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


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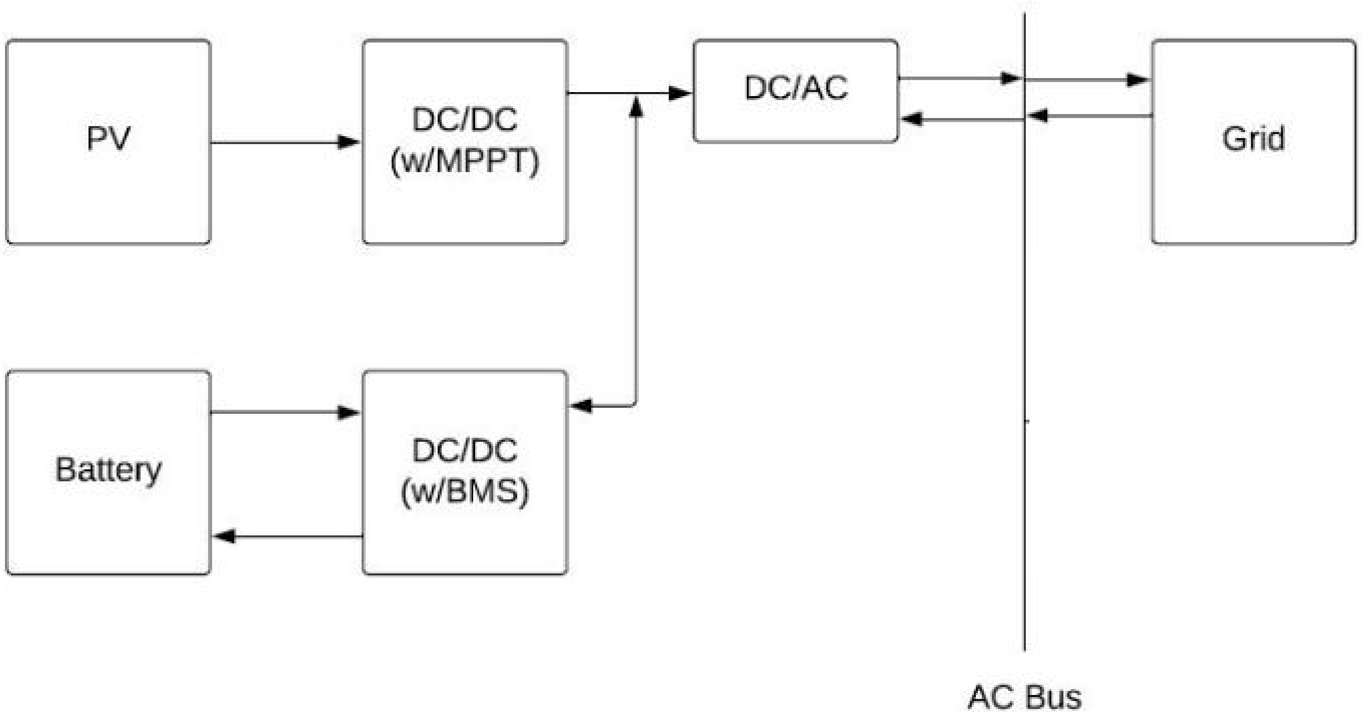
# Overview

- 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.

