NATIONAL RENEWABLE ENERGY LABORATORY





Why Combining Solar and Storage May Actually Make Sense

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UVIG Fall Technical Workshop, October 11, 2017

Based on NREL PR-6A20-69061

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

What I Used to Think….

Truly combining PV and storage is a bad idea.

Combining both resources on the DC side of the inverter means you cannot optimize the operation of the storage system substantially reducing value

And charging only with PV is a truly horrible idea because you never want to charge with a single resource. (Repeat the generic line about “firming your toaster”)

I was wrong.

Study Goals

1. Explore the physical configuration of PV plus storage systems and examine the basic technical parameters including the type and degree of PV/storage "coupling"

2. Identify key metrics useful for evaluating the technical and economic performance of PV plus storage systems

3. Examine the tradeoffs among various PV plus storage configurations and quantify the impact of configuration on system net value

Overview of Configurations Evaluated

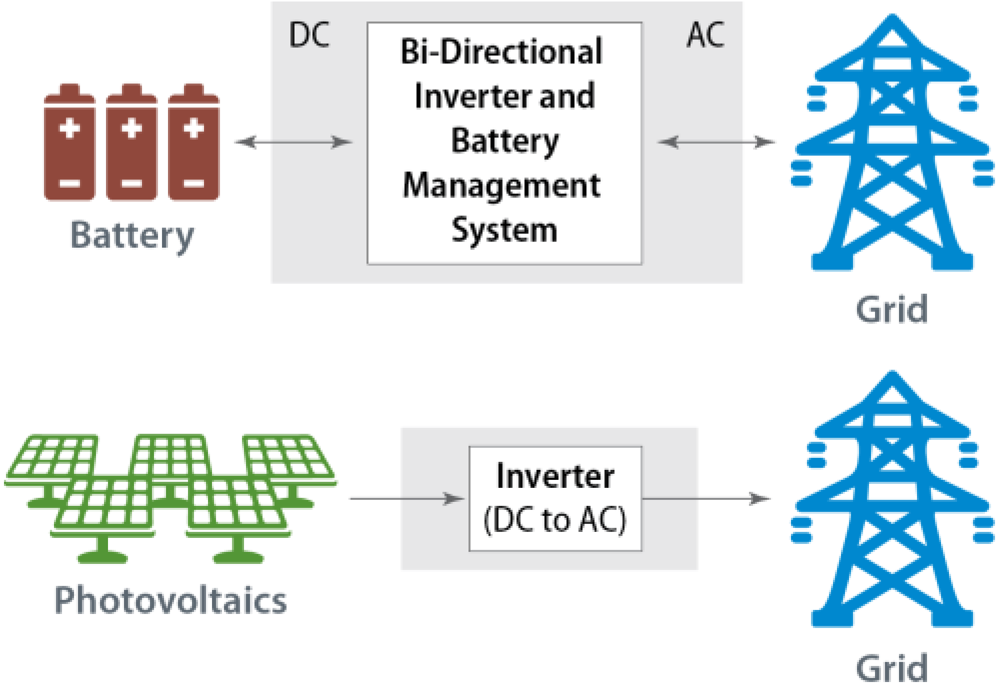
Type of Coupling[a]	Co-Located?	Point of Common Coupling	Energy Stored
Independent	No	None	Grid (including PV virtually through market)[b]
AC-Coupled	Yes	Transmission/Feeder	Grid or PV
DC-Coupled	Yes	Inverter	Grid or PV
DC Tightly Coupled	Yes	Inverter	Only PV

[a] AC = alternating current, DC = direct current.

[b] Although grid-connected storage is typically charged from unspecified off-peak resources, it can "virtually" store energy from a specific source via bilateral market transactions.

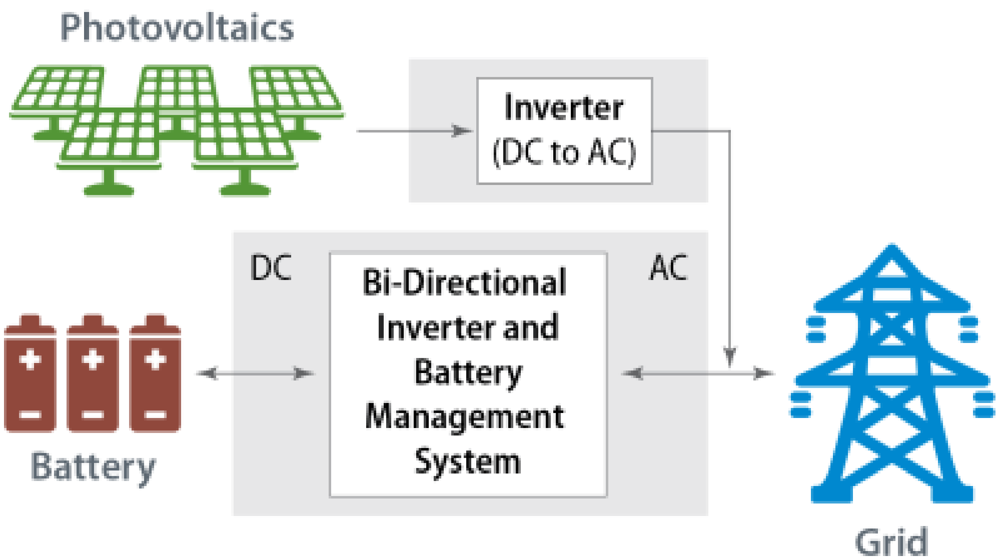
Independent PV Plus Storage

- PV and storage can be sited in completely different locations
- Storage can be sited in areas of congestion, increasing value
- No sharing of hardware
- Stores energy from any grid source



