NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Southern Company

Economic Dispatch for DC-Connected Battery Systems on Large PV Plants

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2018 PV Systems Symposium, Albuquerque, New Mexico

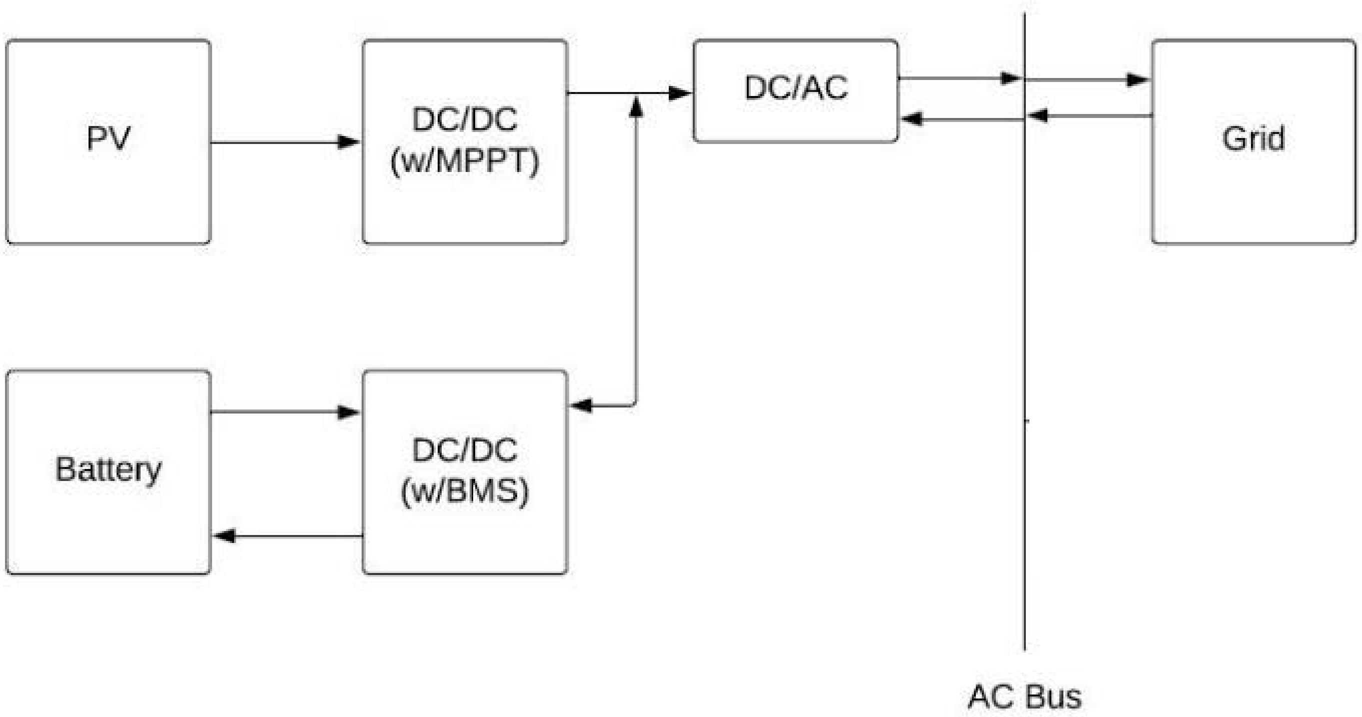
May 3, 2018

NREL/PR-6A20-72513

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.