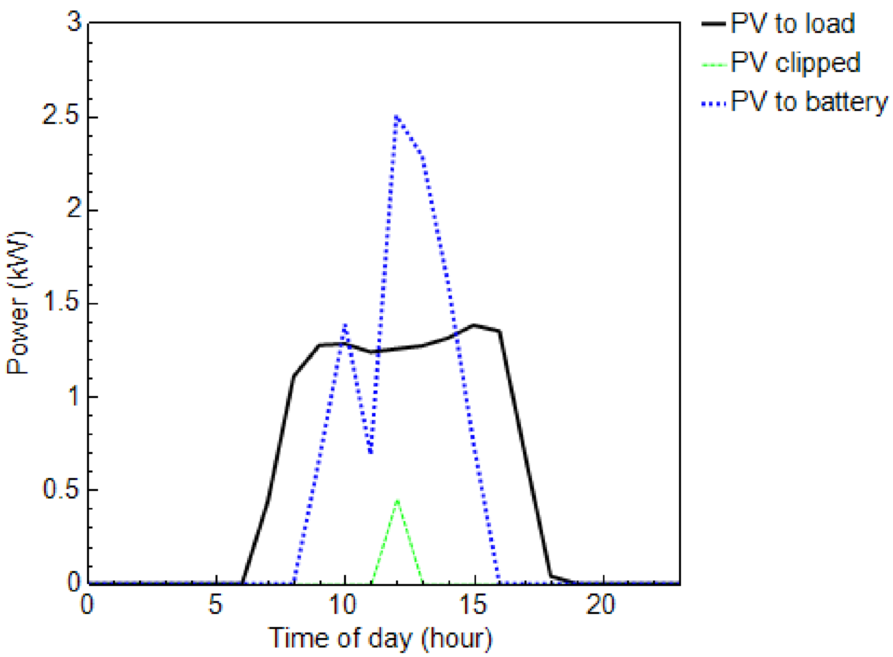
# System Configuration



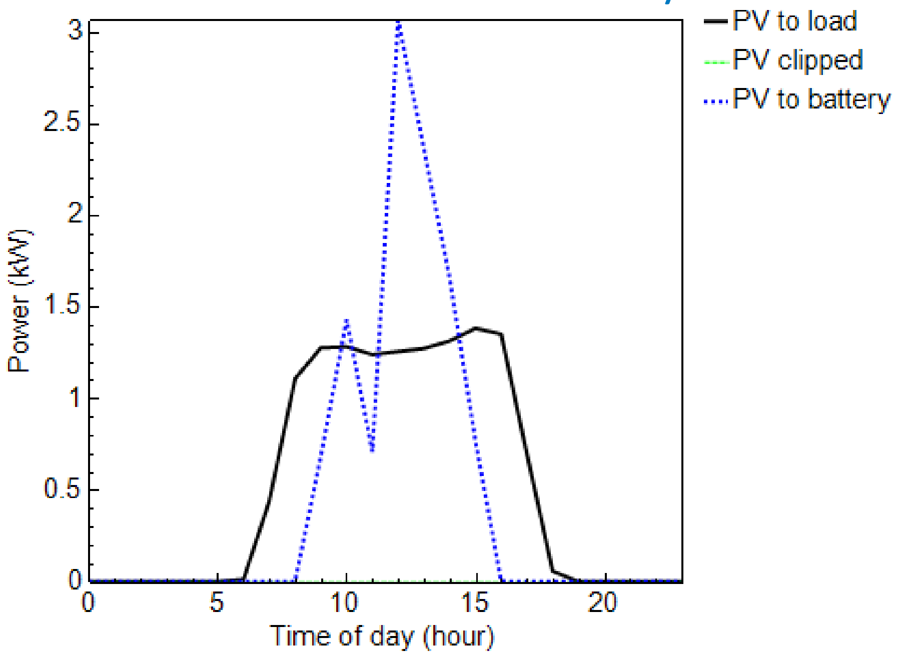

- DC-Coupled battery shares the PV inverter
- PV power can charge the battery without going through the inverter

# Why DC-Connected?

PV + AC-Connected Battery




PV + DC-Connected Battery

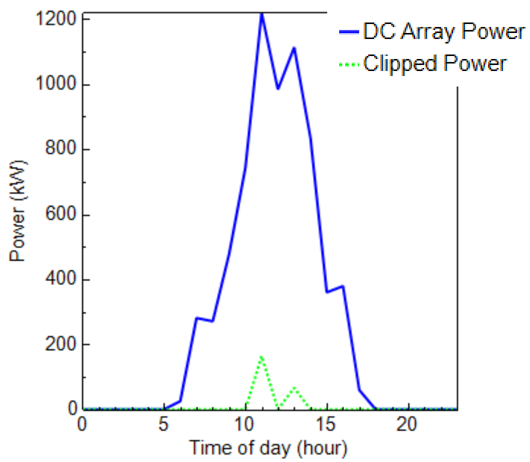



- When the PV DC power output exceeds the inverter DC power input, excess power is clipped
- In an AC connected system, even if PV power is dumped to the battery, it doesn't reduce clipping, since PV power must still pass through the inverter before going to the battery
- In a DC connected system, PV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

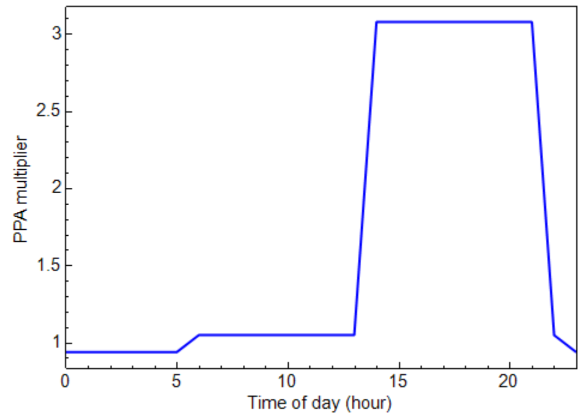
# Controller development

- Develop a controller that at every time, looks ahead 18 hours and decides:
  - Whether to charge from the grid
  - Whether to charge from PV
  - Whether to charge from PV power which would otherwise be clipped.
  - Whether to discharge
- Factor in the PV production forecast, the PPA time-of-delivery factors, and estimated wear cost of the battery