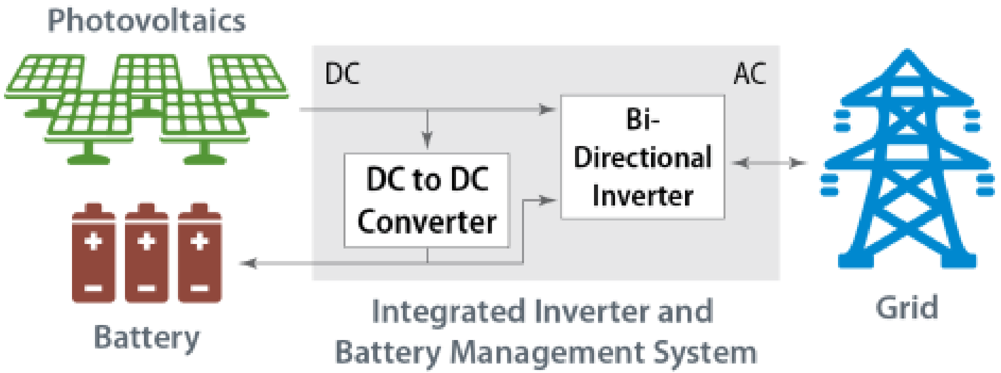
AC-Coupled

- Co-location can reduce balance of system (BOS) costs including siting, permitting, engineering, and land costs
- No significant sharing of hardware (storage is independent of PV)
- Stores energy from PV or grid

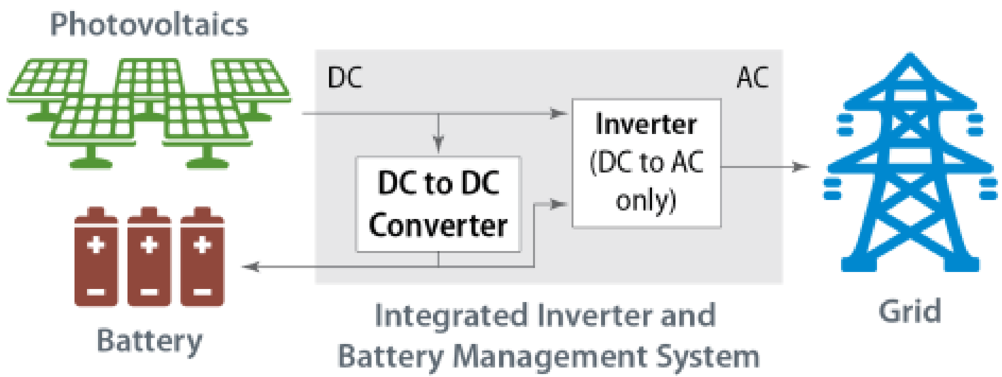


DC-Coupled

- Co-location can reduce BOS costs
- PV and storage share an inverter, thus eliminating second inverter
- Stores energy from PV or grid (a) or from PV only (b)
- Tightly coupled configuration (b) can receive full current federal investment tax credit (ITC)



a) DC-coupled (flexible charging)



b) DC tightly coupled (PV-only charging)

Summary: Qualitative Value and Cost Tradeoffs

Value and cost changes due to coupling, vs. independent system

Type of Coupling	Change in Value (Relative to Independent System)		Change in Cost (Relative to Independent)
	Energy Revenue	**Capacity Value**	
AC	Potentially lower value because it cannot be sited in regions with higher congestion-related prices Also higher losses when storing grid energy (due to additional transmission losses)[a]	None	Reduction in BOS costs[b]
DC (flexible charging)	Storage operation constrained by shared inverter Potentially higher losses when storing grid energy[c] Can store clipped solar that occurs due to ILR > 1[d] Lower losses when storing solar[e]	Limited to inverter capacity	Reduction in BOS costs Reduction in power electronics costs due to shared inverter
DC tight (PV-only charging)	Same as DC-coupled flex PLUS Storage cannot charge from low-cost grid energy	Same as DC-coupled flex PLUS Cannot charge with grid energy to ensure full capacity value	Same as DC-coupled flex PLUS Small (if any) reduction in battery management system cost

[a] Assuming that independent storage is sited closer to load and incurs lower loss rates. [b] Includes interconnection, permitting, overhead, engineering, labor, and land costs. [c] Due to remote location when compared with storage sited in a load center. [d] ILR = inverter loading ratio (PV size relative to inverter power rating); when the ILR is greater than 1, the PV module can produce more energy than can be used by the inverter, so some PV energy may need to be curtailed or "clipped." [e] Not considered in this study.

Quantifying Value and Cost Tradeoffs: Case Study

- Case study in southern California quantifies tradeoffs and determines whether coupling-related change in each PV plus storage system's value outweighs the coupling-related change in costs.
- Comparative metric used is benefit/cost ratio, defined as dividing the annualized benefits (energy revenue and capacity value) by the annualized costs (capital and operating).
- Benefit/cost ratio is used because levelized cost of energy (LCOE) does not capture the fundamental differences in system net value.

System Configuration

Parameter	Value
PV system size	65-MW DC
PV orientation	South facing, fixed at 20-degree tilt
Inverter size	50-MW AC (ILR = 1.3)
Storage power capacity	30-MW AC
Storage energy capacity	4 hours (120 MWh AC)
Storage efficiency	85% (AC-AC)
Location	Southern California (34°51'N 117°39'W)

Calculating Energy Revenue

- Systems are simulated using the NREL Revenue, Operation and Device Optimization (RODeO) model.
- RODeO estimates hourly revenue and optimization of the energy storage system subject to various system constraints.