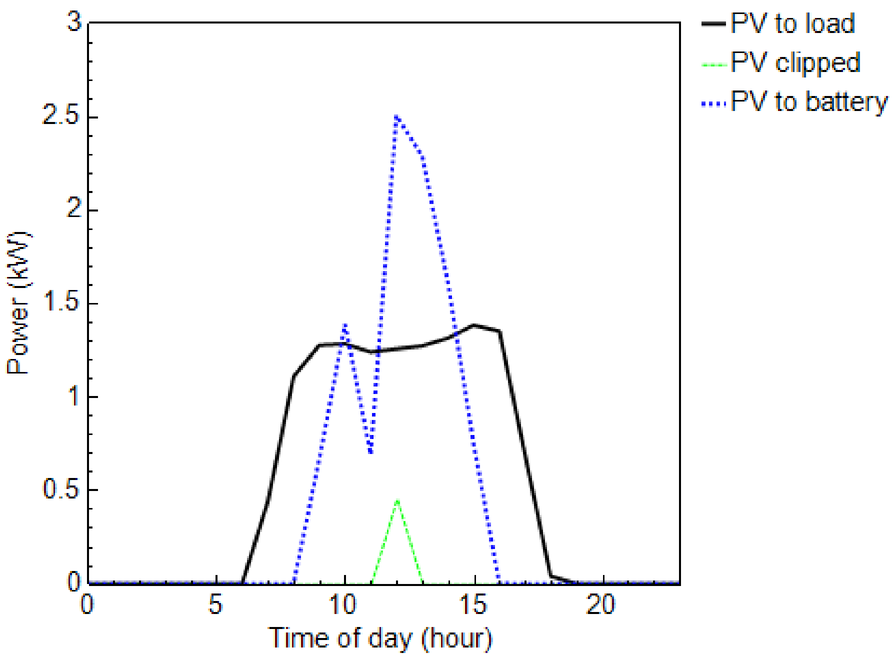
System Configuration



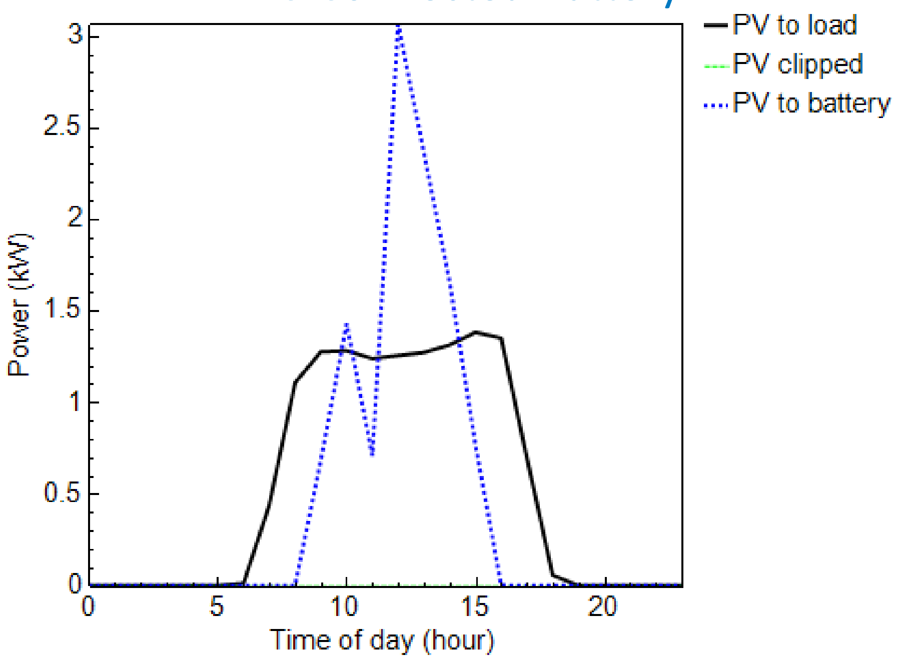
- DC-Coupled battery shares the PV inverter
- PV power can charge the battery without going through the inverter

Why DC-Connected?

