Integration of Solar + Storage

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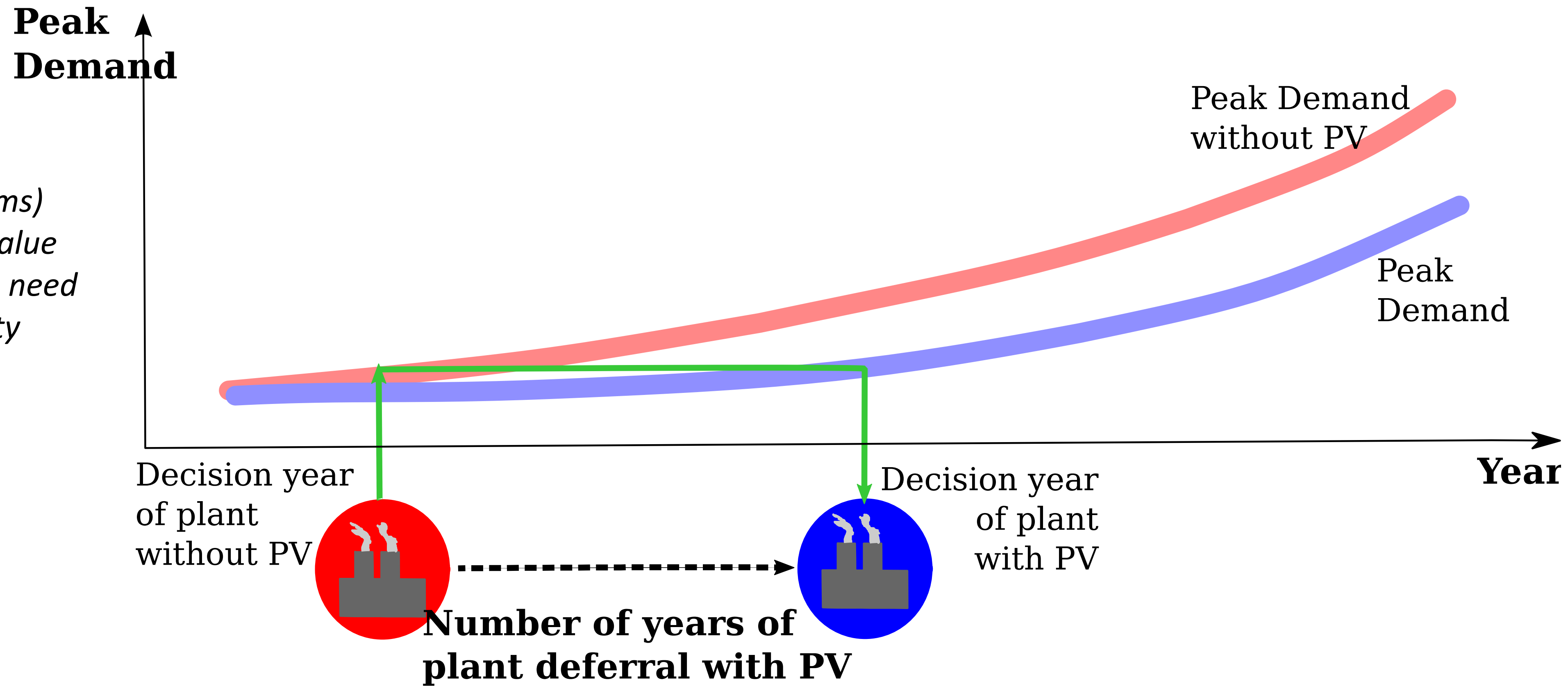
Solar + Storage for Resource Adequacy

Source: Mills and Rodriguez 2019

Contribution to Reliability is One of the Value Streams of Solar+Storage

Capacity value (in $ terms) depends on economic value of avoiding or deferring need to build peaking capacity



Capacity credit: Portion of the nameplate capacity that contributes to meeting utility peak needs

