Grid-Friendly PV: Project Developer Options to Enhance the Value of Solar Electricity as Solar and Storage Penetrations Increase

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SITE: https://emp.lbl.gov/publications/project-developer-options-enhance

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Introduction and motivation

The marginal grid value of PV decreases with increasing PV penetration and PV can retain more value by being more grid-friendly

Increasing PV penetration reduces the marginal grid value of PV

- Declining grid value of PV limits the attractiveness and future demand
- Utilities and PV power purchasers have been buying a product that is progressively less valuable

PV can be made more grid-friendly: retaining more value as PV penetration increases

- Changes include modifications to project configuration and operations
- Alternative PV system configurations can shift the timing of production to higher priced times

Previously studied grid-friendly solutions assumed historical conditions, which may be ill suited to rapidly evolving landscapes

Past grid-friendly PV → Solar Penetration Increases → **Future grid-friendly PV ?**

- Shifting production timing can marginally increase grid value
- Some options reduce total PV generation
- Value increases with westward orientation
- Focus of existing literature is mostly standalone PV

- Continuously evolving net load profiles and electricity prices affect PV grid value
- Declining energy storage costs raise interest in hybrid solar+storage plants for shifting generation to higher-priced hours
- PV plants can provide grid services such as regulation reserves

Conduct comprehensive analysis of the cost and value of multiple PV configurations across various solar penetrations

PV generation profile

NREL SAM

NSRDB Weather

Compare grid-friendly PV options

Calculate marginal net grid value

Market prices

Historical

Future

Energy

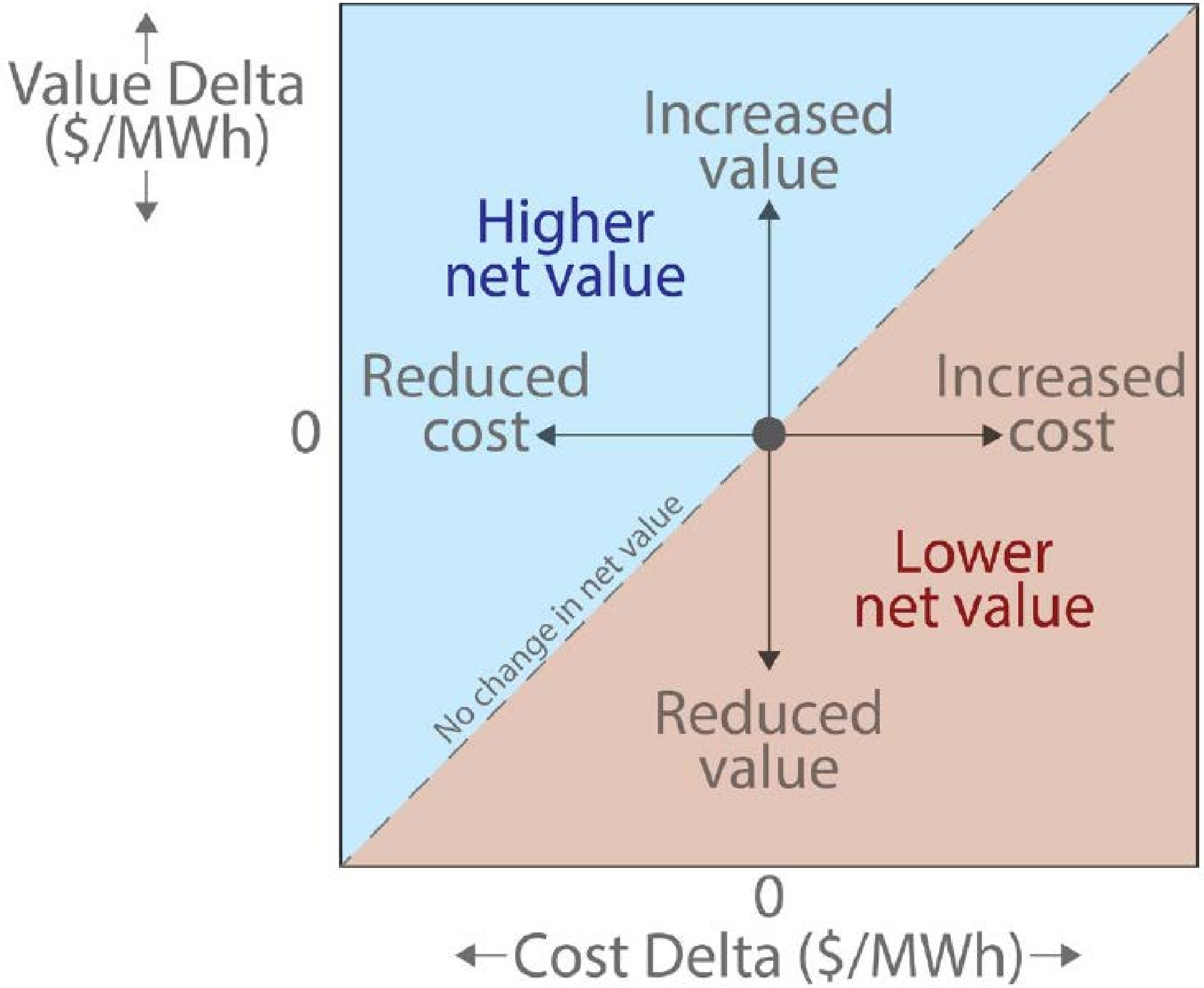
Capacity

Ancillary

Bifacial Modules
Vertical Bifacial
West-Facing
Higher ILR
Tracking
Regulation Reserves
PV+Storage
Alternative Locations

Grid-friendly PV evaluation framework

Decision framework compares grid-friendly PV options with a base PV plant in the same market and with similar underlying component costs



- Compare grid-friendly PV options with a base PV plant

Grid-friendly PV plants increase value by more than they increase costs relative to the Base PV plant

Base PV Plant

- Base PV plant is designed to provide reference point to compare with grid-friendly PV plants
- The characteristics of the base PV plant are consistent with typical systems installed today
  - USS report
  - Literature review

Configuration

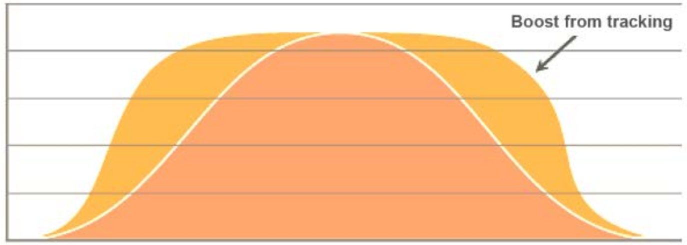
- Standalone
- Fixed module
- South-facing Azimuth
- Tilted at 31 degrees
- Inverter loading ratio of 1.3

Grid-friendly PV options

Some grid-friendly PV options require simple changes to plant configuration using readily available technology