PV + AC-Connected Battery



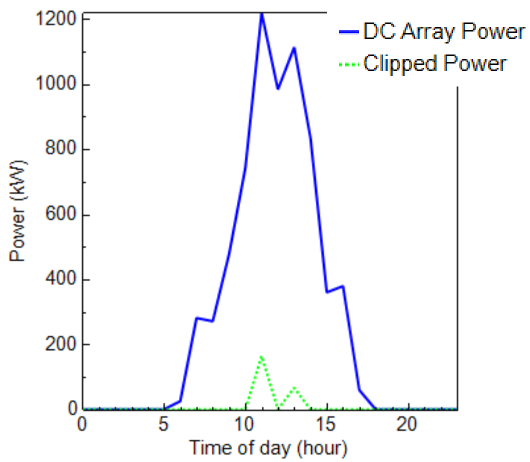
PV + DC-Connected Battery



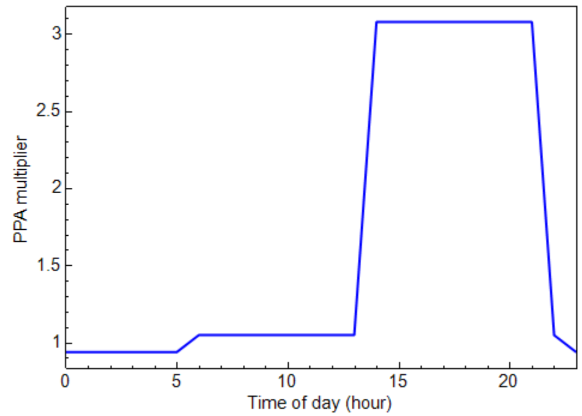
- When the PV DC power output exceeds the inverter DC power input, excess power is clipped
- In an AC connected system, even if PV power is dumped to the battery, it doesn't reduce clipping, since PV power must still pass through the inverter before going to the battery
- In a DC connected system, PV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



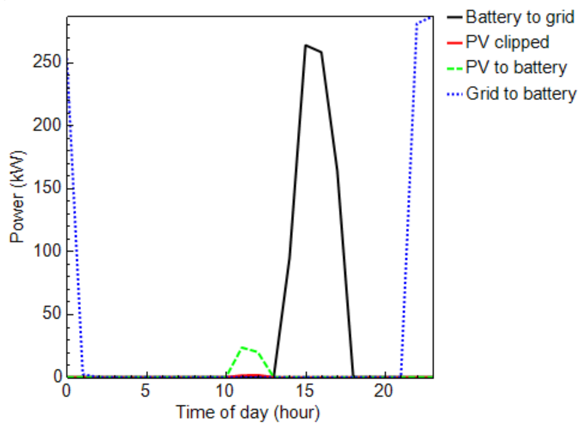
PV and clipping forecast



PPA sell-rate forecast, utility buy-rate

Battery wear costs ($/cycle)

Battery Controller



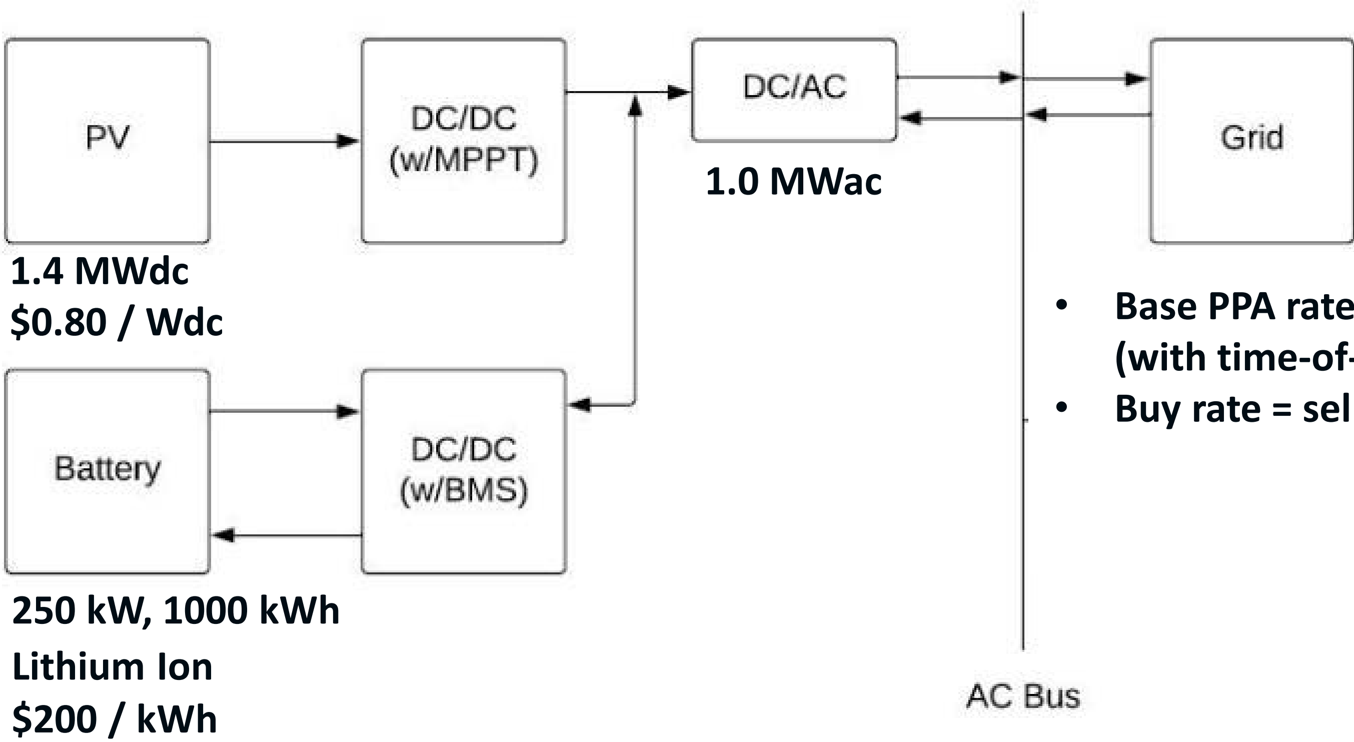
Battery power charge and discharge signal, including whether is from the grid or PV