Constraints Associated with Physical Coupling for PV Plus Storage Systems

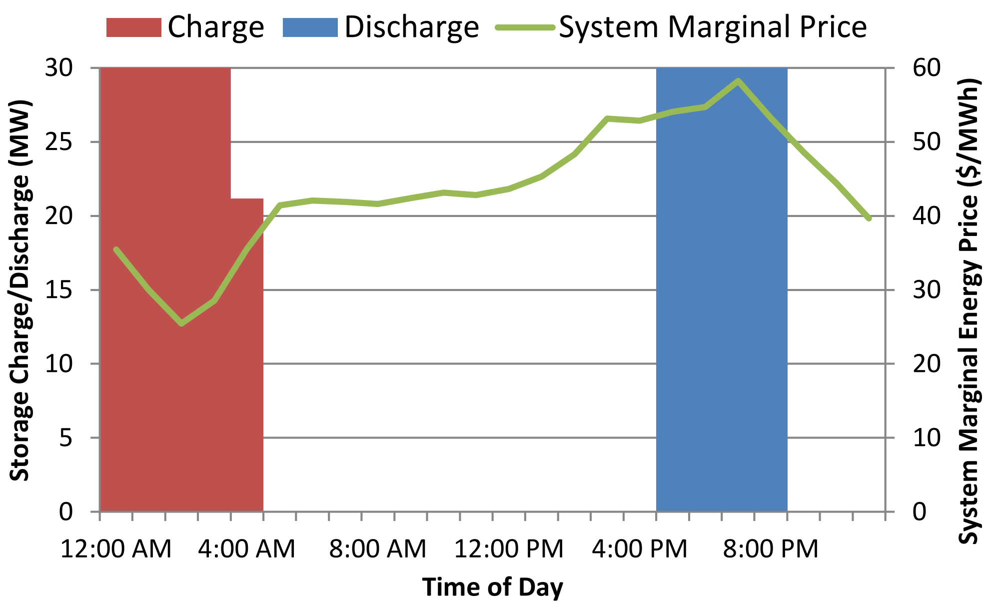
Type of Coupling	Effective Impact on Storage Discharge	Storage Charge Constraint
Independent (roughly equivalent to AC-coupled)	None	None
DC-coupled	Maximum discharge = inverter rating minus PV output	If PV output is greater than inverter rating (due to ILR > 1), then forced to store solar energy
DC tightly coupled	Maximum discharge = inverter rating minus PV output	Only can charge with PV

Calculating Energy Revenue: Solar and Electricity Price Data

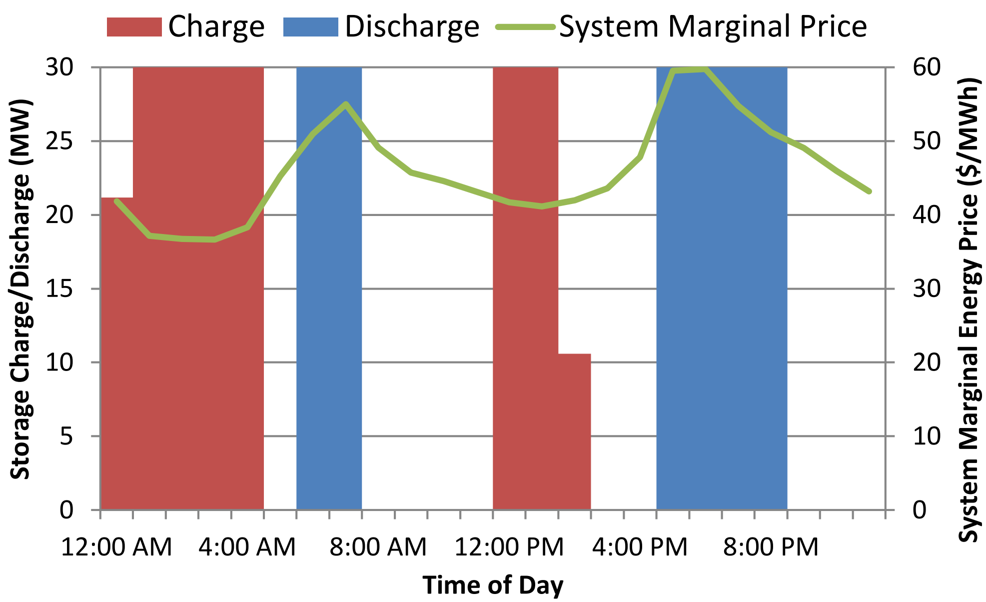
Scenario	PV Penetration	Electricity Price Data Source	Solar Power Output Data
Base Case (recent price and cost data)	6%	2014 California Independent System Operator (CAISO) day-ahead market prices (Southern California Edison Load Aggregation Point)	System Advisor Model (SAM) using National Solar Radiation Database (NSRDB, 2014 weather data)
2020 (sensitivity case)	15% and 24%	Simulated from PLEXOS day-ahead marginal cost. Database from NREL Low-Carbon Grid Study (LCGS).	Weather year for the LCGS study is 2006, so PV simulations use 2006 data. Simulation method same as above (SAM/NSRDB).

Calculating Energy Revenue: Dispatch – Independent Storage

Summer Day (June 16)



Winter Day (January 2)