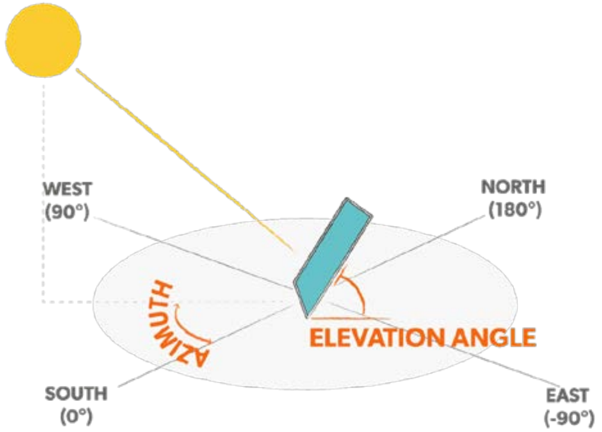
Existing Options

Tracking



- Tracking system adjusts the position of the PV array to track the sun

West-Facing



- West-Facing azimuth can produce more power in the higher price hours in the afternoon

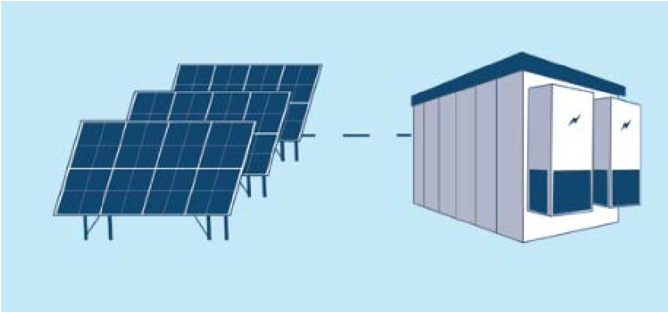
Others

- Higher ILR, Higher/Lower Tilt, Location

Other grid-friendly PV options require emerging technology

Emerging Options

Hybrid (Battery)



- Charge with solar produced in lower priced hours and discharged later in the higher prices hours

Vertical Bifacial

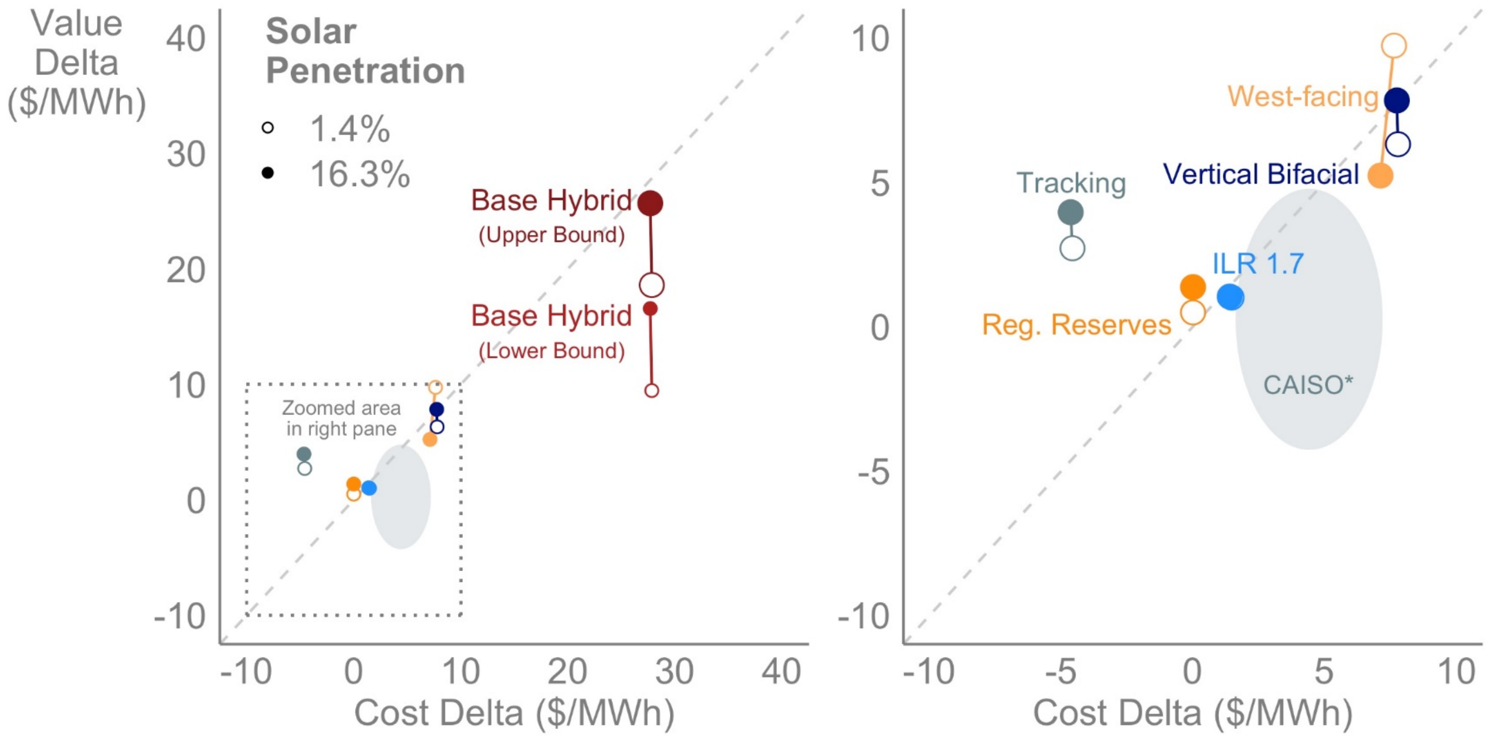
- Bifacial tilted vertically and aligned on a N/S axis, concentrating production in morning and evening