Scope and Objectives

Develop simple methods to explore the capacity credit of solar+storage

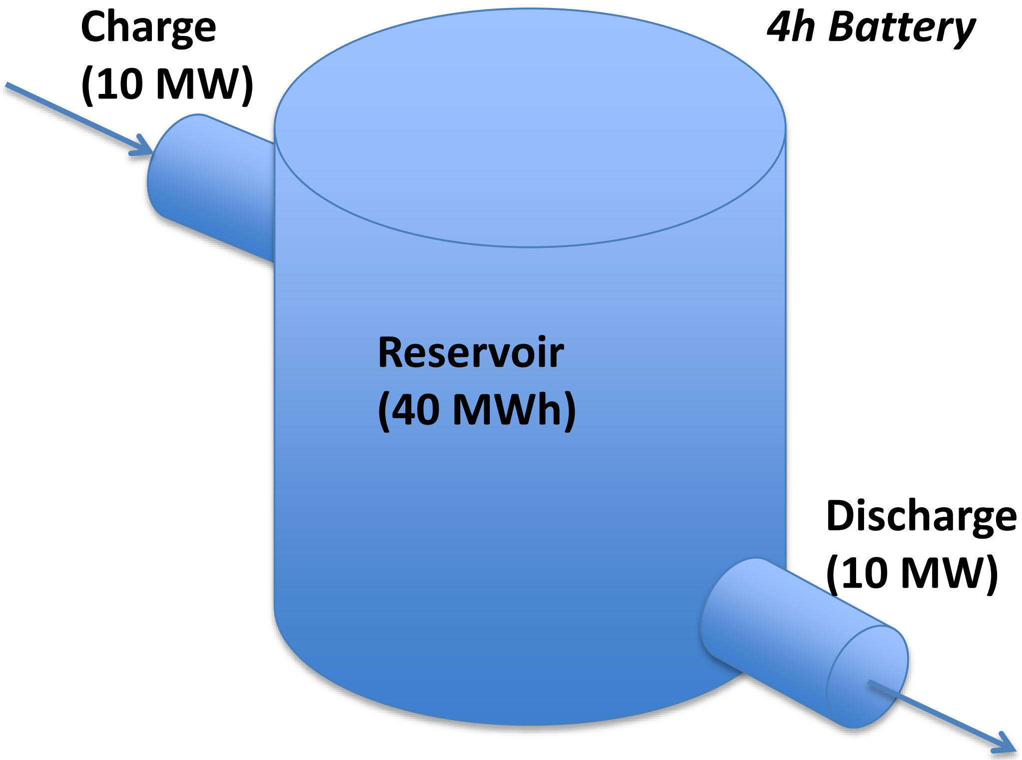
Develop intuition for results from NREL's Resource Planning Model (RPM) model

ID factors that lead to ***relative changes*** in the capacity credit, rather than precise estimates of the capacity credit of any one configuration