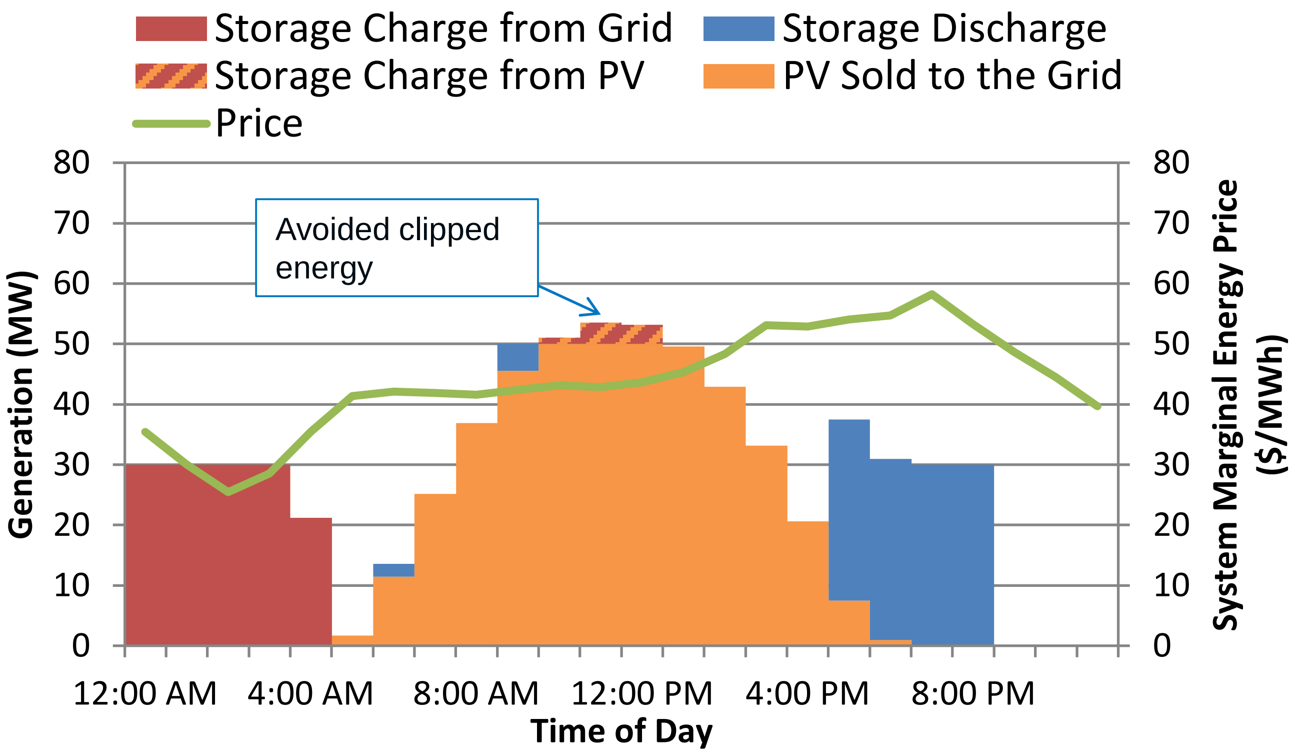


- System configuration is same as AC-coupled storage where the transmission interconnection is sized to the sum of the two inverter systems (80 MW).
- Net revenue is calculated by multiplying hourly price by quantity of energy purchased or sold, e.g., purchased (charge) energy on June 16 (141 MWh) costs $4,336, and sold (discharge) energy (120 MWh) has revenue of $6,608—giving net revenue of $2,272.

Calculating Energy Revenue: Dispatch – DC-Coupled Storage (avoids clipping)

- DC-coupling changes operation of storage plant relative to independent storage case in two ways:
  - Stores otherwise-clipped energy (due to ILR > 1), equivalent to ~2% of potential PV energy on this day.
  - Discharge before noon occurs to make room for clipped PV energy.
- Increases value by about 1% relative to independent PV + storage.

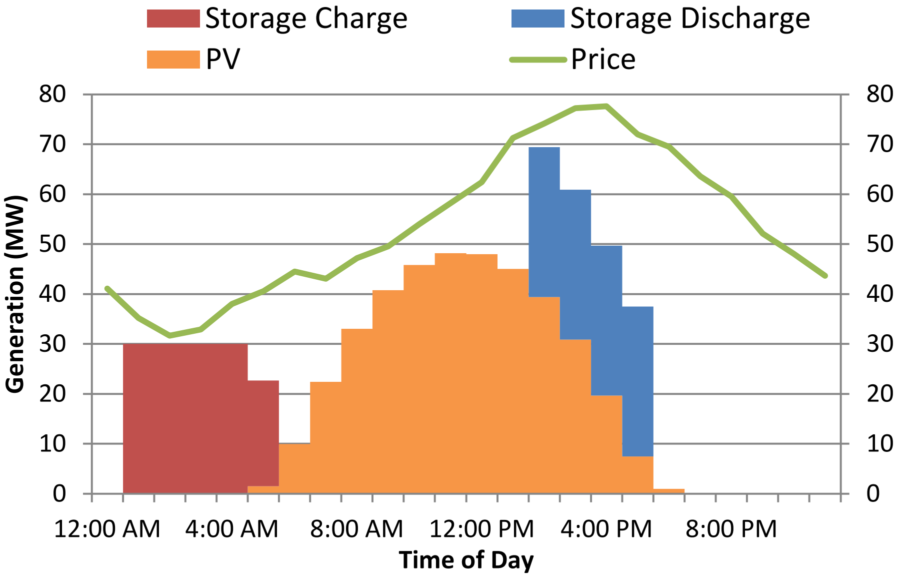
Summer Day (June 16)



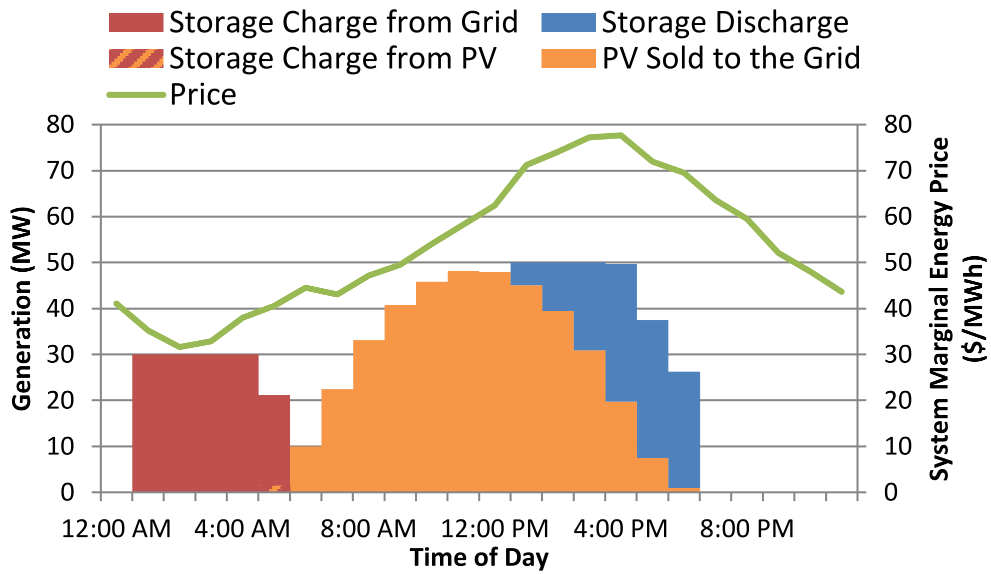
Calculating Energy Revenue: Dispatch – DC-Coupled Storage (constraints due to shared inverter)

- In other periods (July 1 shown here), storage plant cannot be fully utilized because of the operation of the PV system.
  - Combined output of independent PV + storage plant (left figure) is as high as 70 MW, which is possible because of the separate inverters.
  - DC-coupled system (right figure)—with shared 50-MW inverter—must shift storage output to lower-price periods to accommodate PV output.
  - DC-coupled system value decreases by about 1% relative to independent PV + storage system.