Others

- Bifacial, Ancillary Service Provision

Shifting the timing of PV production

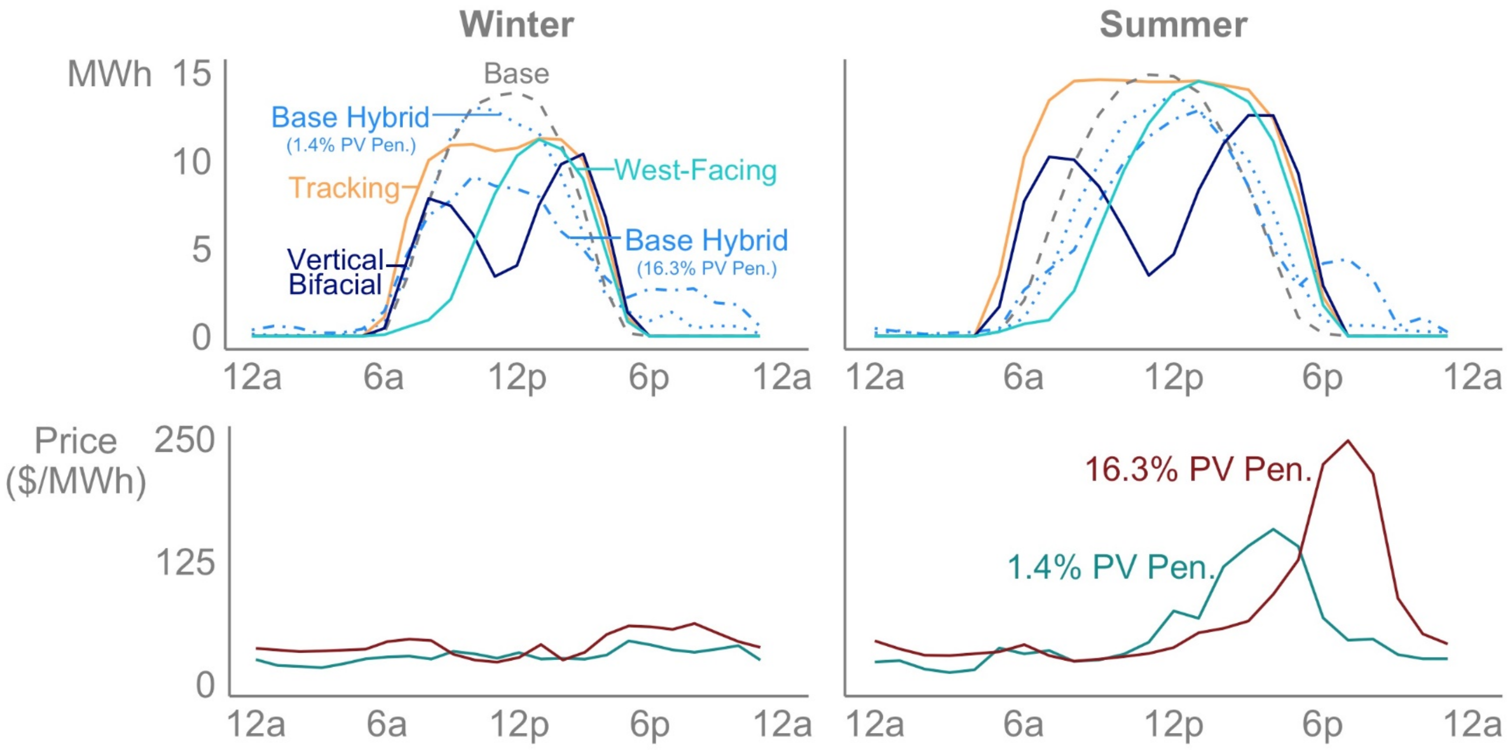
Value increase comes from changing the timing of production to better align with peak system needs, when the prices are higher



- Weather and wholesale market data of CAISO SP15 in 2012 (1.4% of solar penetration) and 2018 (16.3% of solar penetration)
- Gray oval represents location change option

- Largest increase in value is from aligning the timing of production with high prices
  - Hybrid increases value the most
  - Value increase from Tracking, Vertical Bifacial, West-Facing is relatively modest
- The value boost of West-Facing PV is greater at lower solar penetration

The impact of higher solar penetration on value added by a grid-friendly option depends on the way production is shifted by the option

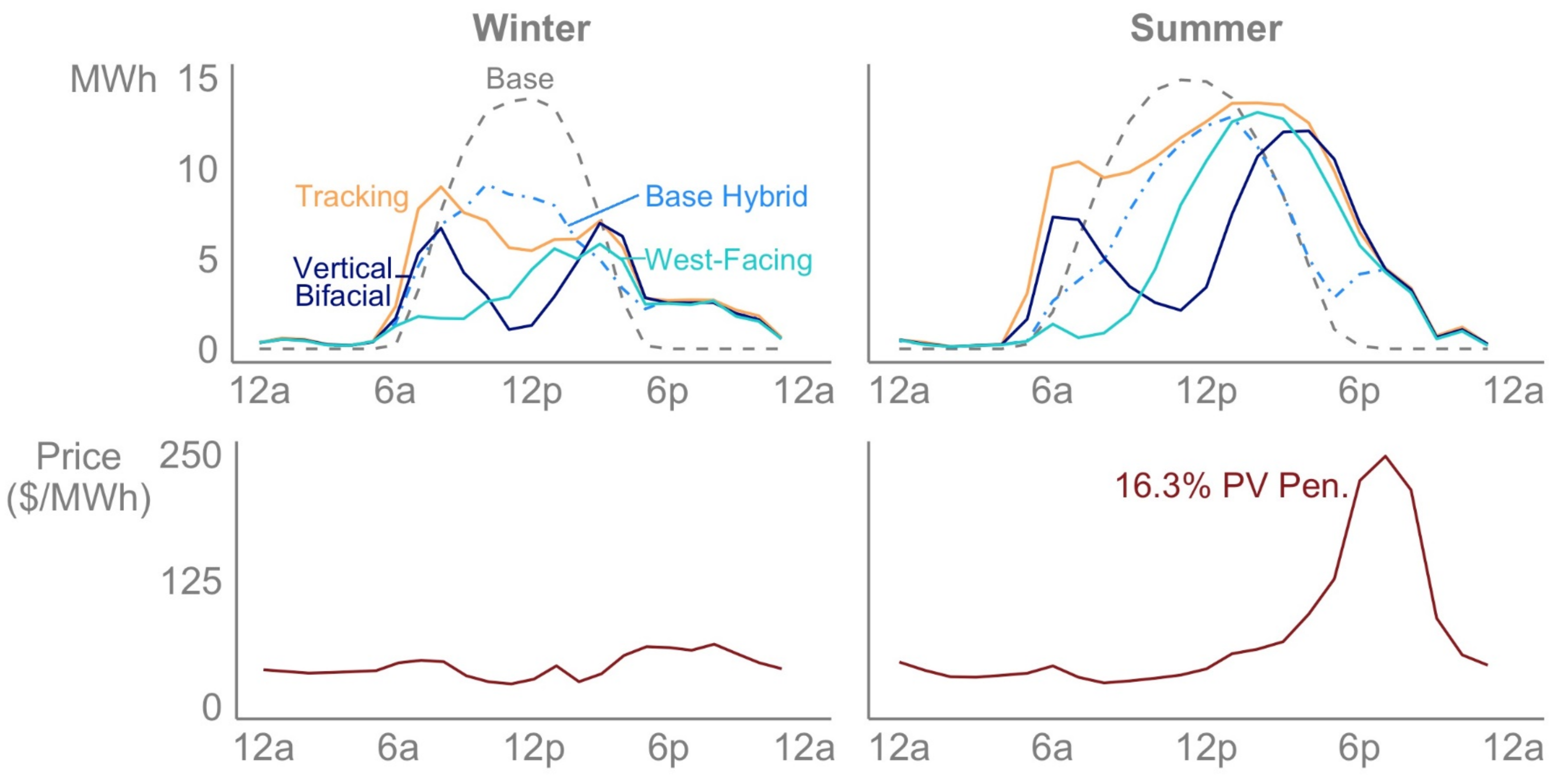


- Hybrid shows the best responsiveness to align PV profile to the higher priced hours
  - Tracking and Vertical Bifacial also shift production

