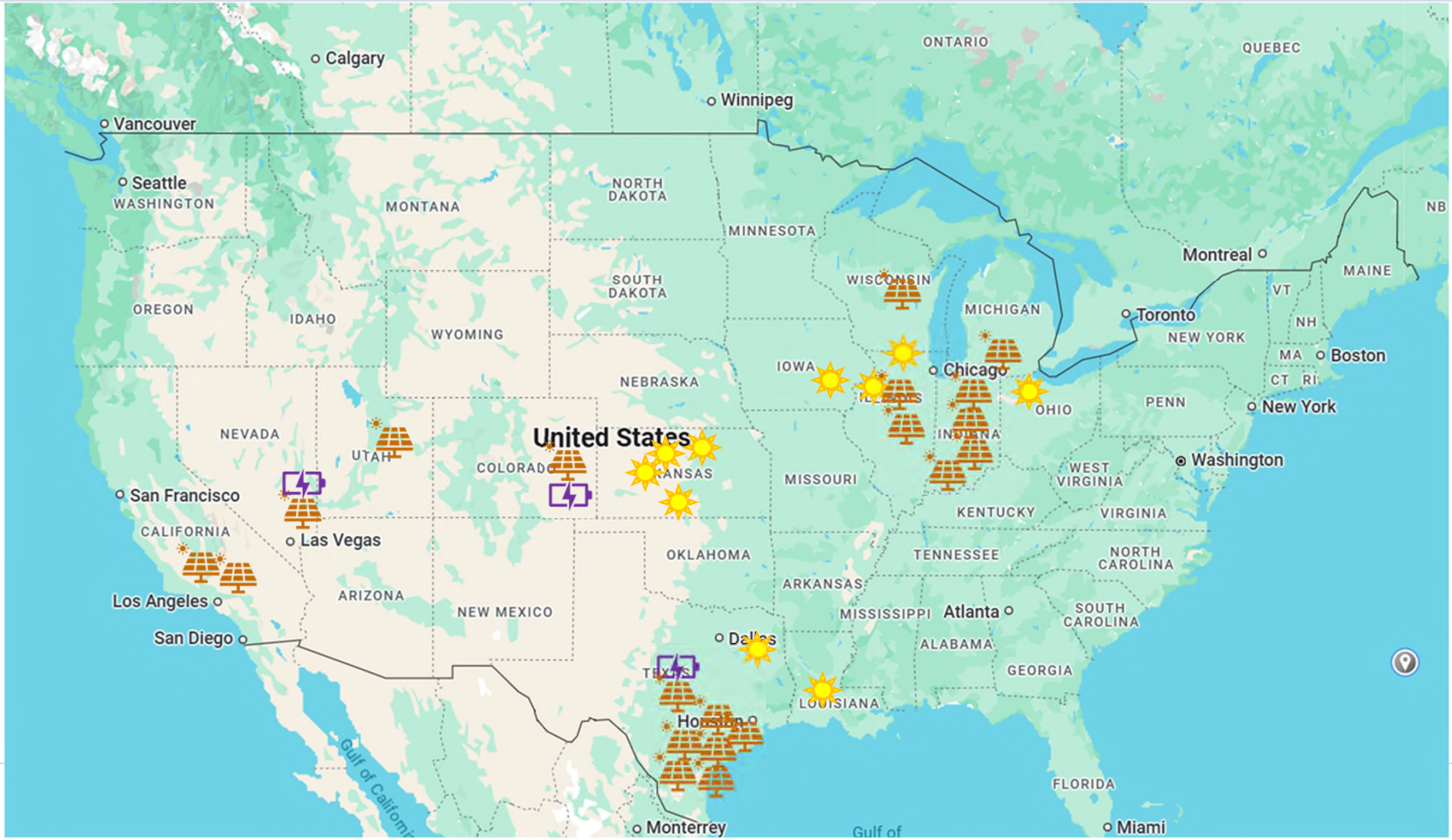
PV + Li-Ion BESS: Modeling & Evaluation of Energy Arbitrage & Ancillary Service Use Cases

Richard Holz, P.E.
Sanjeev Bhatia
Jasper Camacho
Garima Takyar
Mohit Kumar

May 12, 2026

Bechtel US Renewables Projects

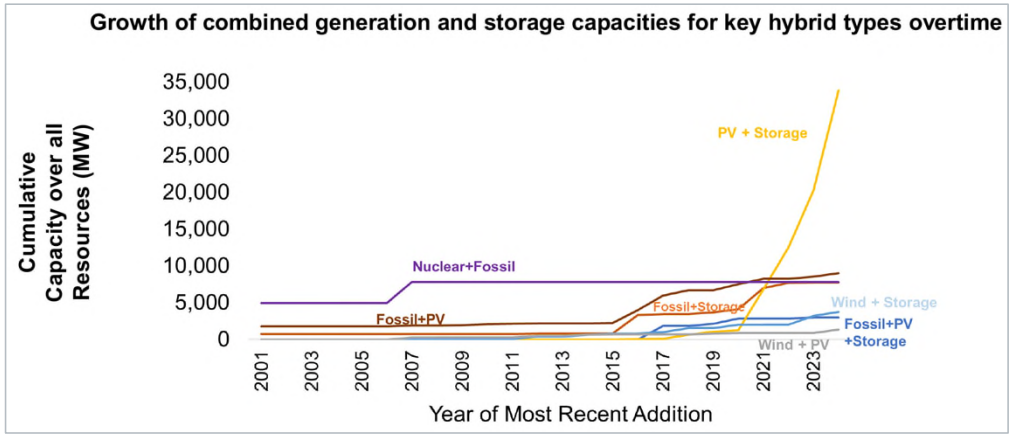
PV System: Early Development
PV System: Installed or In Progress (180-1200 MW at POI)
BESS (Hybrid AC-Coupled)



PV + Storage Hybrids: Where things stood as of 2024-25

According to Berkeley Lab's Oct-2025 Status of Operating and Proposed Hybrid Plants…

- 359 plants in operation (PV = 22.0 GW; Storage = 11.9 GW)
- Top Use Cases:
  - Renewable Firming/Curtailment Mitigation (35%)
  - Arbitrage (30%)
  - Grid Services (22%)
  - Peak Shaving (13%)
- RT efficiency (capacity-weighted) was 85% in 2023
- PV+BESS is dominant hybrid type in interconnection queues
  - PV+BESS has 2,178 plants in queue (20.7% overall)
  - PV+BESS has 432,223 MW in queue (23.1% overall)



Sources: EIA 860 2024 Early Release, Berkeley Lab

- Hybrids comprise 47% of active solar capacity in interconnection queues
- Solar hybridization is highest in CAISO (93%), lowest in MISO (22%), and about 48% in ERCOT
- There are about 82 GW of PV+BESS with an Interconnection Agreement drafted or executed in queues
- There's another 273 GW of PV+BESS at some other stage in the queues

Bechtel Level 3 – General. Non-Confidential Business Information.