# Controller Development



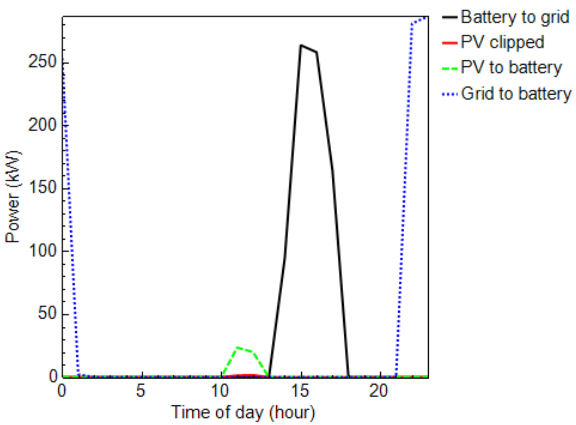

PV and clipping forecast




PPA sell-rate forecast, utility buy-rate

Battery wear costs ($/cycle)

Battery Controller



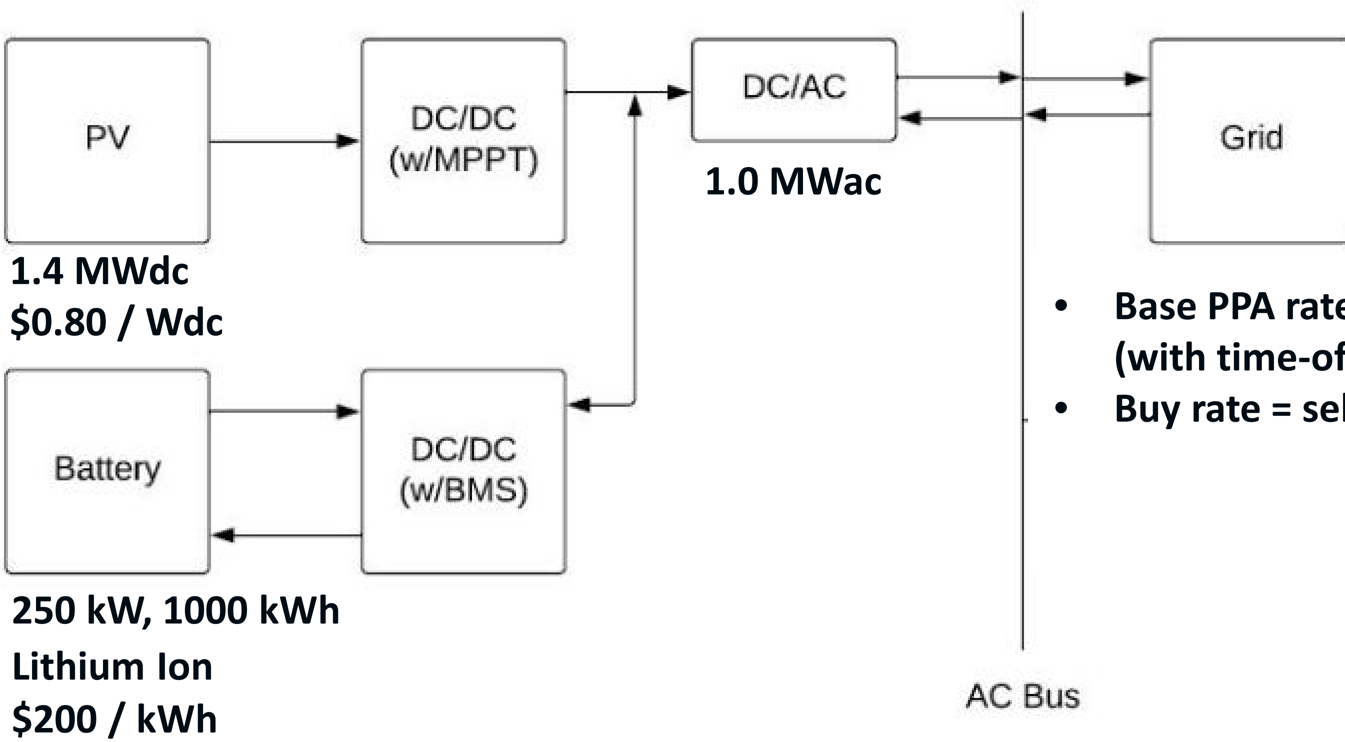

Battery power charge and discharge signal, including whether is from the grid or PV

# Underlying algorithms

- 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.