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

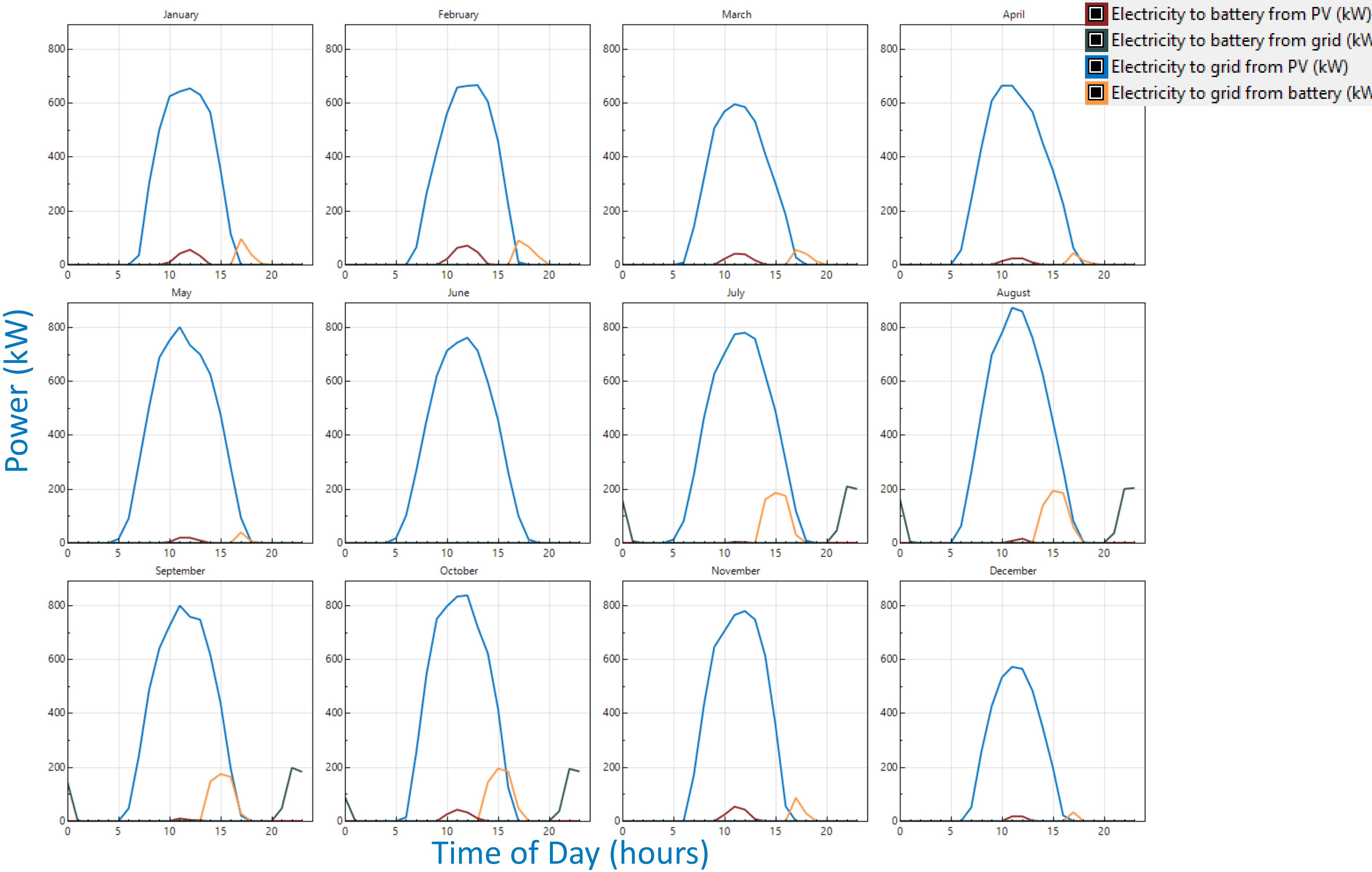
	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4	4	4	4	6	6
Feb	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4	4	4	4	6	6
Mar	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4	4	4	4	6	6
Apr	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	4	4	4	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:

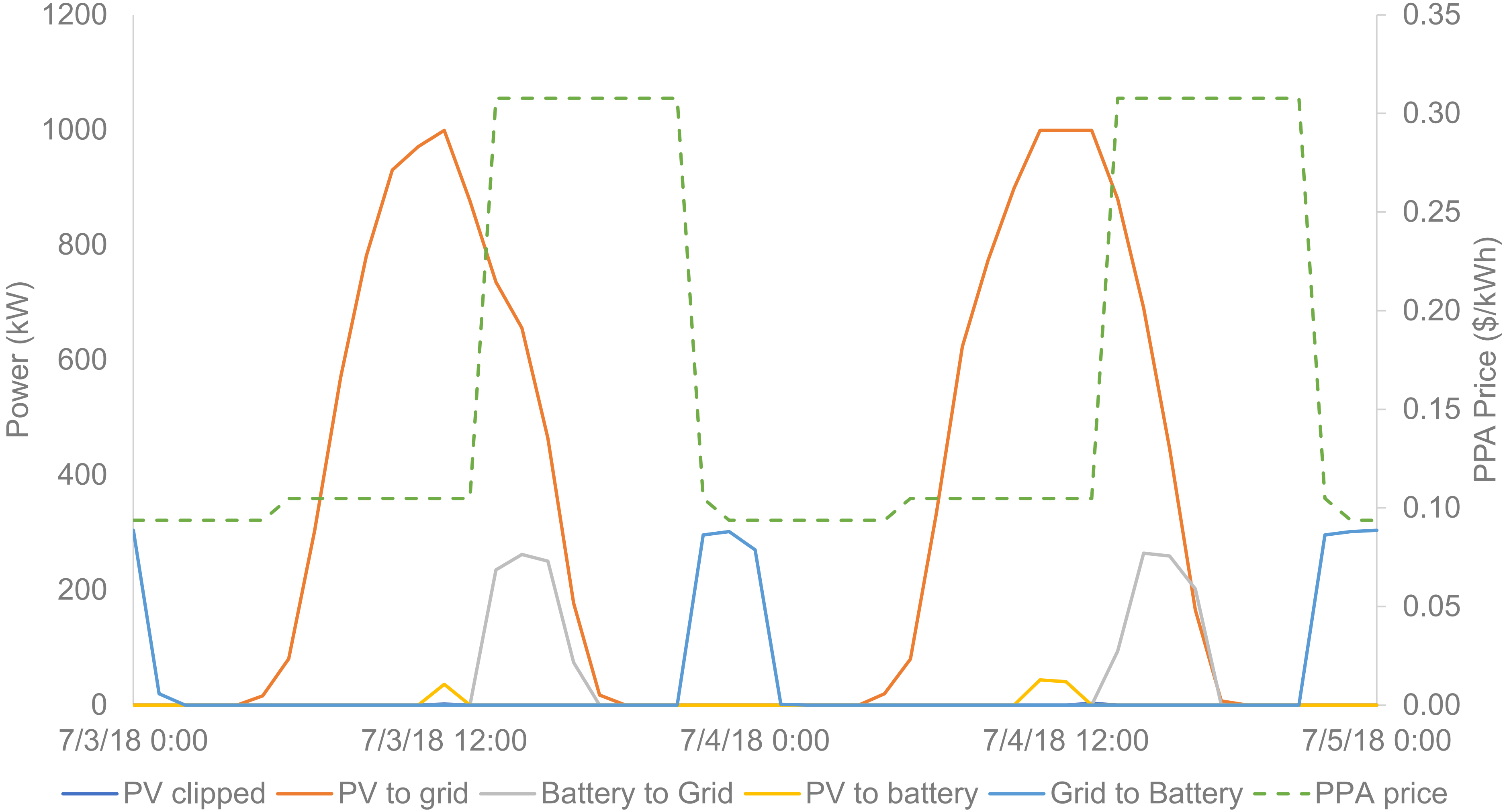
SDG&E 2015 Full Capacity Deliverability Local

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.