PV + Storage Hybrids: Critical Questions

AI Generated

1. What's the best way to **configure** these plants?
2. How should these plants be **dispatched**?
3. Which **off-take/revenue structures** make the most sense?
4. What combinations of **CAPEX, OPEX, tax incentives, and PPA prices** will support financial success, now and in the future?
5. Which **energy, capacity, and ancillary services** should these plants address?

Bechtel Level 3 – General. Non-Confidential Business Information.

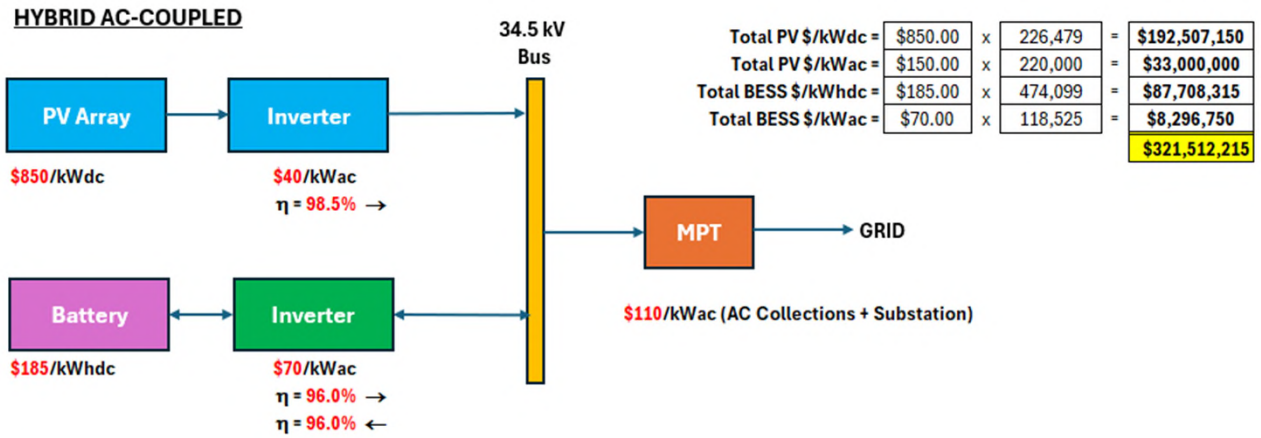
SAM Simulation Run Log

Base Case: AC-Coupled Hybrid, 18.5% Overbuild, 4-hr Battery, Variable PPA Price based on Cambium, Auto Dispatch

5 Groups: (1) Configuration, (2) Overbuild/Battery Life, (3) Dispatch, (4) Revenue Structure, (5) Forecasting Method

Case	Description	IRR Result	AC/DC Coupled	Co-Located	Ovrbld Ratio	Battery Capacity	Hybrid PPA	Fixed PPA	Variable PPA	Avg Price	Tolling $/kW-yr	Grid Charging	Battery Dispatch	Look Ahead
1.1	AC Coupled (Base Case)	14.82%	AC	n/a	1.185	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
1.2A	PV Standalone	4.70%	AC	Yes	1.185	4 hrs	n/a	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
1.2B	BESS Standalone	30.94%	AC	Yes	1.185	4 hrs	n/a	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
1.2	AC Co-Located	13.65%	AC	Yes	1.185	4 hrs	n/a	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
1.3	DC Coupled (Low Cost)	15.92%	DC	n/a	1.185	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
1.4	DC Coupled (High Cost)	14.73%	DC	n/a	1.185	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
2.2	AC Coupled	12.04%	AC	n/a	1.063	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
2.3	AC Coupled	13.63%	AC	n/a	1.125	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
2.4	AC Coupled	15.62%	AC	n/a	1.250	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
2.5	AC Coupled	16.73%	AC	n/a	1.333	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
3.2	AC Coupled	7.38%	AC	n/a	1.185	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	S-1	24 hr/p
3.3	AC Coupled	9.40%	AC	n/a	1.185	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	No	S-2	24 hr/p
3.4	AC Coupled	17.42%	AC	n/a	1.185	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	S-3	24 hr/p
3.5	AC Coupled	14.96%	AC	n/a	1.185	4 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	S-5	24 hr/p
4.2	AC Coupled	4.68%	AC	n/a	1.185	4 hrs	n/a	n/a	Yes/C-2	$41.08	$144	No	No	24 hr/p
4.3	AC Coupled	11.89%	AC	n/a	1.185	4 hrs	n/a	Yes	n/a	$40.00	$144	No	No	24 hr/p
4.4	AC Coupled	14.08%	AC	n/a	1.185	4 hrs	n/a	Yes	n/a	$45.00	$144	No	No	24 hr/p
4.5	AC Coupled	13.12%	AC	n/a	1.185	4 hrs	Yes	Yes/P-2	n/a	$75.00	n/a	Yes	S-3	24 hr/p
4.6	AC Coupled	13.41%	AC	n/a	1.185	4 hrs	Yes	Yes/P-2	n/a	$75.00	n/a	Yes	S-5	24 hr/p
5.2	AC Coupled	15.89%	AC	n/a	1.185	3 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p
5.3	AC Coupled	13.81%	AC	n/a	1.185	2 hrs	Yes	n/a	Yes/C-1	$74.11	n/a	Yes	Auto	24 hr/p