# Birmingham Alabama: example Case Study

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

# PPA Time-of-Delivery Factors

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

| | TOD factors |
|---|---|
| Period 1: | 3.077 |
| Period 2: | 1.048 |
| Period 3: | 0.937 |
| Period 4: | 1.347 |
| Period 5: | 0.726 |
| Period 6: | 0.717 |
| Period 7: | 1 |
| Period 8: | 1 |
| Period 9: | 1 |

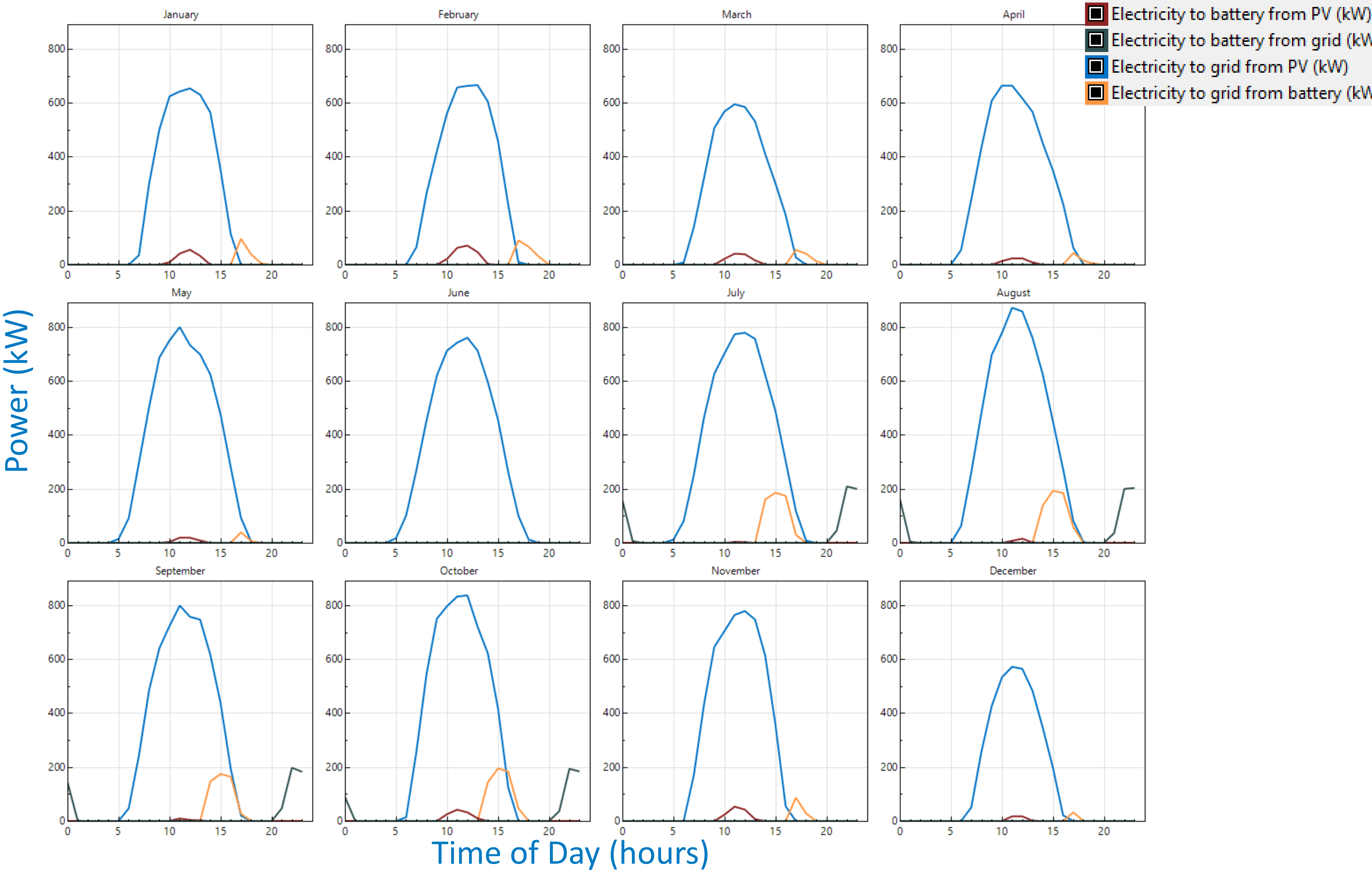
| | 12am | 1am | 2am | 3am | 4am | 5am | 6am | 7am | 8am | 9am | 10am | 11am | 12pm | 1pm | 2pm | 3pm | 4pm | 5pm | 6pm | 7pm | 8pm | 9pm | 10pm | 11pm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |
| Feb | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |
| Mar | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |
| Apr | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |
| May | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |
| Jun | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |
| Jul | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 |
| Aug | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 |
| Sep | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 |
| Oct | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 |
| Nov | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |
| Dec | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |

Evaluated a highly variable PPA option available in SAM:

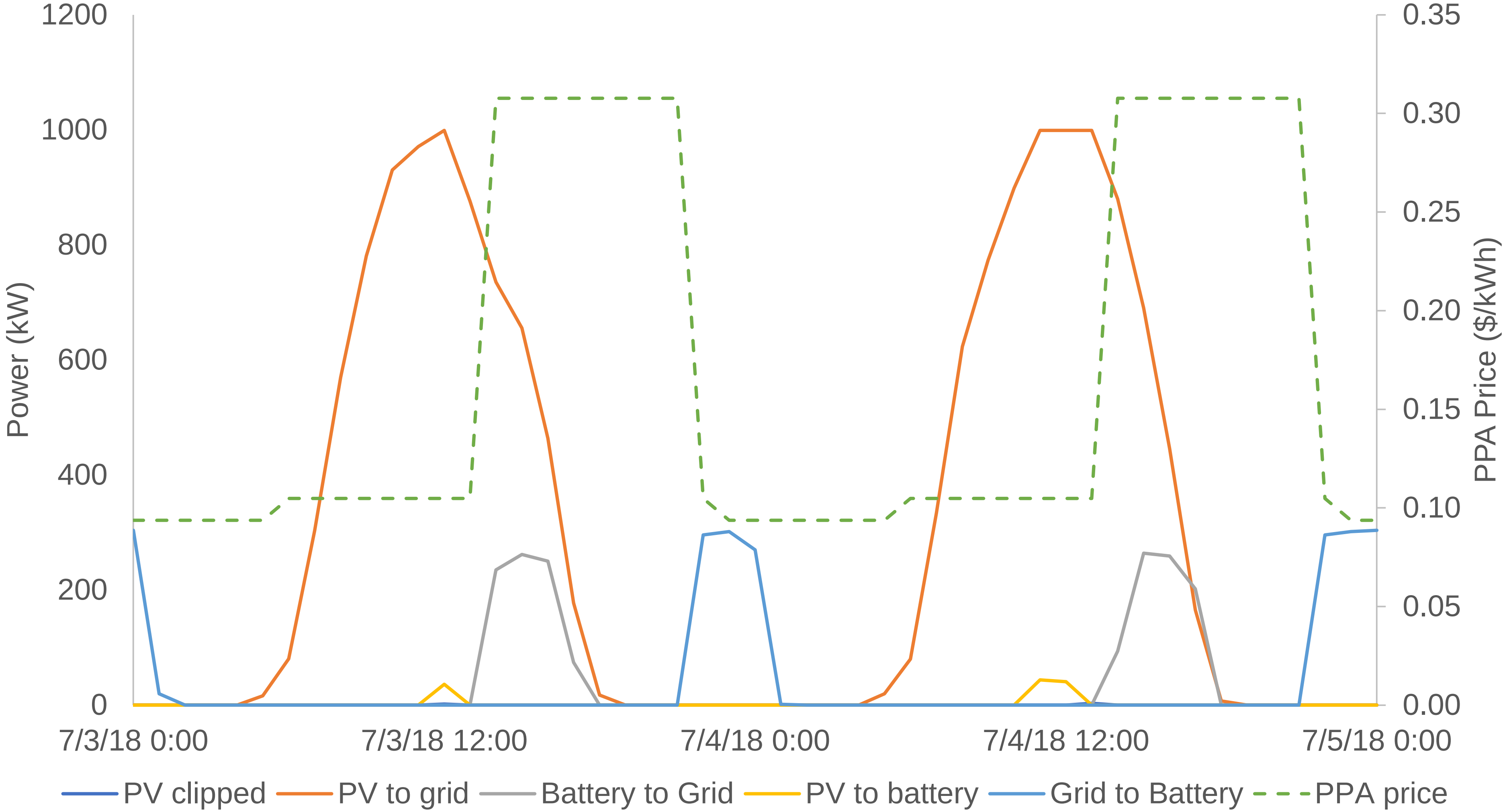
SDG&E 2015 Full Capacity Deliverability Local