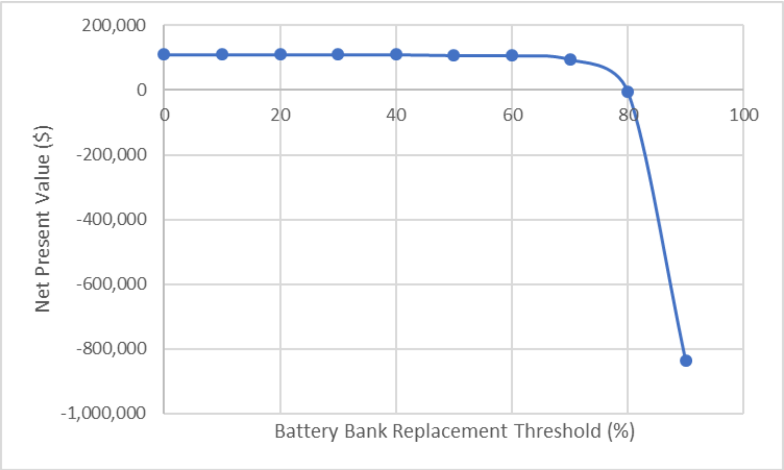
Results Summary

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

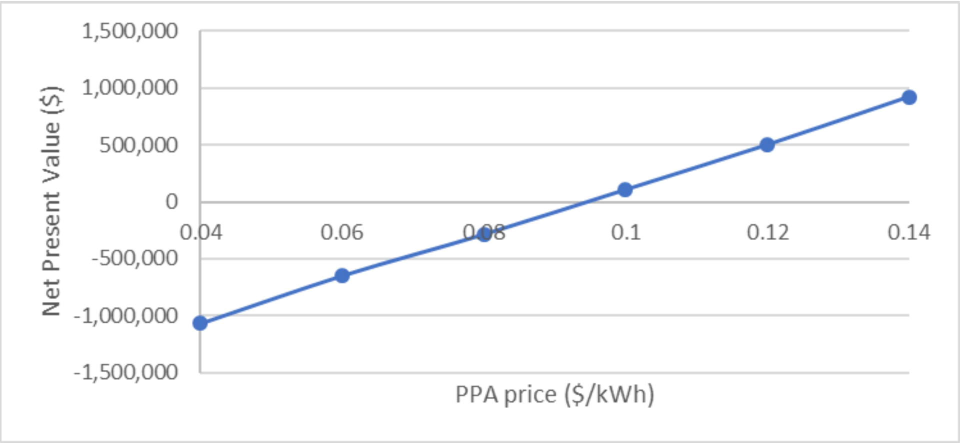
- PV is cost effective, and installing a battery slightly reduces this value
- DC-connected battery reduces clipping by 75%.
- In this case, the battery mostly charges from the grid to take advantage of the difference in buy rate vs. sell rate