Independent (July 1) – can always use full storage capacity



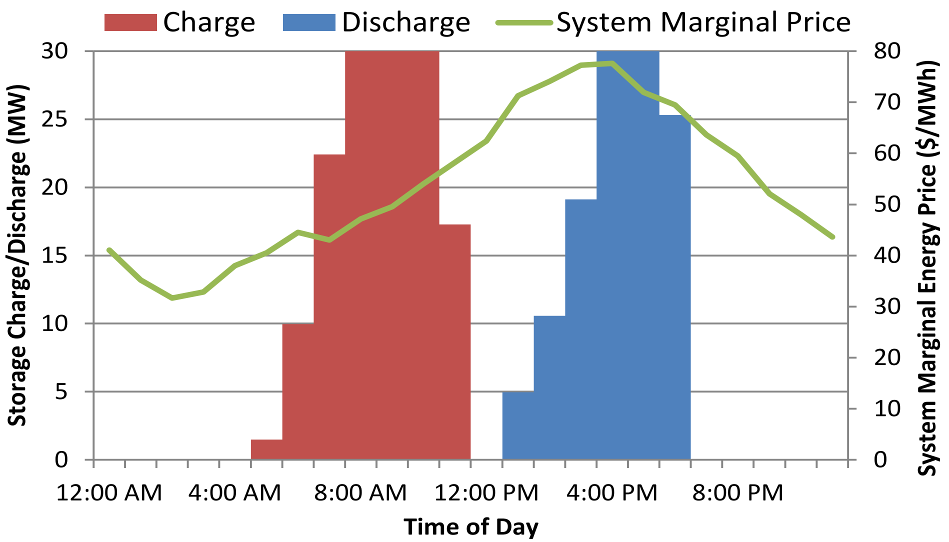
DC-coupled (July 1) – storage output restricted by PV use of inverter



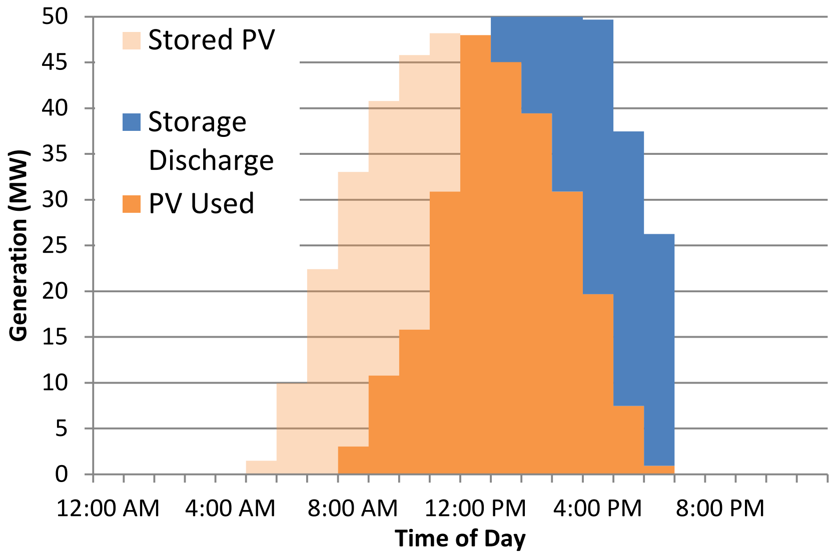
Calculating Energy Revenue: Dispatch – Solar-Only Storage

- Impacts of DC tightly coupled storage systems are more significant.
  - Forcing storage to charge with PV effectively charges with more expensive energy from the middle of the day (left figure).
  - Because the system must store PV energy that could have otherwise been sent to the grid, its overall capacity factor is reduced, having effectively "lost" the opportunity to directly sell the energy in the light orange shaded area (right figure).
  - On this day, the tightly coupled system loses about 7% of revenue compared with the DC-coupled system.

Storage (July 1)



PV and Storage Output (July 1)



Energy Revenue Results: Base Case

- Energy revenue increases less than 1% for DC-coupled system vs. independent/AC-coupled system.
- DC tightly coupled system loses 6% of revenue vs. DC-coupled system.
- For the independent/AC-coupled system, most revenue is from PV (it is difficult to isolate value sources for the coupled systems).

	Independent/ AC-Coupled[a]	DC-Coupled	DC Tightly Coupled
Energy revenue (million $)	6.95 (0.98 from storage, 5.97 from PV)	6.97	6.55
Change due to coupling (million $/%)	—	+0.02 / +0.3%	-0.42 / -6% (compared with DC-coupled)

[a] The independent system configuration is the same as AC-coupled storage where the transmission interconnection is sized to the sum of the two inverter systems (80 MW).

Calculating Capacity Value

- Capacity credit depends on coincidence of PV with net demand: 40% capacity credit assumed at 6% PV penetration in base case.
- Annualized avoided capacity cost of $149/kW is assumed based on an estimate of the financing and operations and maintenance (O&M) cost of a new combustion turbine in California.
- The base 50-MW_{AC} PV system provides a capacity credit of 20 MW_{AC}. Base storage system (30 MW_{AC}) is assumed to have a 100% capacity credit based on rules in several independent system operator/regional transmission organization markets, including CAISO and Midcontinent Independent System Operator (MISO).
- Result is a total capacity value of $7.5 million/year.
- DC-coupling causes no decline in capacity value, because the PV capacity credit (20 MW) plus the storage capacity (30 MW) equals the inverter capacity of 50 MW.