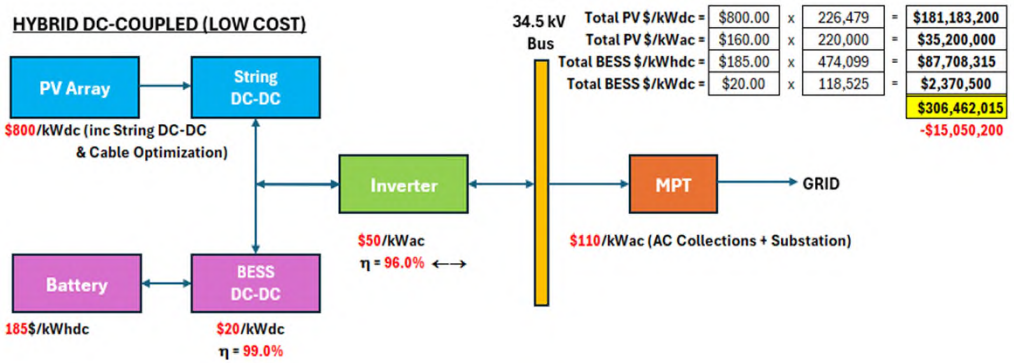
Base Case – Configuration & Common Parameters

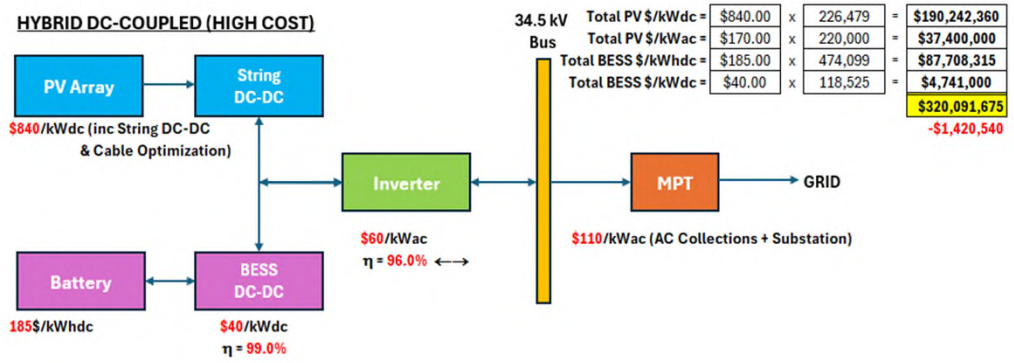


Common Assumptions:

- ✓ Grid connection limit: 185 MWac
- ✓ BESS State of Charge: 10-100%; 60% Initially; 10 min at SOC
- ✓ No cycle degradation penalty
- ✓ O&M Costs: PV = $19/kWdc-yr; BESS = $1.2M/yr
- ✓ Annual land lease cost: $1000/acre; 2%/yr escalation
- ✓ Analysis period: 20 years
- ✓ Nominal discount rate: 9.14% (2% inflation; 7% real discount)
- ✓ Federal/state income tax rates: 21% / 7%
- ✓ Insurance rate: 0.5% of installed cost per year
- ✓ Sales tax rate: 5% of total direct cost
- ✓ Net Salvage Value: Adjusted based on 10% of installed cost
- ✓ Debt amount: 40% of total installed cost (DSCR = 1.3)
- ✓ Debt tenor: 17 years
- ✓ Debt interest rate: 5.5%
- ✓ Up-front fee on debt service: 0.5%
- ✓ Construction Load Period: 12 months
- ✓ Construction Load Interest Rate: 5.5%
- ✓ Interest rate on reserves: 1.75%/year
- ✓ Working capital and debt service reserves: 6 months
- ✓ Depreciation: 5-yr MACRS with 50% bonus federal & state

Group 1: DC-Coupled & Co-Located Configurations





Hybrid DC-Coupled (Low Cost):

- Significant cost reduction due to using string DC-DC converters which allow cable size optimization
- Bi-directional inverter at low-end of cost range
- BESS DC-DC converter at low-end of cost range

Hybrid DC-Coupled (High Cost):

- Each cost at high-end of cost range

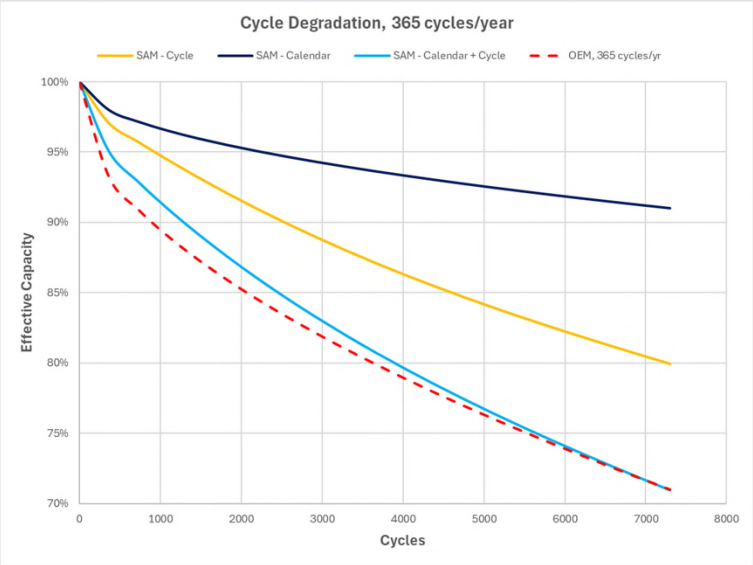
Co-Located:

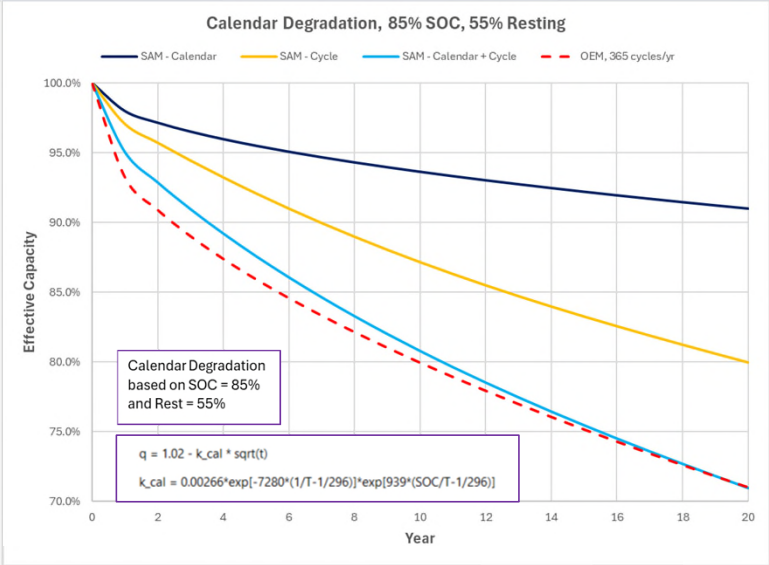
Feature	Hybrid (Integrated)	Co-Located (Separate)
Resource Identity	Single combined resource	Two separate resources
Market Bidding	One bid curve	Separate bid curves
Dispatch	One dispatch instruction from ISO	Separate instructions per component
Metering	Single net meter at POI	Separate meters per component
Pricing	Single combined price	Separate pricing possible
Capacity Credit	Assessed as one resource	Assessed individually
Operator Control	Developer self-optimizes internally	ISO dispatches each independently
Current Dominance	Growing; preferred for new projects	Larger existing fleet by MW

Group 1: Results

	Case 1.1: Hybrid AC-Coupled	Case 1.2A PV Stand-alone	Case 1.2B BESS Stand-alone	Case 1.2 (sum) Co-Located AC	Case 1.3 Hybrid DC-Coupled (Low Cost)	Case 1.4 Hybrid DC-Coupled (High Cost)
After-tax cumulative IRR in Year 20 | (%)	14.82 %	4.70 %	30.94 %	13.65 %	15.92 %	14.73 %
After-tax cumulative NPV in Year 20 | ($)	$39,180,600	-$19,324,100	$50,663,700	$31,339,600	$46,700,000	$39,400,000
Federal ITC Income | ($)	$110,175,000	$80,051,300	$30,510,700	$110,562,000	$105,000,000	$109,000,000
Lifetime Total Revenue | ($)	$966,238,800	$515,941,500	$455,075,300	$971,016,800	$903,600,000	$904,900,000
Lifetime PPA Revenue | ($)	$932,163,600	$491,183,100	$445,638,900	$936,822,000	$871,300,000	$871,300,000
Lifetime Salvage Revenue | ($)	$34,075,200	$24,758,400	$9,436,400	$34,194,800	$32,300,000	$33,600,000
Lifetime Total Operating Expense | ($)	$384,522,200	$232,008,170	$173,856,520	$405,864,690	$314,500,000	$318,900,000
Lifetime Battery Replacement Cost | ($)	$61,840,200	$0	$61,840,200	$61,840,200	$40,300,000	$40,300,000
Lifetime Electricity Purchase | ($)	$24,737,040	$1,062,668	$44,615,840	$45,678,508	$5,659,103	$5,659,103
Lifetime O&M Expense | ($)	$163,871,751	$128,138,083	$35,733,642	$163,871,725	$140,168,458	$140,108,458
BESS annual energy charged | (MWh)	2,152,611	0	2,129,691	2,129,691	1,794,000	1,794,000
BESS annual energy charged from PV | (MWh)	614,277	0	0	0	1,654,085	1,654,085
BESS Energy Discharged DC | (MWh)	1,962,711	0	1,936,363	1,936,363	1,712,869	1,712,869
BESS Average Daily DOD | (%) ~~& Capacity at EOL | (%)~~	56.7%	0.0%	56.0%	56.0%	49.5%	49.5%
Annual energy exported to GRID | (MWh)	11,985,107	10,670,816	1,858,906	12,529,721	10,768,000	10,768,000
Annual energy exported to GRID from PV | (MWh)	10,102,922	10,670,816	0	10,670,816	9,119,073	9,119,073
Annual energy exported to GRID from BESS | (MWh)	1,884,203	0	1,858,909	1,858,909	1,648,823	1,648,823
Annual energy imported from GRID to PV at Night | (MWh)	4,529	4,529	0	4,529	3,702	3,702
Annual energy imported from GRID to BESS | (MWh)	1,538,334	0	2,129,691	2,129,691	139,888	139,888

Group 2: Overbuild & Battery Life



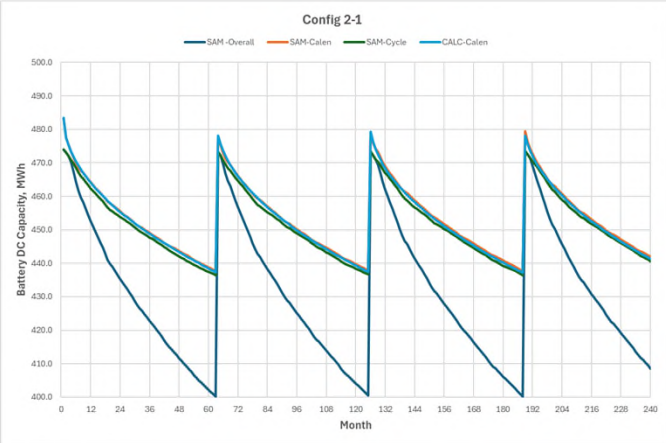


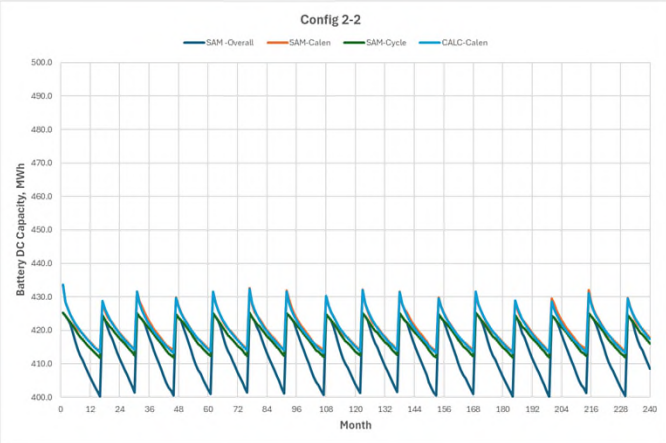
<u>Overbuild 6-Step Process in SAM</u>:

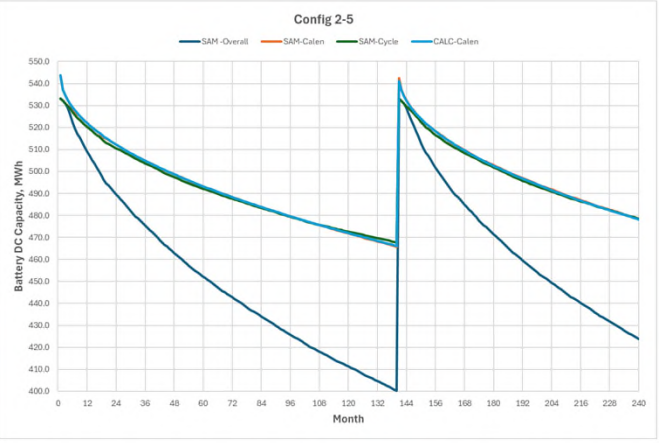
1. On Cell & System sheet, adjust number of strings = N_0 * F_{OB}
2. On Life sheet, set Replacement Threshold = $^{1}/_{F_{OB}}$
3. On Operation Costs sheet, set Replacement Cost = \$185/kWhdc * (1 - $^{1}/_{F_{OB}}$)
4. Run SAM and note the EOL capacity in the Lifetime Hourly Data
5. On Financial Parameters sheet, set the Net Salvage Value = 10% * $(\frac{2.35+EOL\ Cap}{3.35})$
6. Run SAM again and record final results

Group 2: Results

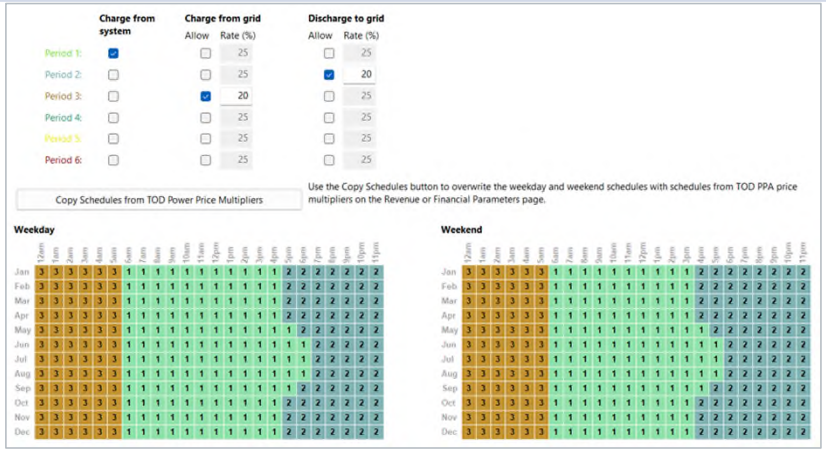
	Case 2.1 OB = 1.185 / 4 hr	Case 2.2 OB = 1.063 / 4 hr	Case 2.3 OB = 1.125 / 4 hr	Case 2.4 OB = 1.250 / 4 hr	Case 2.5 OB = 1.333 / 4 hr
After-tax cumulative IRR in Year 20 | (%)	14.82 %	12.04 %	13.63 %	15.62 %	16.73 %
After-tax cumulative NPV in Year 20 | ($)	$39,180,600	$18,689,200	$29,686,500	$45,418,600	$55,396,900
Lifetime Total Revenue | ($)	$966,238,800	$928,137,000	$948,465,800	$986,379,500	$1,011,216,300
Lifetime Total Operating Expense | ($)	$384,522,200	$421,890,300	$406,043,400	$382,683,200	$366,616,500
Lifetime Battery Replacement Cost | ($)	$61,840,200	$104,522,120	$85,517,000	$57,660,300	$37,963,100
Lifetime Electricity Purchase | ($)	$24,737,040	$22,646,600	$24,165,140	$25,371,230	$26,811,710
BESS annual energy charged | (MWh)	2,152,611	2,021,295	2,088,843	2,231,425	2,322,056
BESS Energy Discharged DC | (MWh)	1,962,711	1,842,478	1,904,657	2,033,436	2,113,469
BESS Average Daily DOD | (%)	57%	53%	55%	59%	61%
Annual energy exported to GRID | (MWh)	11,985,107	11,893,518	11,940,912	12,038,466	12,100,720