Help prioritize additional research directions

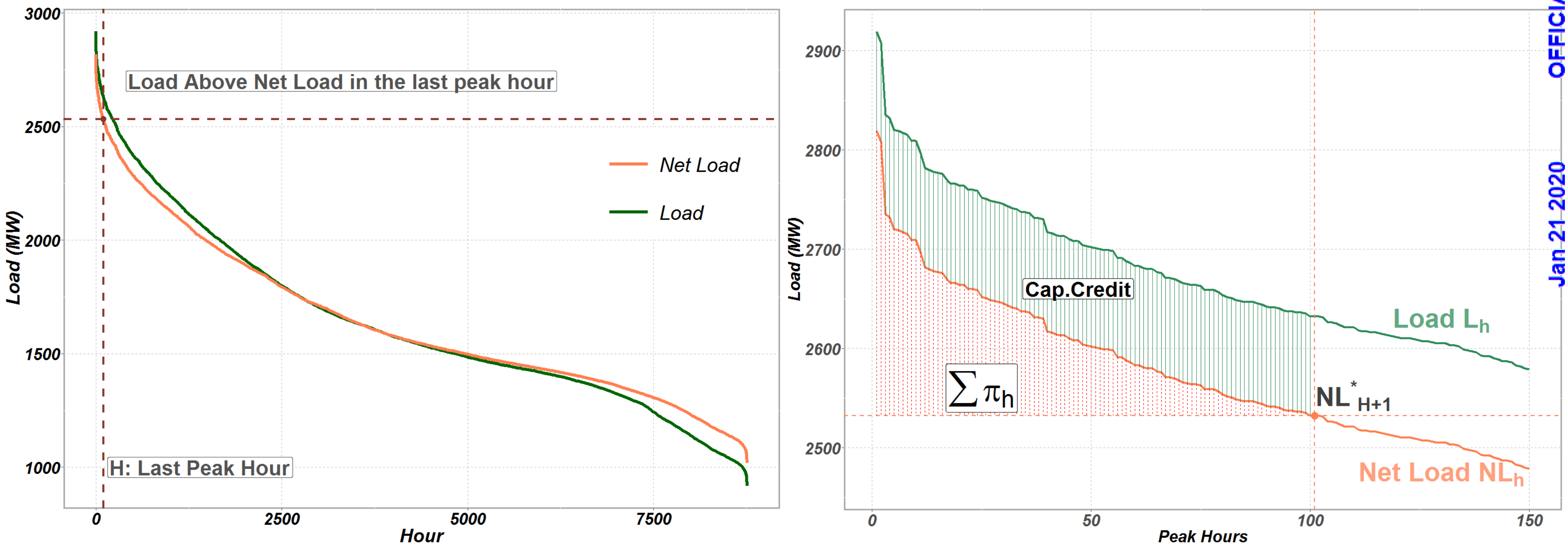
A Note on Storage Sizes

- Batteries have a maximum rate of charge or discharge (the MW nameplate rating).
- And they have a limited amount of energy that can be stored in a reservoir (MWh rating).
- We refer to the size of the battery based on the number of hours that it can be discharged at its full rate of discharge.
- Here a 10 MW battery can provide 10 MW of power or consume 10 MW of load.
- If the 10 MW battery can store 40 MWh of electricity then we call it a 4-hour battery.



Real batteries may not be able to fully charge and discharge (i.e. may not achieve 100% depth of discharge). We use the* **accessible energy, *which may be less than the rated energy.*