- West-Facing PV profile is not aligned with highest priced hour at higher solar penetration

Maximizing the benefits of storage

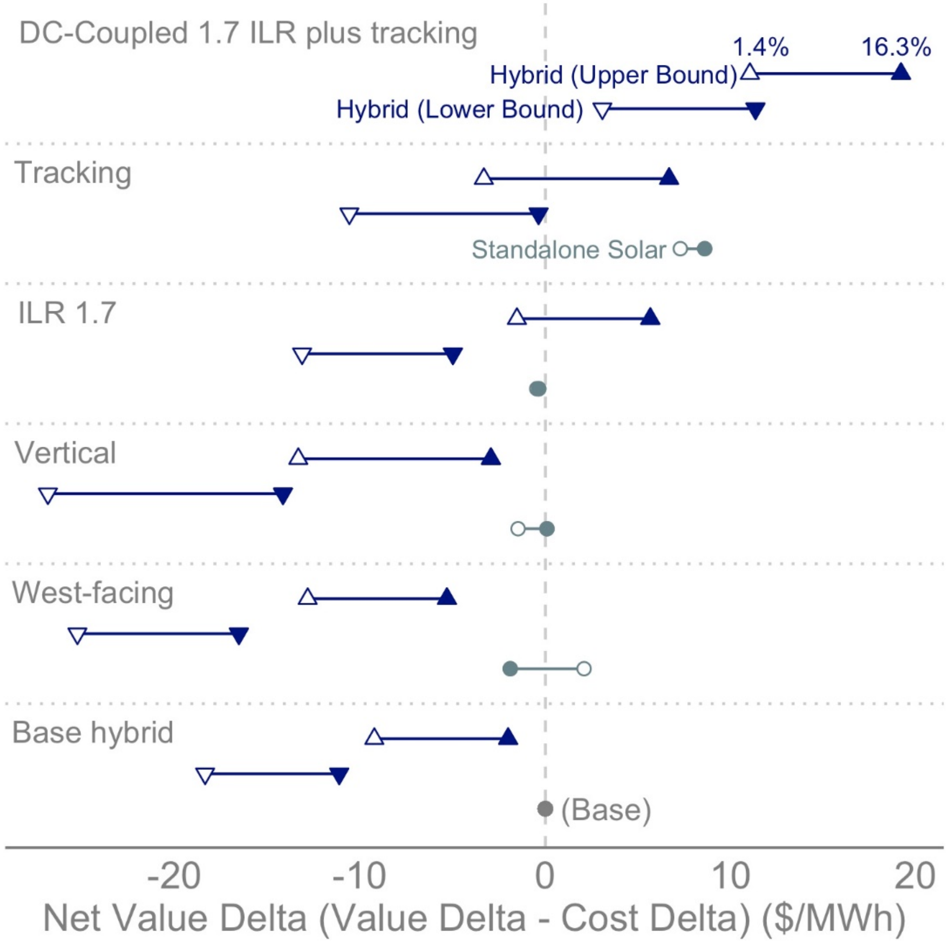
Irrespective of the PV subsystem profile, the output of hybrid plants during the higher priced hours is similar



- Storage: 4-hour duration, AC-coupled storage sized to 50% of the PV nameplate capacity
- Dispatched with perfect foresight of wholesale prices and PV production
- To qualify for full federal ITC, storage can only charge from the solar plant, not from the grid

- The PV subsystem differences lead to different total production
- However, storage acts like a buffer shifting energy to the highest-priced hours
- Configurations of the PV subsystem that change the timing of production become redundant

Generation-maximizing strategies with energy-shifting capabilities of hybrids yield the most net-value benefits at higher solar penetration

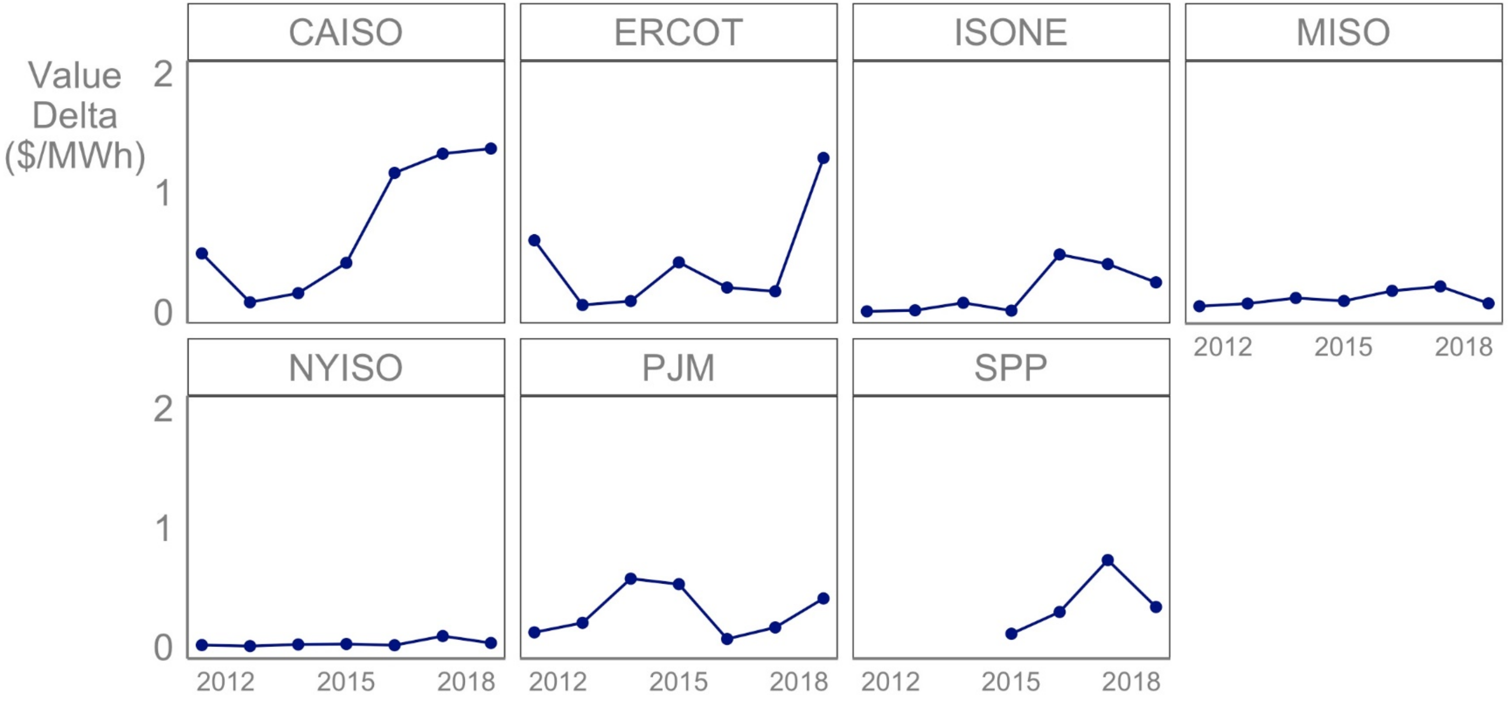


- Upper bound: Perfect foresight of real-time prices and solar production
- Lower bound: Imperfect foresight