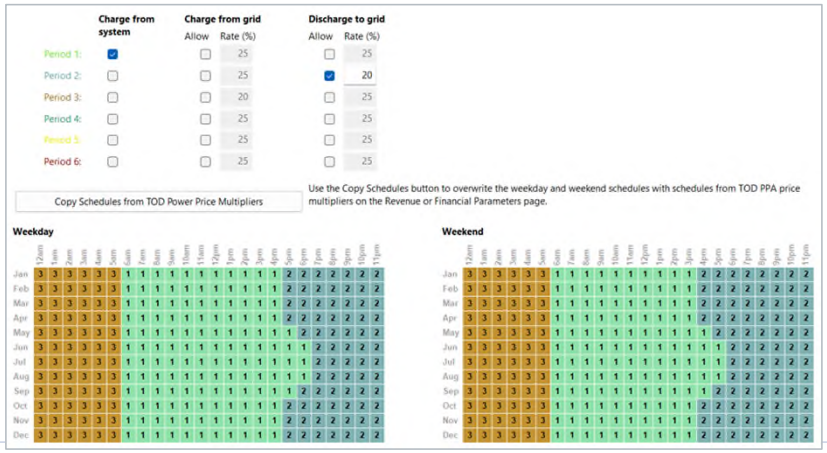


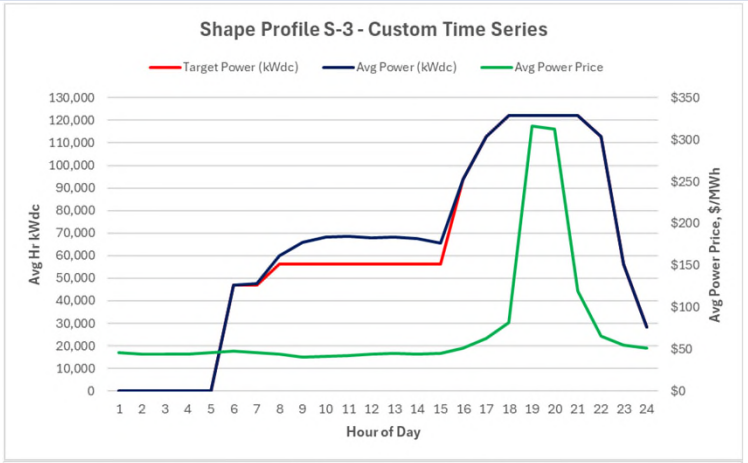


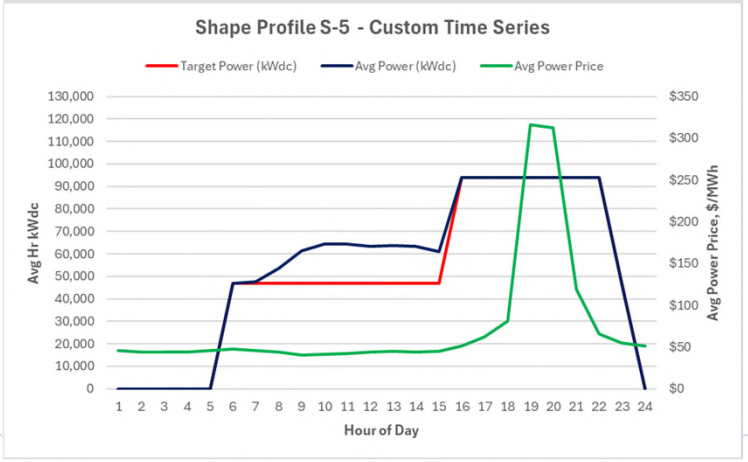


Group 3: Dispatch Strategy

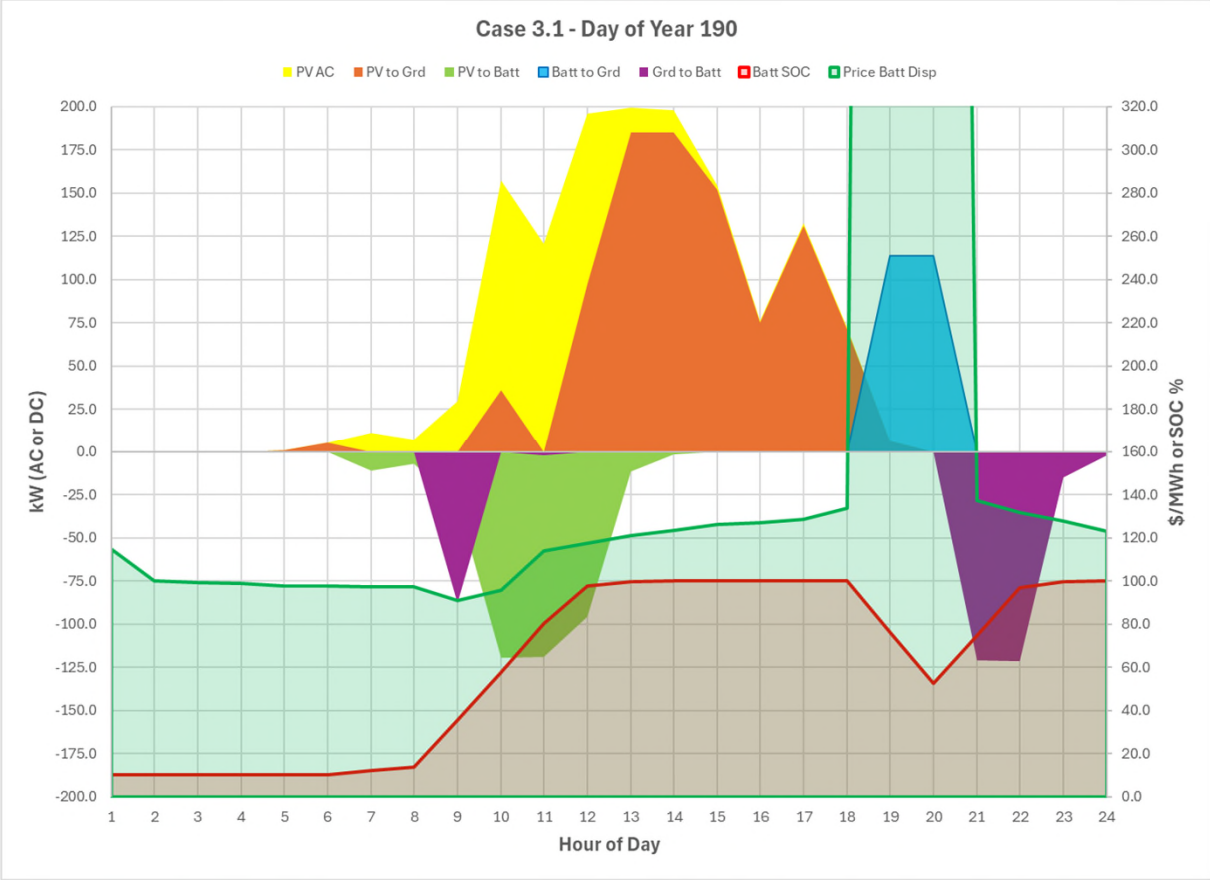




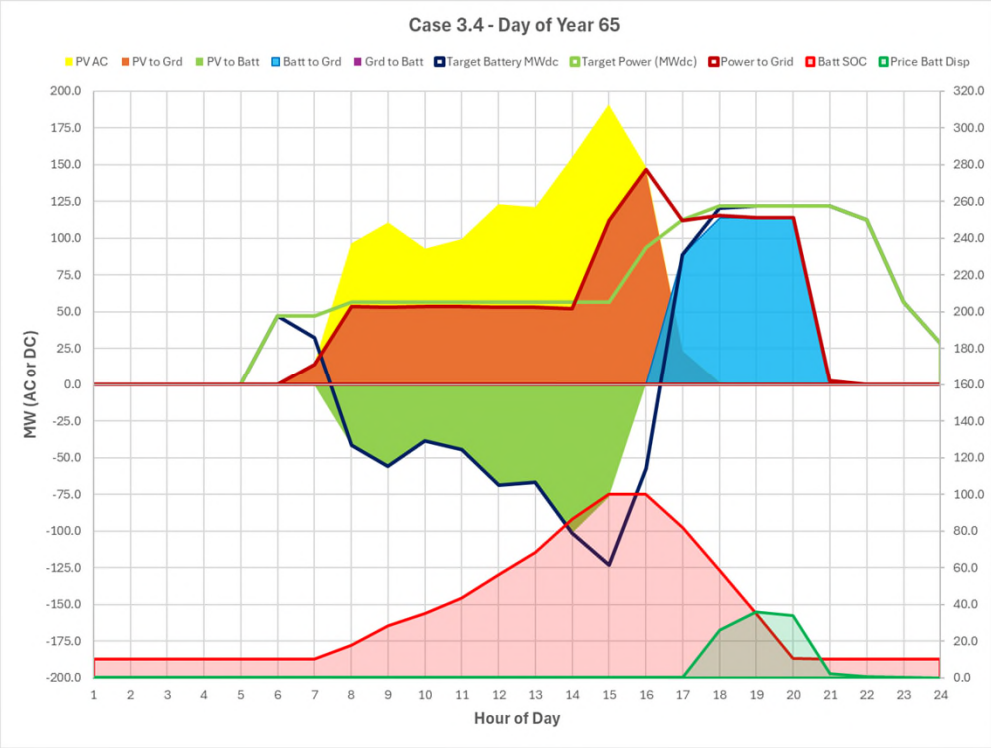


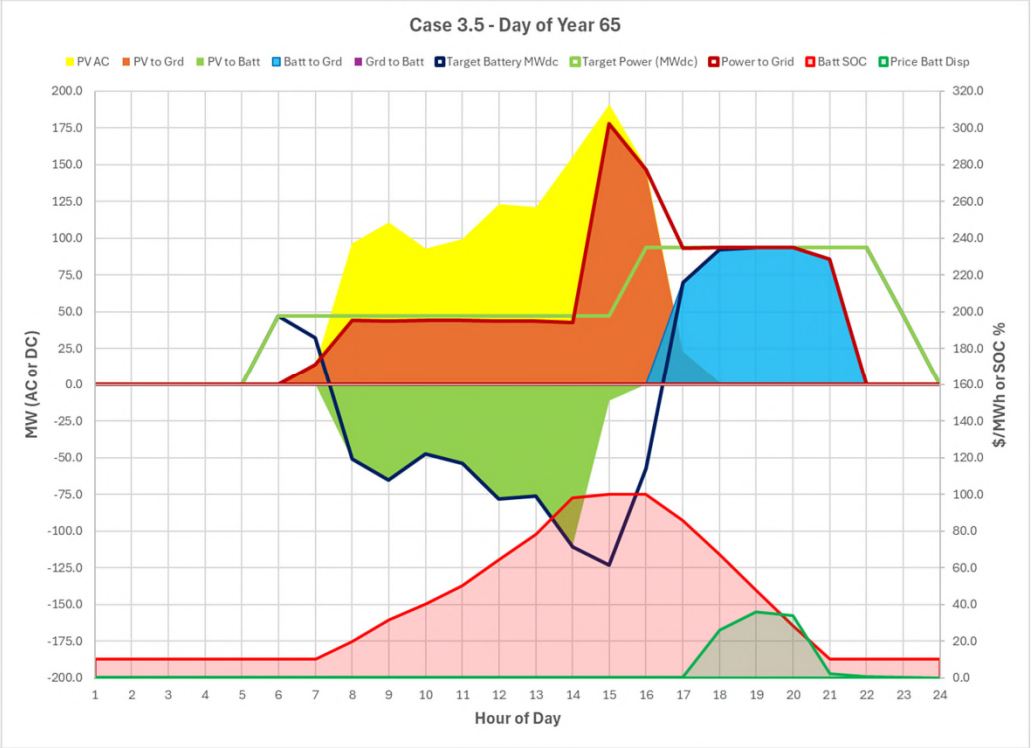


Group 3: Base Case (Auto Dispatch)



Group 3: Results (Custom Time Series S-3 and S-5)





Group 3: Results

	Case 3.1 SAM Auto Dispatch	Case 3.2 Manual Dispatch S-1	Case 3.3 Manual Dispatch S-2	Case 3.4 Custom Series S-3	Case 3.5 Custom Series S-5
After-tax cumulative IRR in Year 20 | (%)	14.82 %	7.38 %	9.40 %	17.42 %	14.96 %
After-tax cumulative NPV in Year 20 | ($)	$39,180,600	-$11,082,800	$1,644,560	$59,174,300	$39,827,200
Lifetime Total Revenue | ($)	$966,238,800	$968,087,600	$832,124,900	$1,000,489,600	$942,665,300
Lifetime Total Operating Expense | ($)	$384,522,200	$529,506,100	$360,175,900	$365,728,400	$365,651,300
Lifetime Battery Replacement Cost | ($)	$61,840,200	$82,664,300	$61,840,200	$67,261,800	$67,261,800
Lifetime Electricity Purchase | ($)	$24,737,040	$148,897,220	$391,161	$522,007	$444,712