Storage Dispatch to Maximize Capacity Credit of Storage

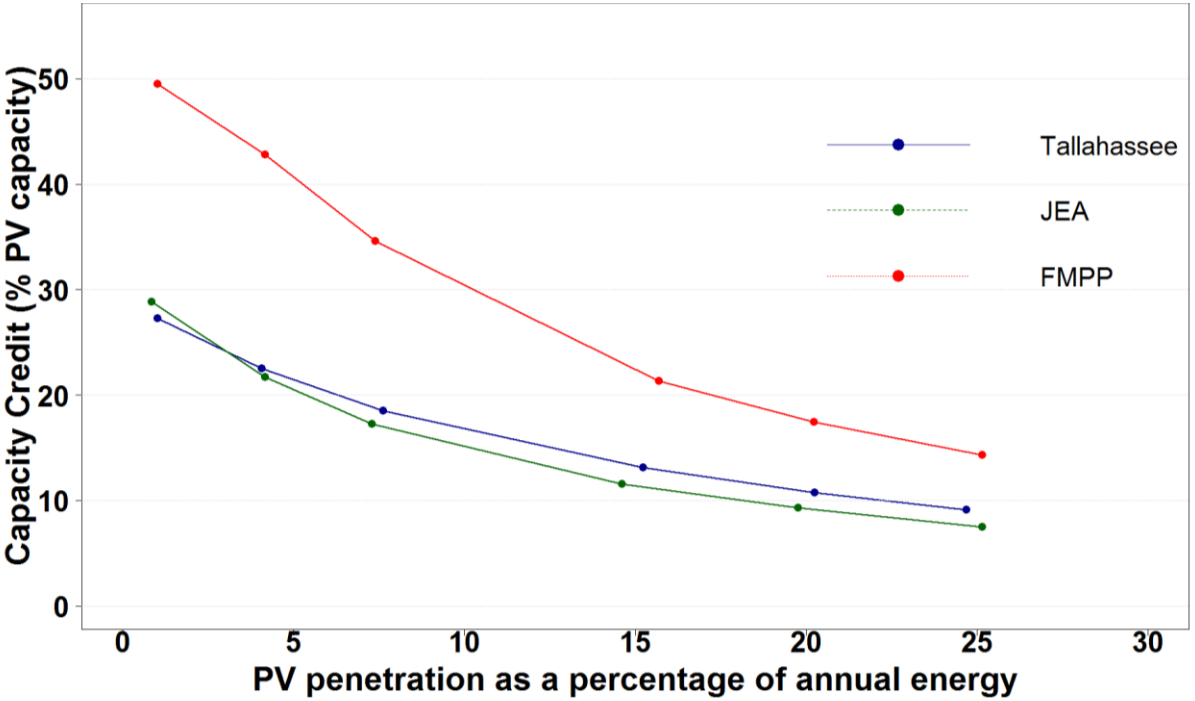


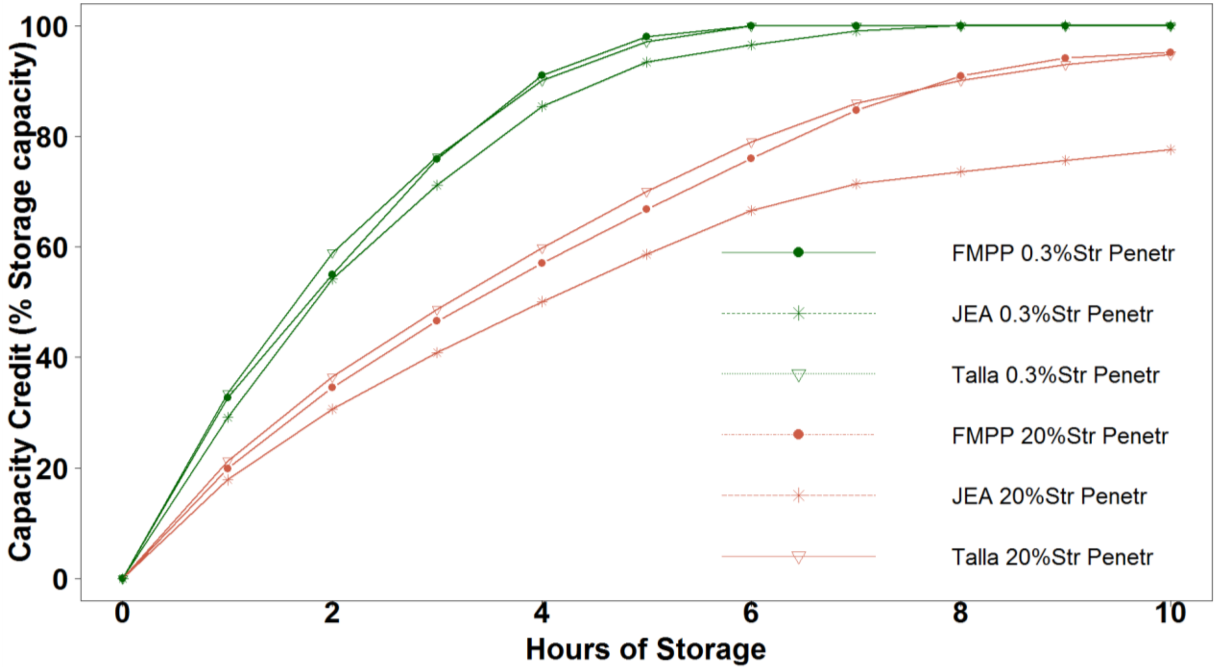
Define capacity credit similar to NREL's "Resource Planning Model": difference of the highest peak load hours and highest peak net load hours. Use a simple linear model to find the storage dispatch that maximizes this capacity credit.

Analytical Approach

Configuration	Questions
PV Alone	• How does the capacity credit vary by site/utility combination? • How much does the capacity credit change depending on solar deployment?
Storage Alone	• How does the capacity credit of storage change with the size of the storage reservoir? • Does the capacity credit of storage change with storage deployment?
PV+Storage	• How does the capacity credit depend on the PV+storage configuration? • How do results change with the battery size relative to the PV size?