In summer months, peak PPA rate is almost three times greater than off-peak

# Resulting monthly system operation



# Example peak summer day operation




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

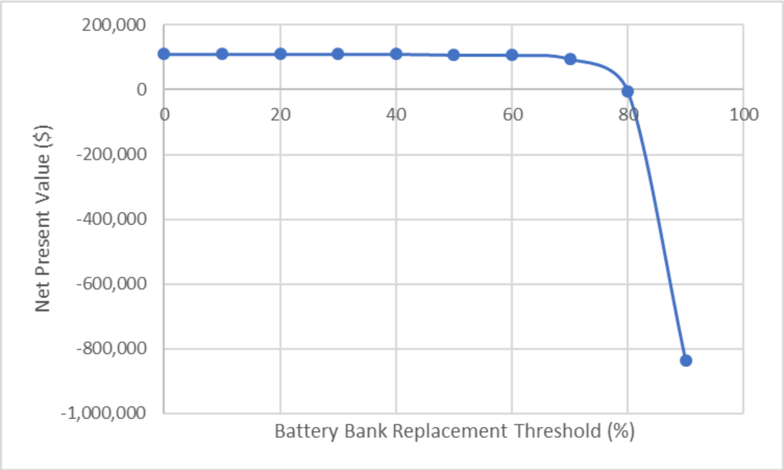
# Results Summary

| Variable | PV Only | DC-Connected Battery |
|---|---|---|
| Annual Energy (year 1) | 1,912 MWh | 1929 MWh |
| Year 1 Energy Clipped | 44.0 MWh | 11.2 MWh |
| Year 1 Battery Energy Charged | 0 kWh | 107 MWh |
| Year 1 Battery Energy Charged from PV | 0 MWh | 35 MWh |
| Year 1 Battery Energy Charged from Grid | 0 MWh | 72 MWh |
| Year 1 Battery Energy Discharged | 0 kWh | 92 MWh |
| Net Present Value | $118,080 | $107,570 |

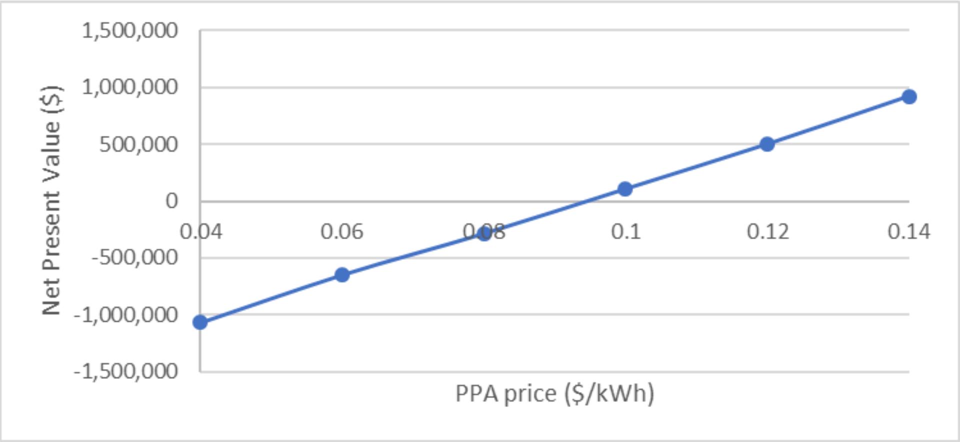
- PV is cost effective, and installing a battery slightly reduces this value
- DC-connected battery reduces clipping by 75%.
- In this case, the battery mostly charges from the grid to take advantage of the difference in buy rate vs. sell rate