Calculating Costs: Cost Assumptions

Assumed Cost Components for Independent PV (Fixed Tilt, ILR = 1.3) Plus Storage Systems

Component	2016 Cost	2020 Cost
PV system	$1,343/kW (DC)	$912/kW (DC)
PV O&M	$12/kW-yr	$11/kW-yr
Battery module	$304/kWh	$217/kWh
Battery BOS	$612/kW	$398/kW
Battery O&M	$9/kW-yr	$9/kW-yr

Reduction in Battery BOS Costs Associated with Coupling

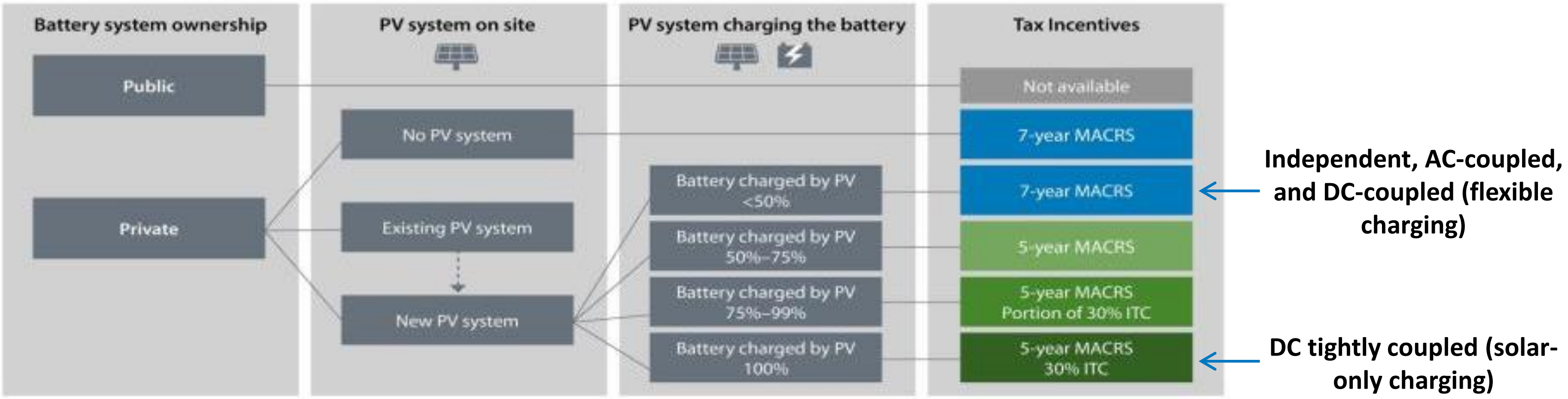
Degree of Coupling	Avoided Cost with Coupling	
	2016	**2020**
AC-coupled (customer acquisition; engineering, procurement, and construction; interconnection)	$161/kW	$118/kW
DC-coupled (above plus inverter)	$221/kW	$158/kW
DC tightly coupled	Same as DC-coupled	

Calculating Costs: Financing Parameters

Component	PV	Battery
Inflation Rate	2.5%	2.5%
Economic Lifetime (Years)	20	15
Interest Rate - Nominal	4.4%	4.4%
Calculated Interest Rate - Real	1.9%	1.9%
Interest During Construction — Nominal	4.4%	4.4%
Rate of Return on Equity — Nominal	9.5%	9.5%
Calculated Rate of Return on Equity — Real	6.8%	6.8%
Debt Fraction	40.0%	40.0%
Tax Rate (Federal and State)	40.0%	40.0%
WACC — Nominal	6.7%	6.7%
WACC — Real	4.1%	4.1%
Depreciation Period	5	7
Construction Finance Factor	1.013	1.009
Present Value of Depreciation	0.837	0.805
Project Finance Factor	1.233	1.233
Capital Recovery Factor (CRF) — Nominal	9.0%	10.7%
Capital Recovery Factor (CRF) — Real	7.4%	9.1%

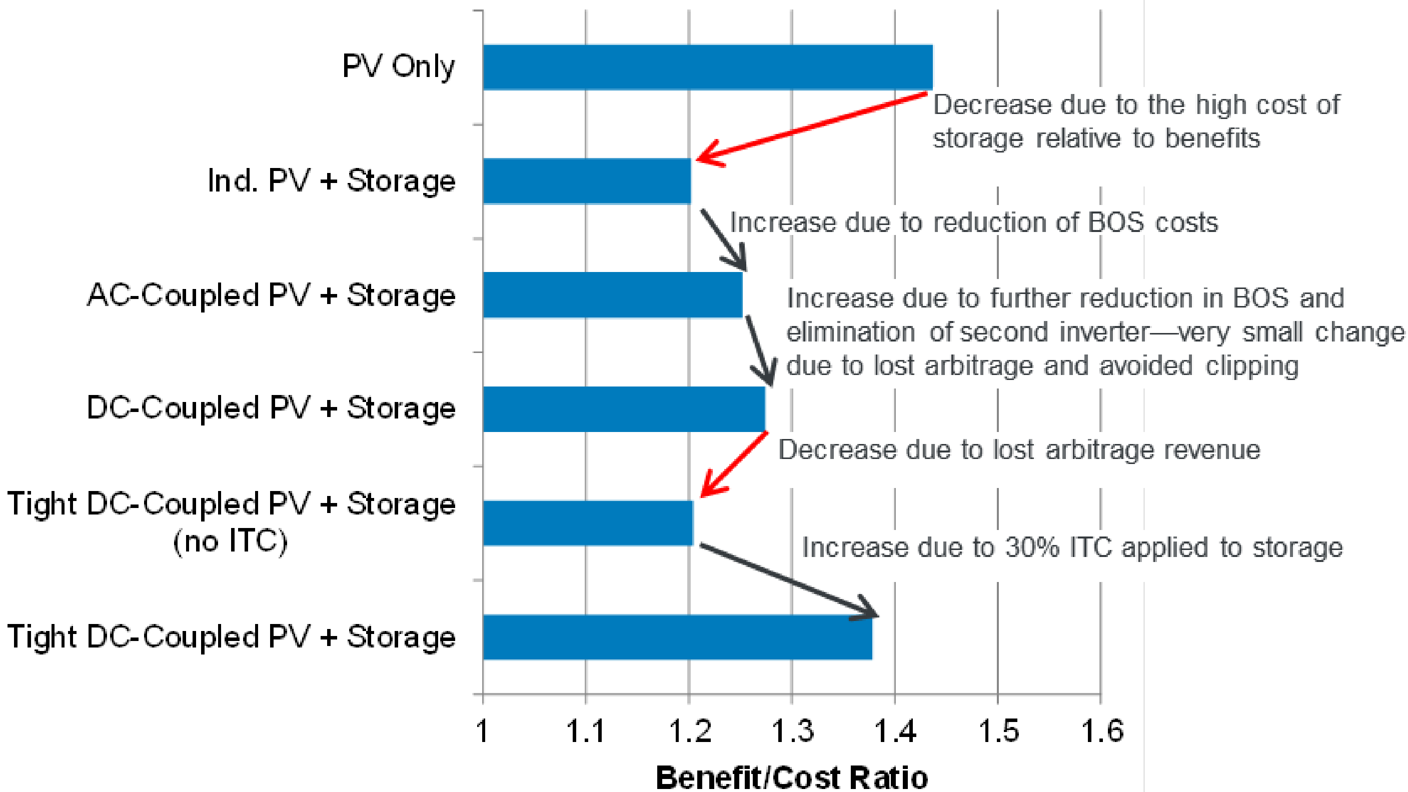
Calculating Costs: Eligibility for Tax Incentives