- Net value rankings of options with storage differ from the ranking of standalone PV options
- PV subsystems that sacrifice overall production to better align solar production is less attractive
  - West-Facing, Vertical Bifacial
- Options that increase annual production are more attractive
  - 1.7 ILR, Tracking
  - Best: DC 1.7 ILR + Tracking

Enhancing grid services

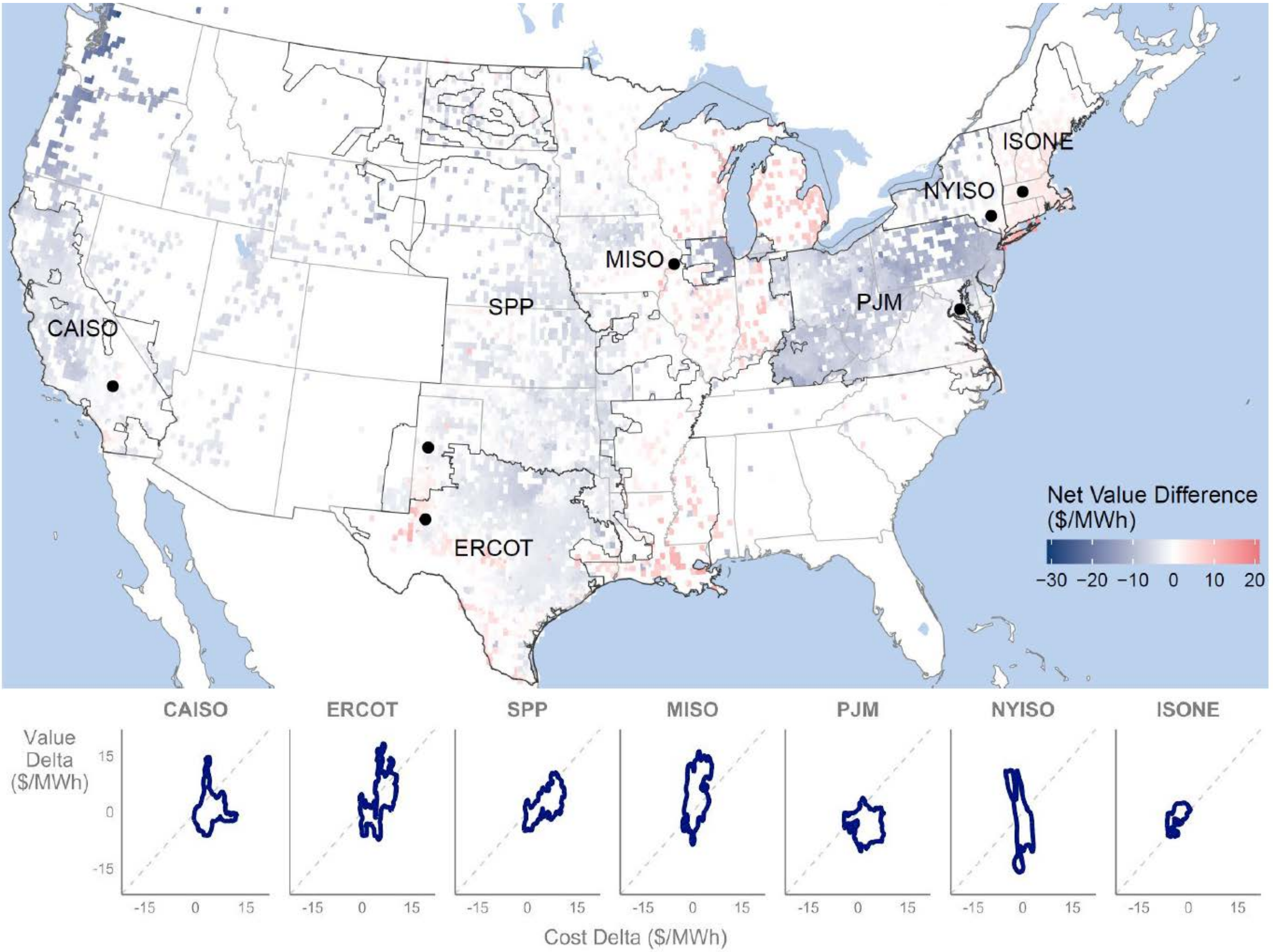
Providing Regulation Services from standalone PV modestly increases net value



- Optimistic assumption: PV plant has the option of providing regulation and is capable of scheduling the regulation reserves with perfect foresight of market conditions including regulation reserve prices, energy prices, and solar production

- PV plants can provide regulation with advanced control capability
  - The cost of adding controls is insignificant
- The increase in value is variable across years and regions and sensitive to changes in market conditions

If currently installed PV plants are not near these high-price regions, then an alternative site may have higher value



- Grid value varies with location due to the marginal cost of balancing supply and demand varies across the market
- Locational prices are higher close to demand centers owing to the congestion caused by limited transmission capacity

- Black dots: Location of base PV plant at the centroid of currently installed PV
- Contour line: 95th percentile of alternative locations

Conclusions

Generation-maximizing strategies today yield increasing net-value benefits as PV and storage deployments continue to accelerate

- PV standalone design options can help maintain PV's grid value, but the net value (grid value–system cost) is marginal and varies with solar penetration

- Adding storage to the PV configurations alters the cost and value dramatically
  - Strategies that shift the timing of PV generation at the expense of total generation results in net value penalties
  - These strategies become redundant when the energy-shifting capabilities of storage are added

- Strategies that maximize PV generation provide the largest net-value gains when combined with storage, especially at high PV penetrations

- These findings may aid stakeholders who are seeking to achieve (or understand the implications of) high solar penetration