# Effect of sensitivities on project economics

## Battery Bank Replacement Criteria



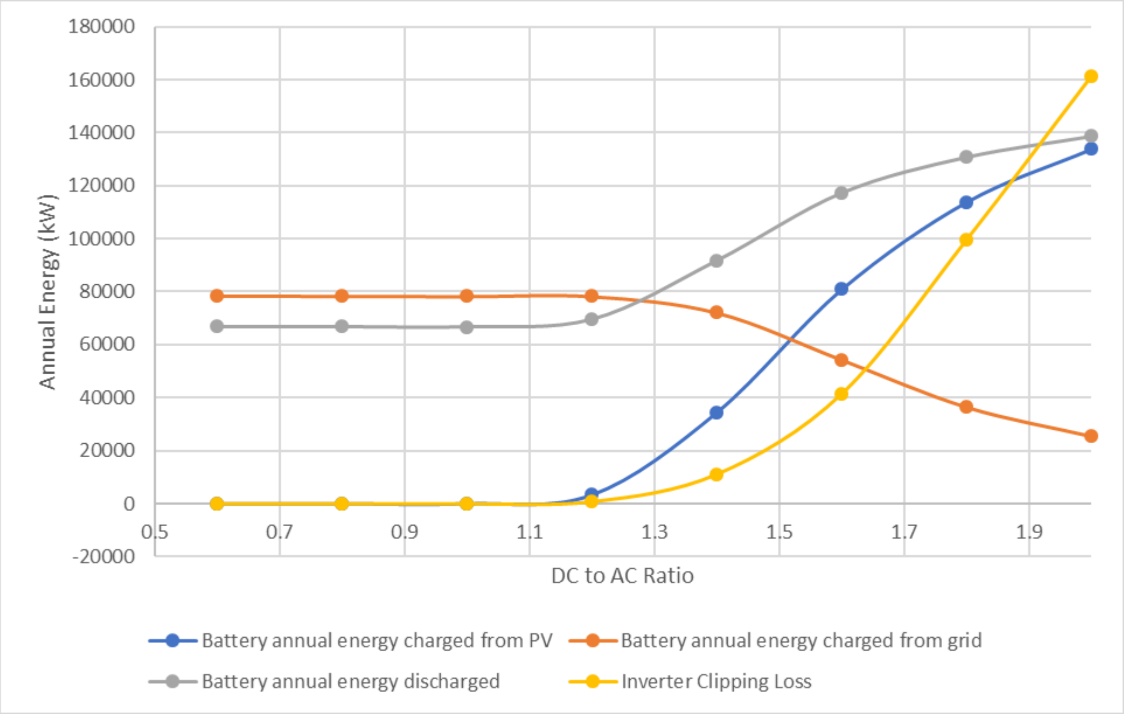

## PPA Price



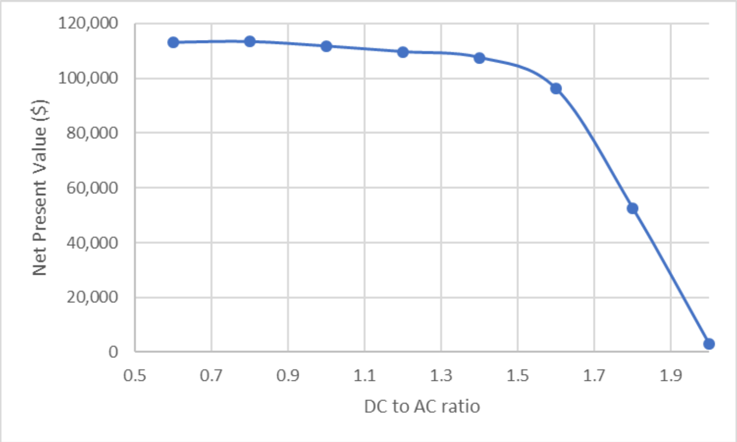

- Choosing when to replace the battery bank plays a large role in the total project economics.
- In this scenario, project economics are maximized when the battery bank is replaced after degrading to 50% or less of its original capacity.

- 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



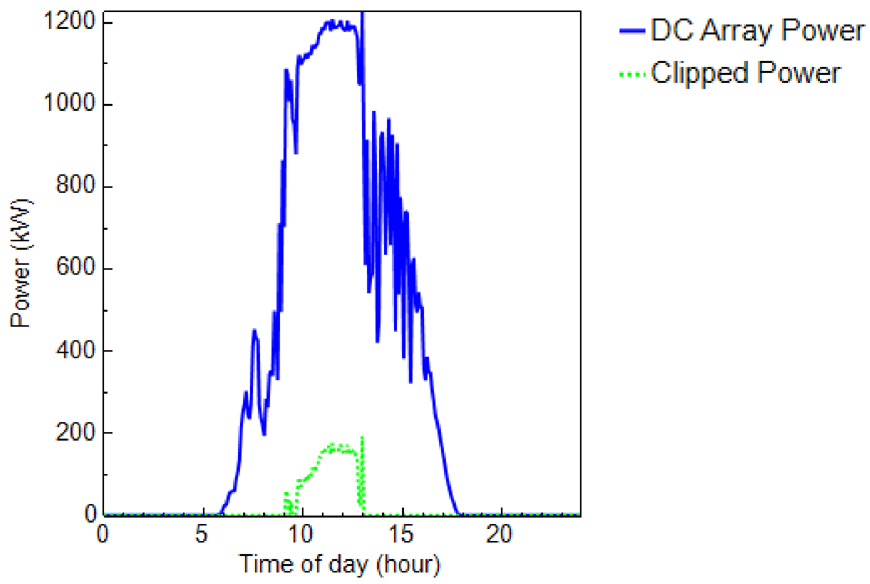

- Battery utilization from PV increases as DC to AC ratio increases
- At high ratios, battery power and capacity limits are overwhelmed and cannot capture all of the clipped power