Effect of sensitivities on project economics

Battery Bank Replacement Criteria



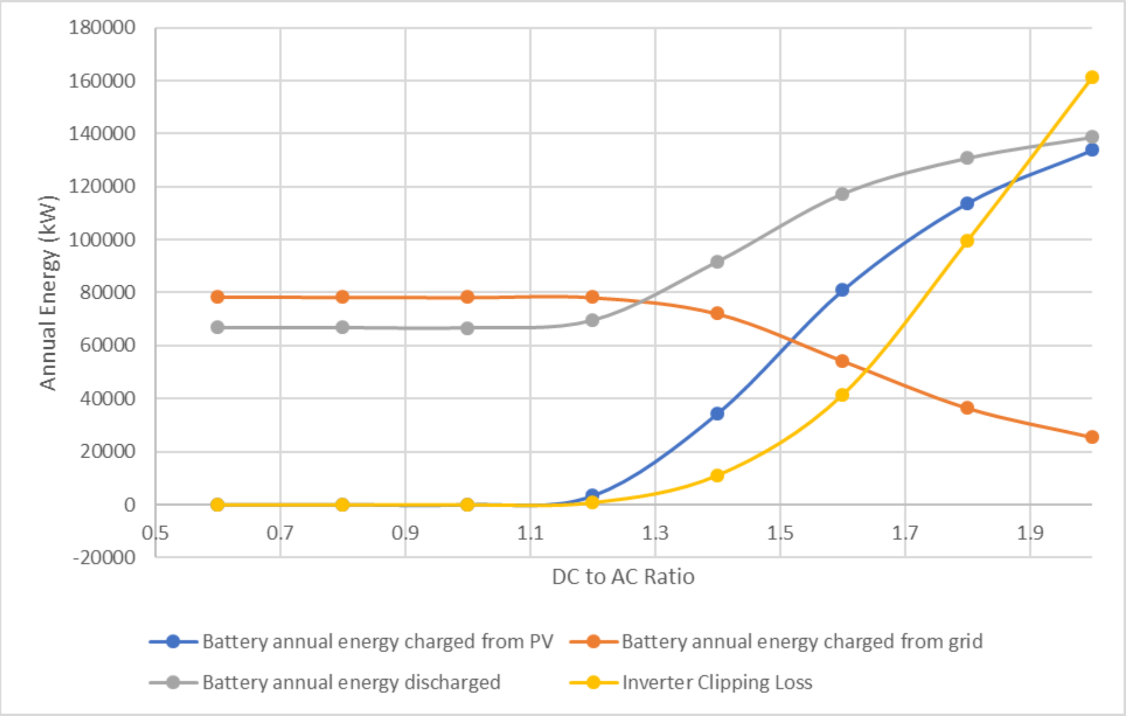
PPA Price



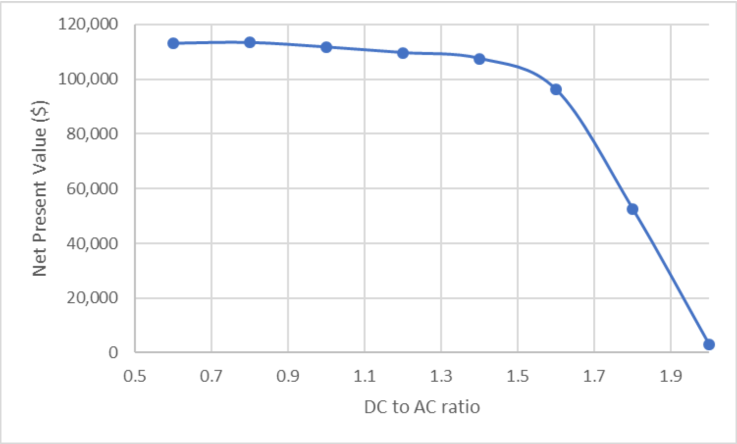
- Choosing when to replace the battery bank plays a large role in the total project economics.
- In this scenario, project economics are maximized when the battery bank is replaced after degrading to 50% or less of its original capacity.

- 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



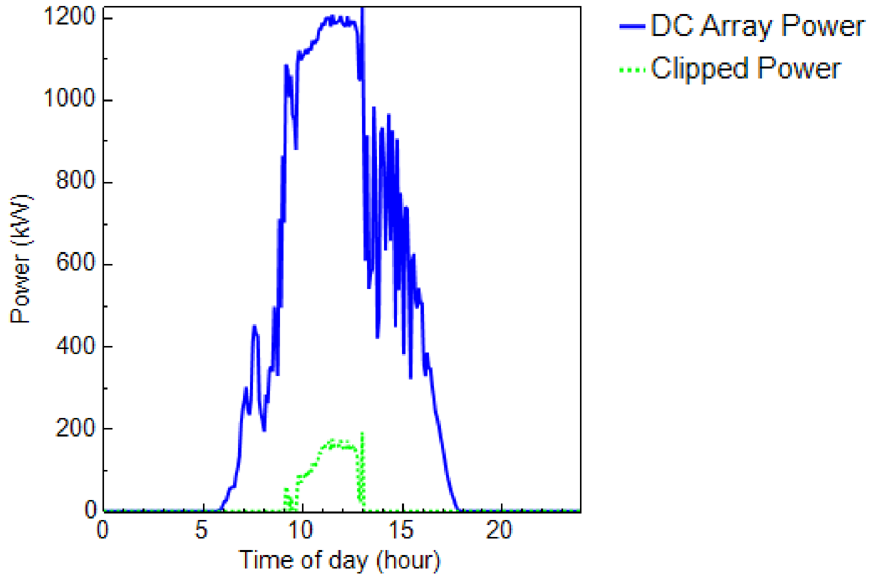
- Battery utilization from PV increases as DC to AC ratio increases
- At high ratios, battery power and capacity limits are overwhelmed and cannot capture all of the clipped power