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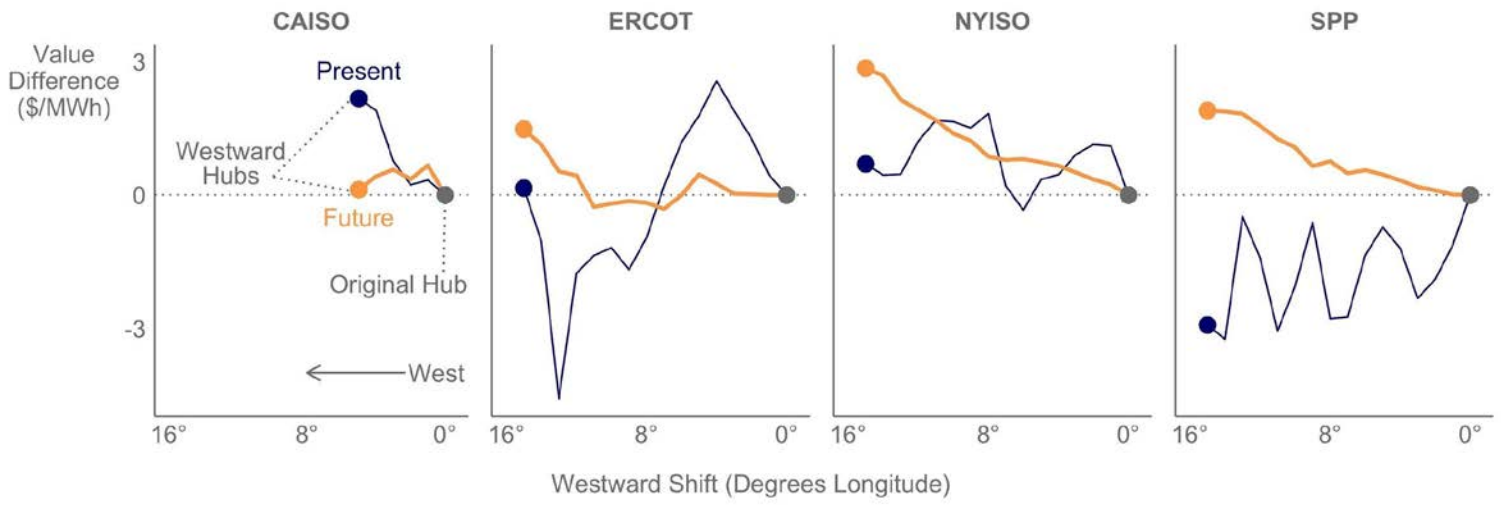
Appendix

The westward shift of the PV plants increases value in some regions by aligning solar production with high prices, yet less than transmission cost

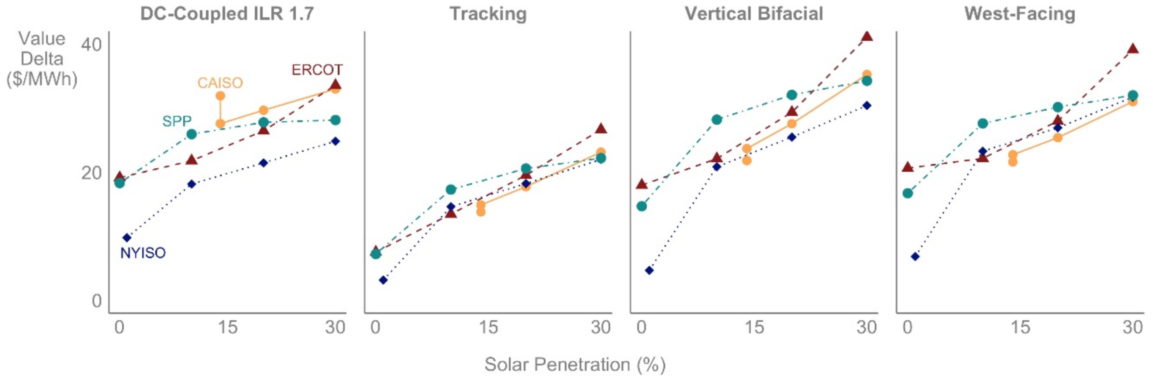


- Present prices use observed wholesale prices from major trading hubs in each market
- The shift in production by moving westward is modeled in NREL's SAM by selecting weather data from a site further to the west
- Future prices are from the high solar scenario based with at least 30% solar penetrations
- The original trading hubs are: SP15 in CAISO, HB_Houston in ERCOT, SPPSOUTH_HUB in SPP, and HUD VL (ZONE G) in NYISO

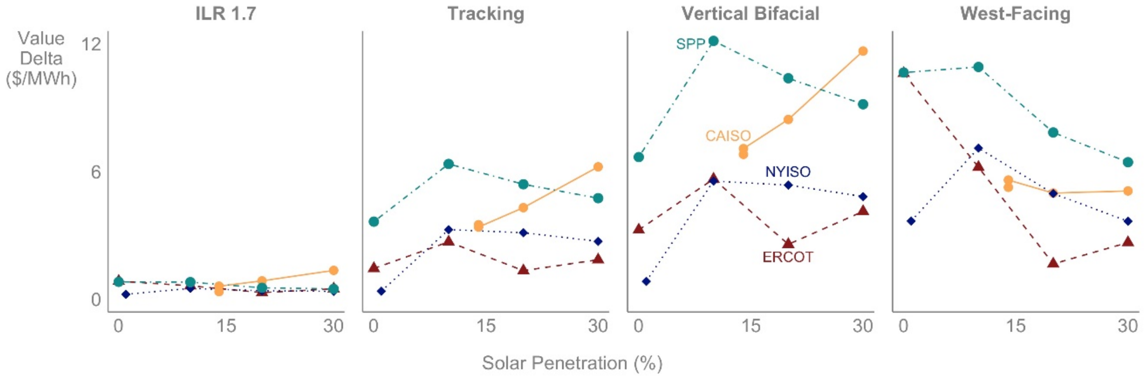
- PV plant shifts westward from the pricing node, the timing of production shifts later into the day
- The magnitude of value increase is far lower than the cost of additional transmission
  - 15-degree westward shift would impose a transmission cost of $20–$53/MWh

The other regions show similar trend in grid value changes with higher solar penetration

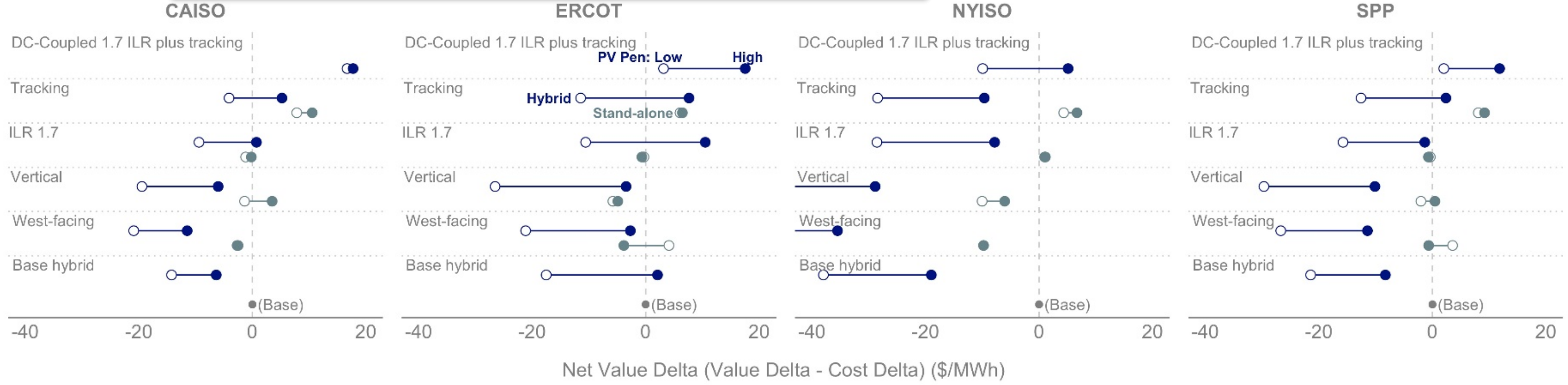
Hybrid grid-friendly PV options in future scenarios