- NPV decreases at higher ratios due to a severe decrease in annual AC energy produced

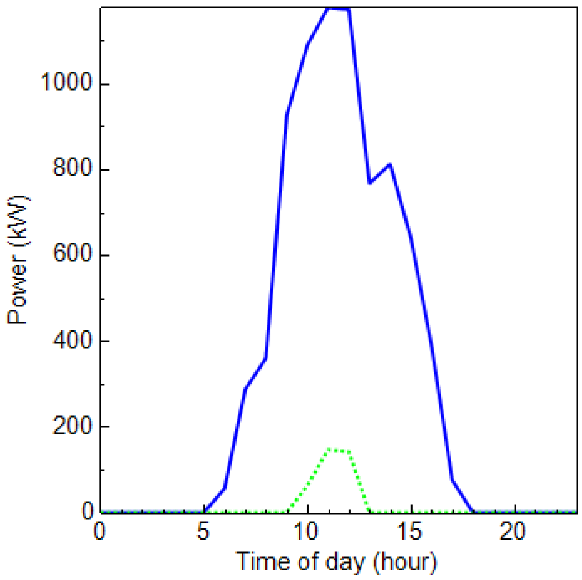
# Effect of time step on project economics

5-minute weather data




Annual energy clipped without battery: 61.2 MWh

Hourly weather data

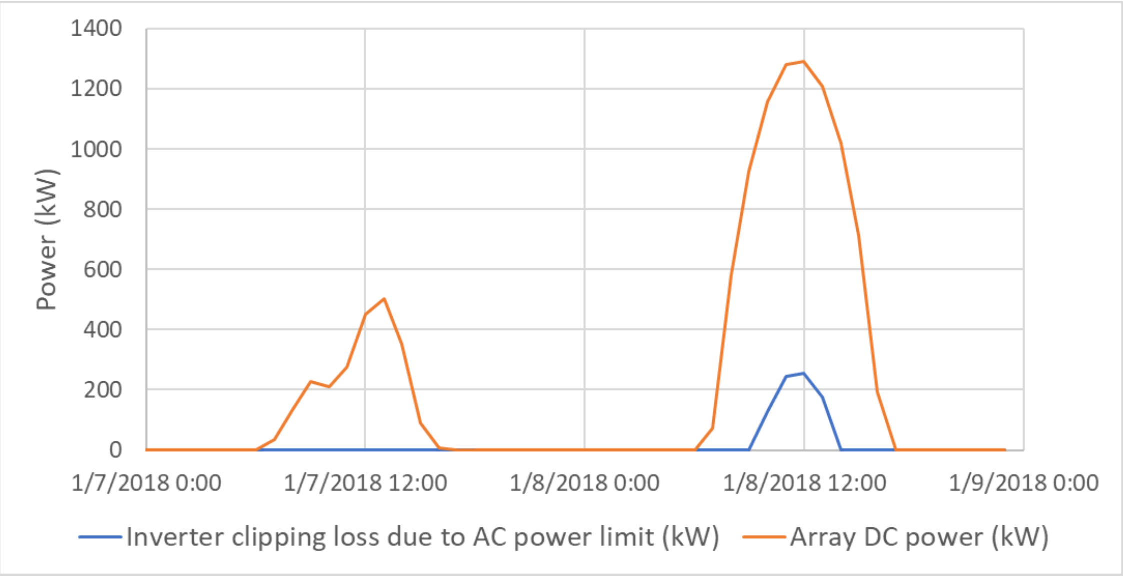



Annual energy clipped without battery: 44.0 MWh

| **Variable** | **5-minute weather with DC battery** | **Hourly weather with DC battery** |
|---|---|---|
| Annual Energy (year 1) | 1934 MWh | 1929 MWh |
| Year 1 Energy Clipped | 17.2 MWh | 11.2 MWh |
| Net Present Value | $93,084 | $107,570 |

# Effect of forecast on project economics

- Initially assumed perfect forecast on PV clipping.
- Consider worst case, using yesterdays clipping




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

| Variable | PV only | Perfect Look-ahead Forecast | Look-behind forecast |
|---|---|---|---|
| Annual Energy (year 1) | 1,912 MWh | 1929 MWh | 1924 MWh |
| Year 1 Energy Clipped | 44.0 MWh | 11.2 MWh | 15.1 MWh |
| Net Present Value | $118,080 | $107,570 | $53,009 |

# 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

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# 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