- Different configurations are assumed eligible for different tax incentives:
  - Independent, AC-coupled, and DC-coupled (flexible charging) storage receives 7-year MACRS (Modified Accelerated Cost Recovery System).
  - DC tightly coupled storage receives 5-year MACRS plus the full 30% ITC.
- In all cases the 30% ITC is applied to the PV portion of the system.



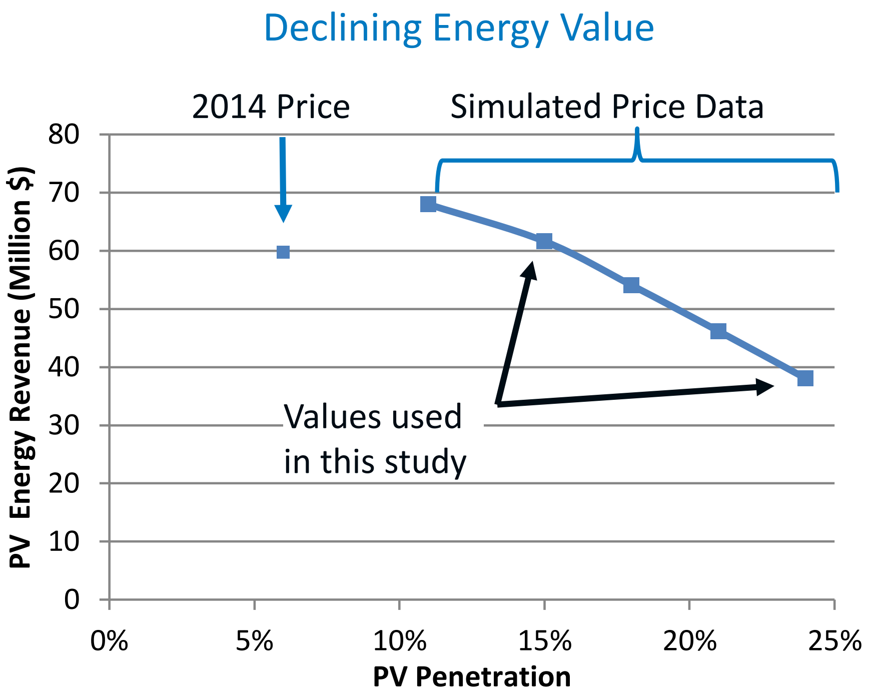
Results: Base Case Benefit/Cost Ratios

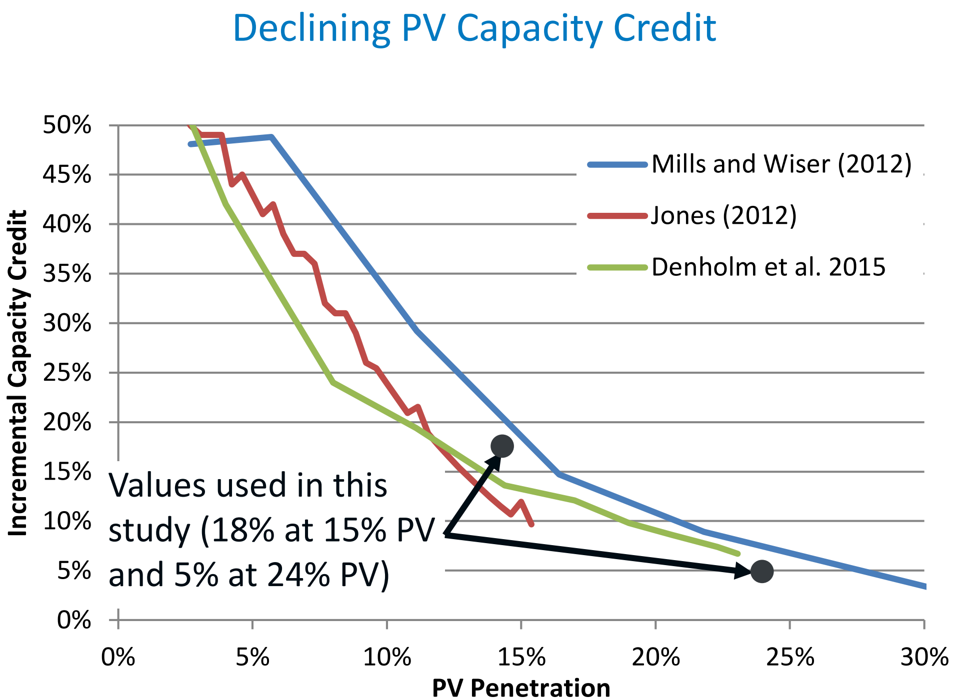
- Benefit/cost ratios are calculated by dividing annualized benefits by costs.
- The PV-only system has the highest benefit/cost ratio.
- These results follow historical trends that have resulted in very limited deployment of PV plus storage systems.
- This analysis does not consider the impacts of increased PV penetration and reduced storage costs, which are considered in the following 2020 case.