BESS annual energy charged | (MWh)	2,152,611	3,308,486	3,249,895	3,080,600	3,115,672
BESS annual energy charged from PV | (MWh)	614,277	71	3,249,893	3,080,254	3,115,328
BESS annual energy charged from GRID | (MWh)	1,538,334	3,308,413	0	345	345
BESS Energy Discharged DC | (MWh)	1,962,711	3,034,668	2,970,926	2,811,321	2,854,166
BESS Average Daily DOD | (%) & ~~Capacity at EOL | (%)~~	57%	88%	86%	81%	82%
Annual energy exported to GRID | (MWh)	11,985,107	13,574,275	10,321,871	10,343,056	10,347,880
Annual energy exported to GRID from PV | (MWh)	10,102,922	10,670,744	7,474,357	7,646,934	7,611,513
Annual energy exported to GRID from BESS | (MWh)	1,884,203	2,913,280	2,852,088	2,698,868	2,739,999
Annual energy imported from GRID | (MWh)	1,548,480	3,310,832	7,589	9,764	8,877

Group 4: Revenue Structure

Bundled Hybrid PPA

Structure: A single contract covering both solar and storage with one combined $/MWh price for all energy delivered, regardless of whether it originates from the solar panels or the battery. The storage premium is embedded in a higher overall rate compared to solar-only PPAs.

