
<td>$53,009</td>
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</table>

On January 7, there was no clipping, so using as forecast for a day with clipping will result in missed opportunity.
Conclusions and suggested future work

• As the price of PV and battery energy storage drop, new opportunities for system configuration and operation are emerging.

• Coupling a battery to the DC-side of a PV array to use a shared inverter may improve project economics and reduce losses due to clipping in certain market scenarios.

• Challenges remain to fully optimize system operation and include other value streams.

• Would be interesting (and challenging) to formulate and solve as a Mixed Integer Program
SAM Battery Model Overview

- Techno-economic model for residential, commercial, and third-party ownership systems
  - Lead acid, lithium ion, and flow battery chemistries
  - System lifetime analysis including battery replacement costs
  - Models for terminal voltage, capacity, temperature
  - Multiple dispatch controllers available

![Graph showing after-tax cash flow system lifetime](image)

- Battery replacements result in additional costs

![Graph showing voltage discharge](image)

- Depth of discharge (%) vs. Voltage (V)