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

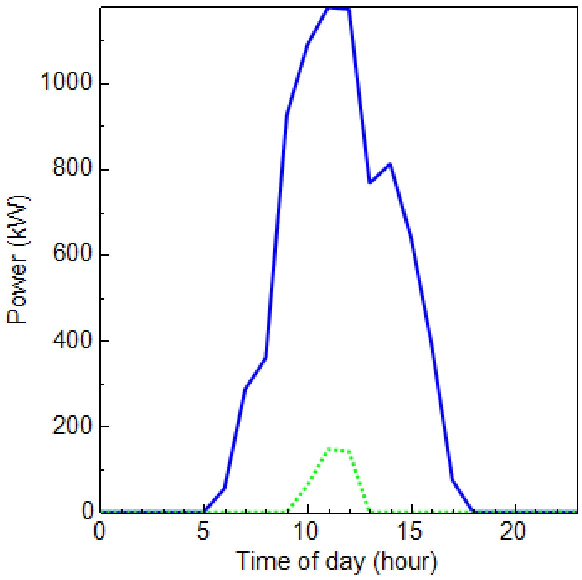
Effect of time step on project economics

5-minute weather data



Annual energy clipped without battery: 61.2 MWh

Hourly weather data

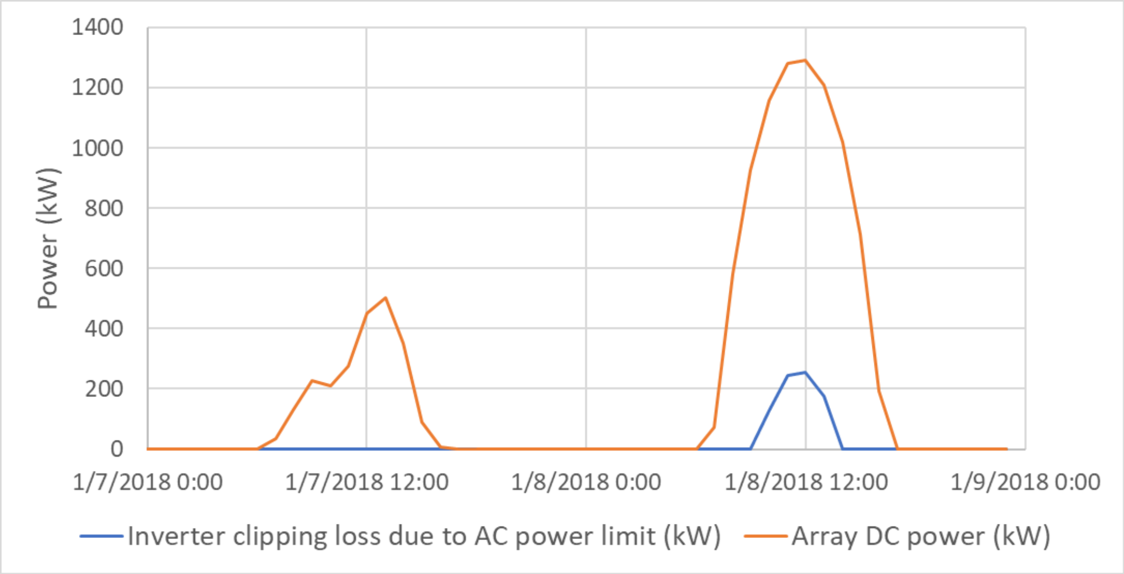


Annual energy clipped without battery: 44.0 MWh

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

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