Dispatch Control: Developer retains operational control of both technologies and optimizes internally to meet delivery obligations.

Typical Terms: 15–25 year terms. Most common in corporate PPAs and CCA procurement.

Tolling Agreement

Structure: The battery is treated as a separate asset. The off-taker pays a fixed monthly capacity payment ($/kW-month) for the right to dispatch the battery, plus variable O&M per MWh of throughput. The utility decides when to charge and discharge, bears charging costs, and captures arbitrage value. Solar may be contracted separately.

Dispatch Control: Off-taker/utility has full dispatch control of the battery.

Typical Terms: 20-year terms for utility procurement. Capacity payments typically $7.70–$11.70/kW-month.

Shaped Delivery PPA

Structure: The developer commits to delivering a specified MW quantity during defined hours (e.g., 6am–10pm, or peak hours only). How the developer achieves this—through direct solar generation, battery discharge, or a combination—is entirely their decision. The off-taker purchases a shaped energy product.

Dispatch Control: Developer retains full control; must meet contractual delivery shape.

Typical Terms: 12–20 year terms. Growing rapidly as off-takers demand firm, shaped clean energy.

Group 4: Results

	Case 4.1 Var. Price C-1 ($74) No Tolling	Case 4.2 Var. Price C-2 ($41) Tolling	Case 4.3 Fixed Price ($40) Tolling	Case 4.4 Fixed Price ($45) Tolling	Case 4.5 Shaped PPA ($75) No Tolling	Case 4.6 Shaped PPA ($75) No Tolling
After-tax cumulative IRR in Year 20 | (%)	14.82 %	4.68 %	11.89 %	14.08 %	13.12 %	13.41 %
After-tax cumulative NPV in Year 20 | ($)	$39,180,600	-$30,756,400	$20,936,400	$38,774,600	$25,970,900	$28,086,300
Lifetime Total Revenue | ($)	$966,238,800	$703,564,200	$857,965,500	$911,319,900	$899,362,400	$905,805,700
Lifetime PPA Revenue | ($)	$932,163,600	$272,430,900	$426,832,700	$480,186,700	$864,362,400	$870,947,900
Lifetime Capacity Payment Revenue | ($)	$0	$396,204,100	$396,204,100	$396,204,100	$0	$0
Lifetime Total Operating Expense | ($)	$384,522,200	$298,483,000	$298,431,200	$298,492,200	$365,818,700	$365,678,900
Lifetime Battery Replacement Cost | ($)	$61,840,200	$0	$0	$0	$67,261,800	$67,261,800
Lifetime Electricity Purchase | ($)	$24,737,040	$538,272	$486,592	$547,416	$611,941	$472,228
BESS annual energy charged from PV | (MWh)	614,277	0	0	0	3,080,254	3,115,328
BESS annual energy charged from GRID | (MWh)	1,538,334	0	0	0	345	345
BESS Average Daily DOD | (%) & Capacity at EOL | (%)	57%	0%	0%	0%	81%	82%
Annual energy exported to GRID from PV | (MWh)	10,102,922	10,670,816	10,670,816	10,670,816	7,646,934	7,611,513
Annual energy exported to GRID from BESS | (MWh)	1,884,203	0	0	0	2,698,868	2,739,999
Annual energy imported from GRID to BESS | (MWh)	1,538,334	0	0	0	345	345
Electricity generated without storage | (MWh)	10,850,623	10,850,623	10,850,623	10,850,623	10,850,623	10,850,623
TOD Factor Maximum | & Ratio Max/Avg	8.294	5.023	1.000	1.000	0.210	0.210

Bechtel Level 3 – General. Non-Confidential Business Information.

Group 5: Battery Capacity (Hours)

	Case 5.1 4 hr Battery	Case 5.2 3 hr Battery	Case 5.3 2 hr Battery
After-tax cumulative IRR in Year 20 | (%)	14.82 %	15.89 %	13.81 %
After-tax cumulative NPV in Year 20 | ($)	$39,180,600	$44,477,100	$27,565,600
Federal ITC Income | ($)	$110,175,000	$103,295,000	$96,415,100
Lifetime Total Revenue | ($)	$966,238,800	$922,419,300	$810,090,100
Lifetime Total Operating Expense | ($)	$384,522,200	$354,439,300	$323,240,000
Lifetime Battery Replacement Cost | ($)	$61,840,200	$46,380,200	$30,920,100
Lifetime Electricity Purchase | ($)	$24,737,040	$17,255,631	$8,656,975
BESS annual energy charged | (MWh)	2,152,611	1,594,970	1,004,962
BESS annual energy charged from PV | (MWh)	614,277	443,105	305,002
BESS annual energy charged from GRID | (MWh)	1,538,334	1,151,865	699,960
BESS Energy Discharged DC | (MWh)	1,962,711	1,432,679	877,014
BESS Average Daily DOD | (%) & Capacity at EOL | (%)	57%	55%	51%
Annual energy exported to GRID | (MWh)	11,985,107	11,641,935	11,238,702
Annual energy exported to GRID from PV | (MWh)	10,102,922	10,268,120	10,397,787
Annual energy exported to GRID from BESS | (MWh)	1,884,203	1,375,372	841,933
Annual energy imported from GRID | (MWh)	1,548,480	1,162,474	711,109

Conclusions

- The System Advisor Model™ (SAM™) has provided consistent and reasonable results which suit it well for the purpose of making comparative analyses of PV + BESS systems.
- These simulations have shown that DC-Coupled hybrid systems can be competitive with AC-Coupled hybrid systems however more vetting of the pricing assumptions for DC-Coupled systems is needed.
- SAM™ battery life models appear to be consistent with battery life data received from BESS suppliers.
- High overbuild ratios had the highest IRRs due to the shape of the battery life curves however there are practical limits as to how much overbuild customers may be willing to purchase.
- A technique was developed to create reasonable custom time series for battery dispatch in SAM™.
- Techniques were developed to simulate tolling agreements and shaped PPAs in SAM™.