Standalone grid-friendly PV Options in future scenarios

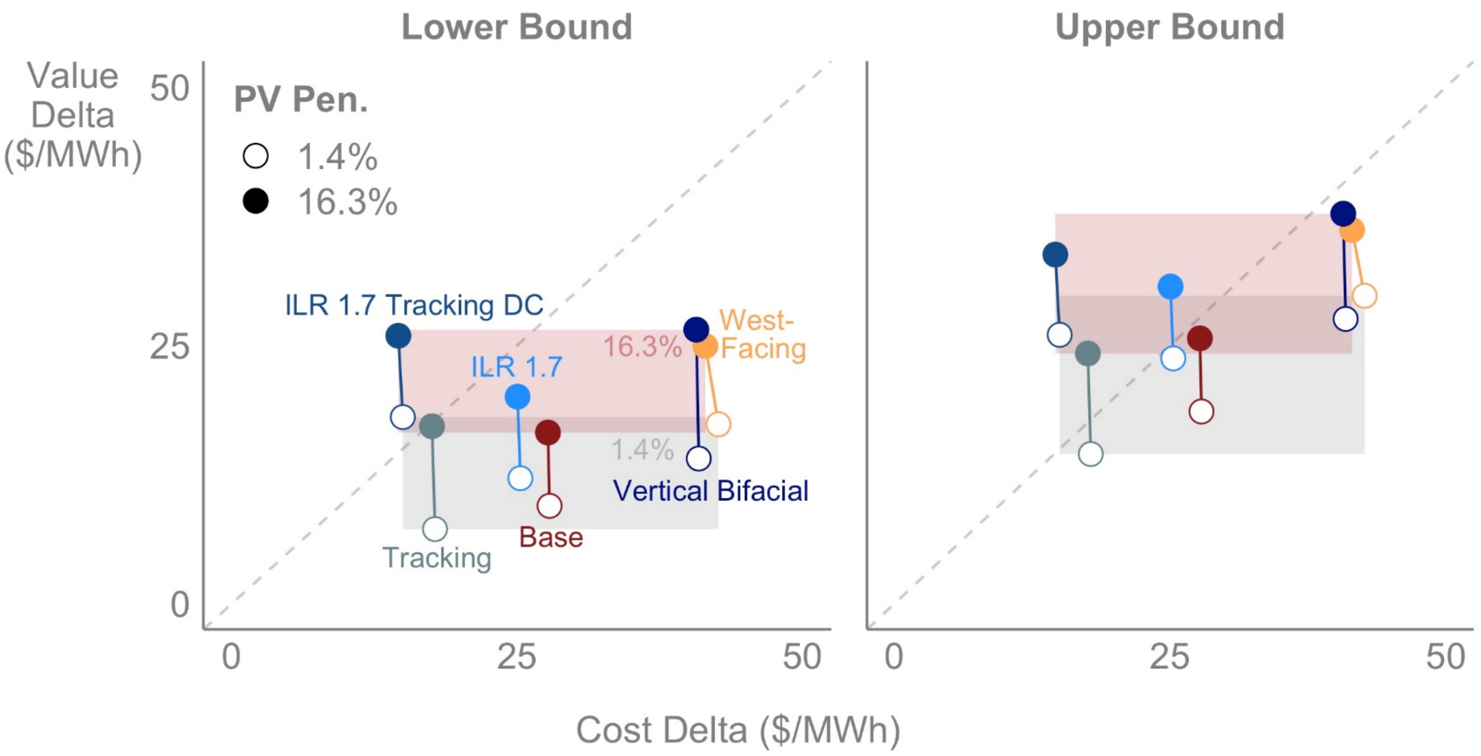


Net value of grid-friendly PV options in future scenarios



- The impacts of high shares of solar in CAISO may appear elsewhere as solar continues to grow

The similar output of hybrid plants in the higher priced hours leads to a narrower range in hybrid value across different configurations



- The shaded rectangular boxes represent ranges of value and cost changes across hybrid configurations relative to the base PV plant

- The output of hybrid plants during the higher priced hours is similar
- The range in increased value across various hybrid PV configurations is narrower than cost
- Rectangular boxes are wider than their heights at different penetration levels

Configurations of the considered grid-friendly PV options

	ILR	Tilt	Azimuth	CF (%, 2018)[a]
Base	1.3	31	180	29.2
West-facing	1.3	31	270	23.5
Bifacial	1.3	31	180	30.3
Vertical Bifacial	1.3	90	270	24.4
Tracking[b]	1.3	0	180	36.0
Tilt-20deg	1.3	11	180	27.5
Tilt+20deg	1.3	51	180	27.8
ILR 1.1	1.1	31	180	24.8
ILR 1.7	1.7	31	180	33.7
Base Hybrid (Base + Storage)	1.3	31	180	29.2

Location	Base configuration with weather and prices from other locations[c]
Regulation Reserves	Base configuration with capability of following automatic generation control signal[c]
Westward shift	Base configuration with weather from locations west of chosen pricing hub and additional interconnection cost

[a]CF is the AC capacity factor of PV options using National Solar Radiation Database (NSRDB) weather in 2018. The CF of the underlying standalone PV configuration is used in the denominator of cost and value calculations.
[b]Single-axis tracking is employed only in the 'Tracking" configuration, all others use fixed modules.
[c] Figure 2 summarizes the impact of PV plant location or provision of regulation reserves in CAISO in Section 3.1. Additional details for CAISO and other U.S. markets are in Section 3.2 "Options for Enhancing Grid Services without Shifting Production".

- Hybrid value calculation within bounds
  - Upper bound: Perfect foresight of real-time prices and solar production
  - Lower bound: Imperfect foresight