2020 Case: Declining PV Value, Declining Costs

- In the 2020 case, PV penetration increases to 15% or 24%, and PV value decreases:
  - PV energy value declines owing to higher PV curtailment and lower value of energy offset by PV (left figure).
  - PV capacity value declines owing to the lower capacity credit caused by the net load shifting to later in the day (right figure).
- At the same time, the costs of PV and storage decrease.

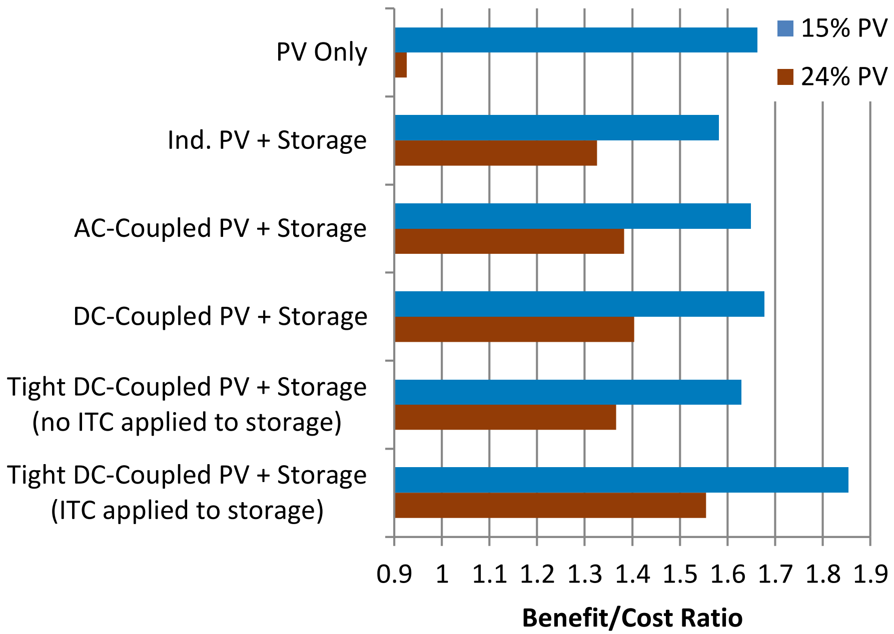




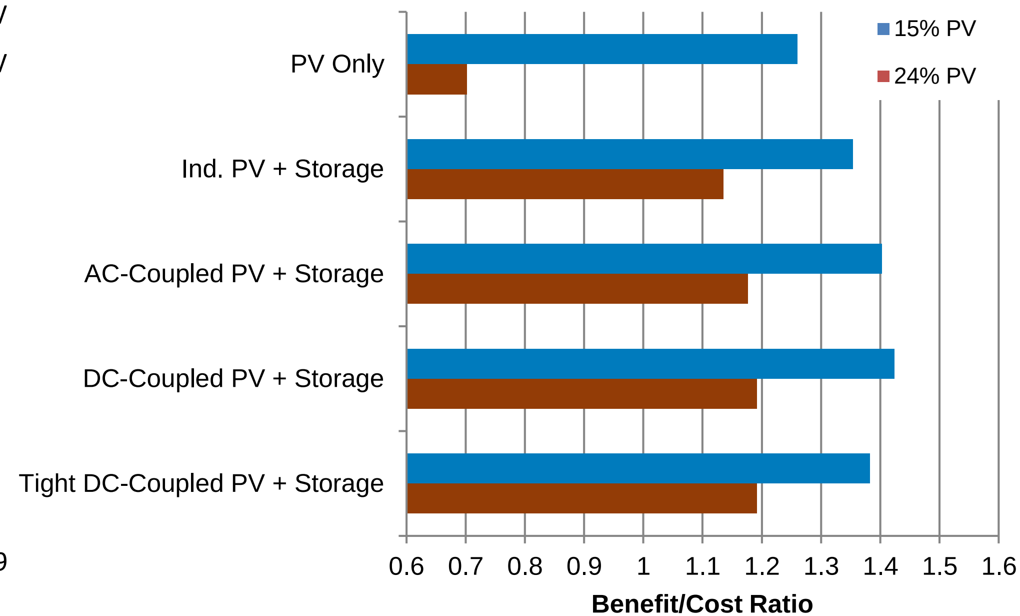
2020 Case Results: Benefit/Cost Ratios

- With the existing PV ITC (left figure), the PV-only benefit/cost ratio drops below 1 at 24% PV.
  - Adding storage increases the ratio at 24% PV, and the ratio increases with greater degrees of coupling (highest is DC tightly coupled with ITC).
- With no ITC for PV or storage, the benefit/cost ratio declines in all cases but remains above 1 for the PV plus storage systems (highest is DC-coupled with flexible charging, although at 24% PV the tightly coupled system has little penalty because much of the storage charging is from PV).

With ITC for PV



No ITC for PV or Storage



Conclusions

- PV plus storage systems can have multiple configurations, depending on the degree of coupling and the sizing of components.
- LCOE is a incomplete metric for evaluating PV plus storage because of the significant increase in value associated with storage—benefit/cost ratio is an alternative metric that accounts for the added value.
- Coupling by co-locating storage and solar can decrease the overall net costs of deploying PV and storage (AC coupling).
- Further cost reductions are possible via sharing the inverter (DC coupling).
  - This can reduce clipping but can result in non-optimal storage dispatch, especially if the storage capacity is sized close to the size of the inverter.
- Tightly coupling or charging only with PV can result in significant lost value.
  - This loss is currently less than the value of the 30% ITC, so this configuration currently provides the highest benefit/cost ratio.
- These results are for a single location and set of assumptions, so more work is needed to draw more generalized conclusions.

Future Work

- Analyze other regions
- Examine higher ILRs
- Assume different storage sizes
- Apply to other generation resources, including wind

For More Information

Download the report:

https://www.nrel.gov/docs/fy17osti/68737.pdf

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