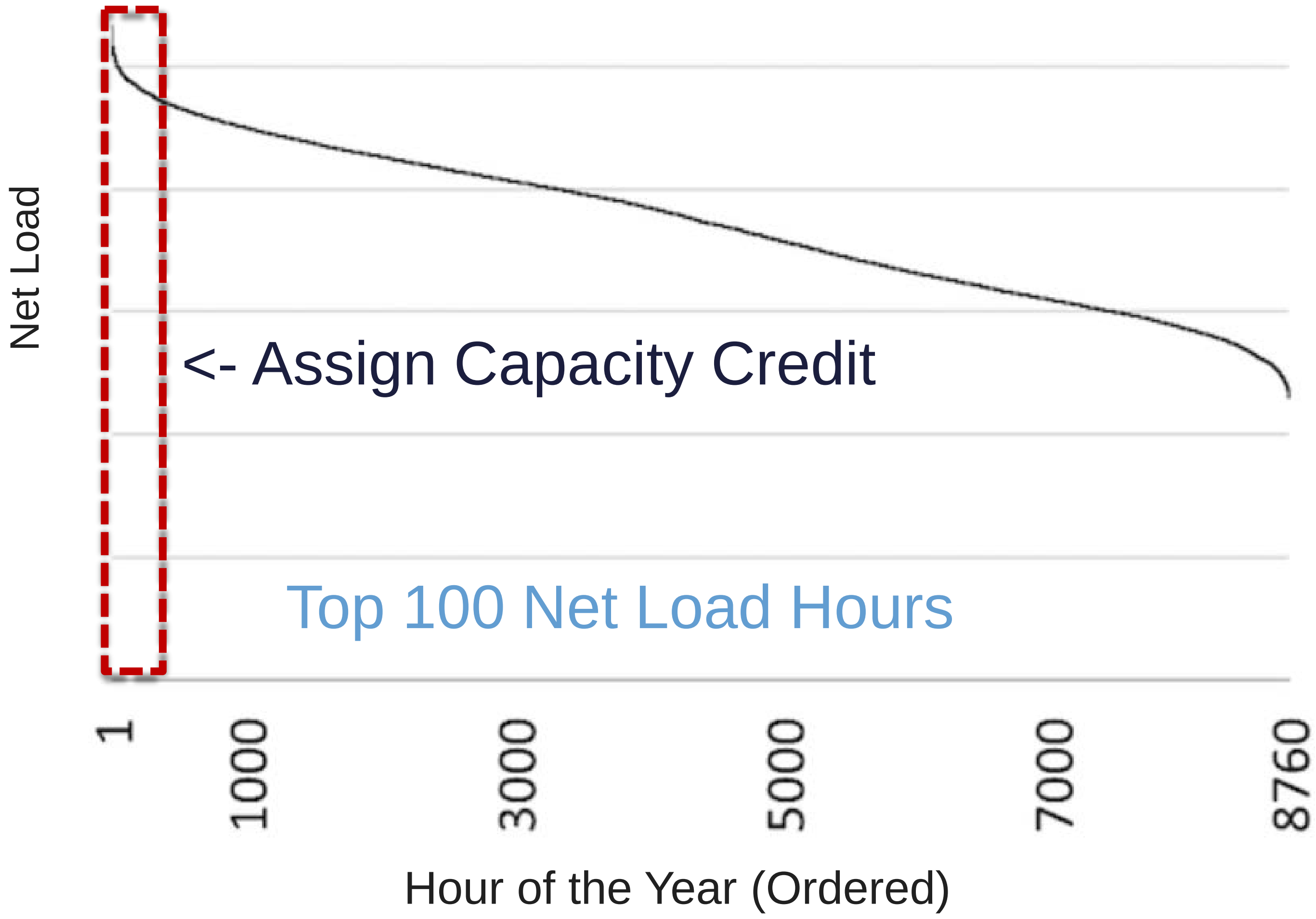
Configurations for LCOE calculation

Table 2: Cost Assumptions of the Grid-Friendly PV Options

	Parameter	Value	Unit	Applies to
Project Finance Factor	*PFF*	1.046		All
Construction Finance Factor	*CFF*	1.014		All
Real Weighted Average Cost of Capital	*WACC*	0.0271	yr^-1	All
Solar Annual Degradation Rate	*d*	0.007	yr^-1	All
Solar Lifetime	L_{PV}	30	years	All
Solar Fixed O&M	FOM_{PV}	20	$\$/kW_{ac}$-yr	All
Solar Field Capital Cost	CC_{field}	982	$\$/kW_{dc}$	All
Solar Power Block Capital Cost	CC_{inv}	47	$\$/kW_{ac}$	All
Solar Field Tracking Cost Adder	Add to CC_{field}	70	$\$/kW_{dc}$	Tracking
Solar Field Bifacial Cost Adder	Add to CC_{field}	50	$\$/kW_{dc}$	Bifacial, Vertical Bifacial
Solar Field Vertical Bifacial Cost Adder	Add to CC_{field}	32	$\$/kW_{dc}$	Vertical Bifacial
Storage Lifetime	$L_{Storage}$	10	years	All Hybrids
Storage Fixed O&M	$FOM_{Storage}$	10	$\$/kW_{storage}$-yr	All Hybrids
Storage Power Block Capital Cost	$CC_{Storage:Power}$	280	$\$/kW_{storage}$	All Hybrids
Storage Energy Capital Cost	$CC_{Storage:Energy}$	325	$\$/kWh_{storage}$	All Hybrids
AC Hybridization Cost-reduction Factor	*HCF*	0.93		AC-Coupled Hybrids
DC Hybridization Cost-reduction Factor	*HCF*	0.92		DC-Coupled Hybrids

- Fu et al (2018): U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (NREL)
- Fu et al(2018) for Battery: 2018 U.S. Utility-Scale Photovoltaics Plus-Energy Storage System Costs Benchmark (NREL)
- Deline et al (2019): Bifacial PV System Performance: Separating Fact from Fiction (NREL)
- Mongird et al(2019): Energy Storage Technology and Cost Characterization Report (PNNL)

Capacity credit is based on average production during top 100 net load hours calculated by capacity credit times an assumed capacity price



- To maintain a simple uniform approach, we assume the following capacity prices:
  - All historical markets and years: $50/kW-yr
  - Future scenarios: Scenario-specific capacity prices from LCG simulations (~$20-75/kW-yr)

- Assumptions are equivalent to adding ~$500/MWh capacity price adder to energy prices in top 100 net load hours

Results from past literature

Author	Year	Results
Brown and O'Sullivan	2019	Compared to capacity-factor optimized fixed-tilt arrays, orientation optimization increases revenues by 1%~20%, 1-axis tracking increases 1%~ 32%, and curtailment increases revenues by 1%~9%. California in 2017 prices showed the highest increases in the market values.
Chudinzo et al.	2019	Relative to the conventional PV systems, the vertical bifacial PV plants showed slightly higher value factors (0.5~1%) in recent years in the selected European countries
E3	2018	The simulated results for different solar penetration scenarios showed that the downward dispatchable PV increase the average solar value increase by 1%~35%
Denholm et al.	2017	In the empirical (past) and simulated results (future) for different solar penetration level in the California, the benefit-cost ratio of solar + PV is from 1.2 to 1.85 while standalone solar is from 0.7 to 1.45
Bogenrieder et al.	2016	The newly installed PV plants in 2014 faced towards east or west could profit from higher spot market prices in the morning and afternoon, which changes revenue by from –1% to 5%.
Alexander Zipp	2015	Adopting market value optimized orientation, the relative market values of the location Stötten for 2011 till 2013 increased by 1%~6%.
Hartner et al.	2015	The simulated results for different solar penetration scenarios showed that the value maximizing tilt and azimuth can increase the market value of solar by 0~20%.
Rhodes et al.	2014	Percent change in the value of energy generated from value maximizing orientation as compared to a South facing array for an entire year was 0.71 considering Austin's TOU rate
Hummon et al.	2013	Adopting market value optimized orientation, the relative market values of the various states in the U.S increased by 1%~8%
Rudolf et al.	2013	The differences in NPV by adding battery on the existing PV system after 25years of operation is minus 12.62MEuro.