Capacity Credit of PV and Storage Alone

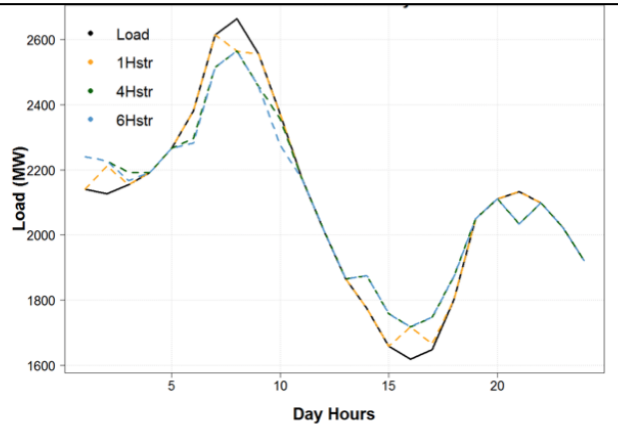
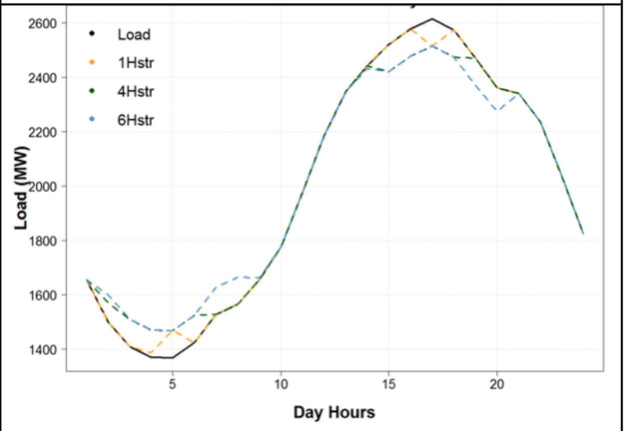




- Capacity credit of PV varies by utility, depending on how well correlated PV production is with peak load.
- Capacity credit of PV declines with increasing penetration.

- Capacity credit of storage depends on duration.
- Duration required to achieve near 100% capacity credit increases with storage deployment.

Impact of Storage Duration on Storage's Ability to Reduce Winter and Summer Peak Load Hours

<table>
<tr><th></th><th>Peak Winter</th><th>Peak Summer</th></tr>
<tr><td>Load and Net Load</td><td>
</td><td>
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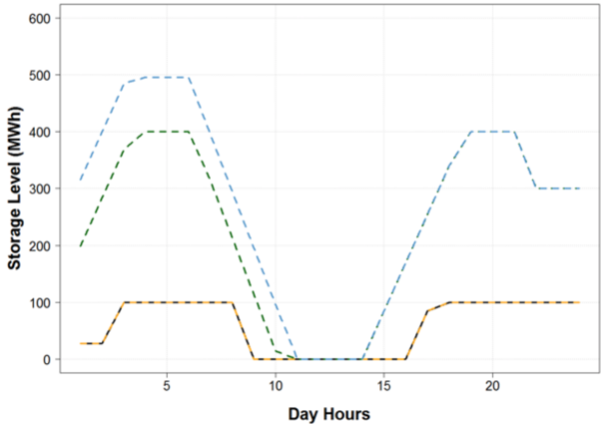
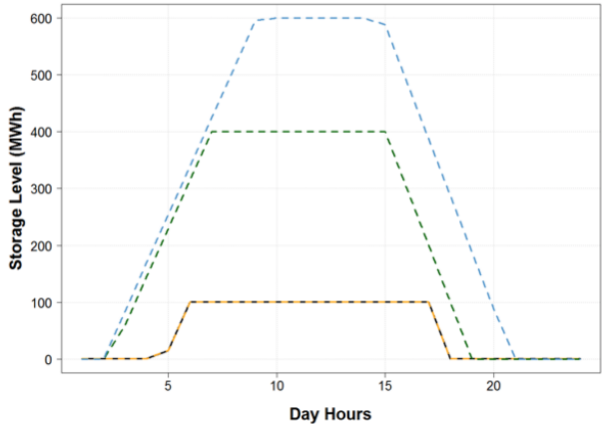
<tr><td>Storage Level</td><td>
</td><td>
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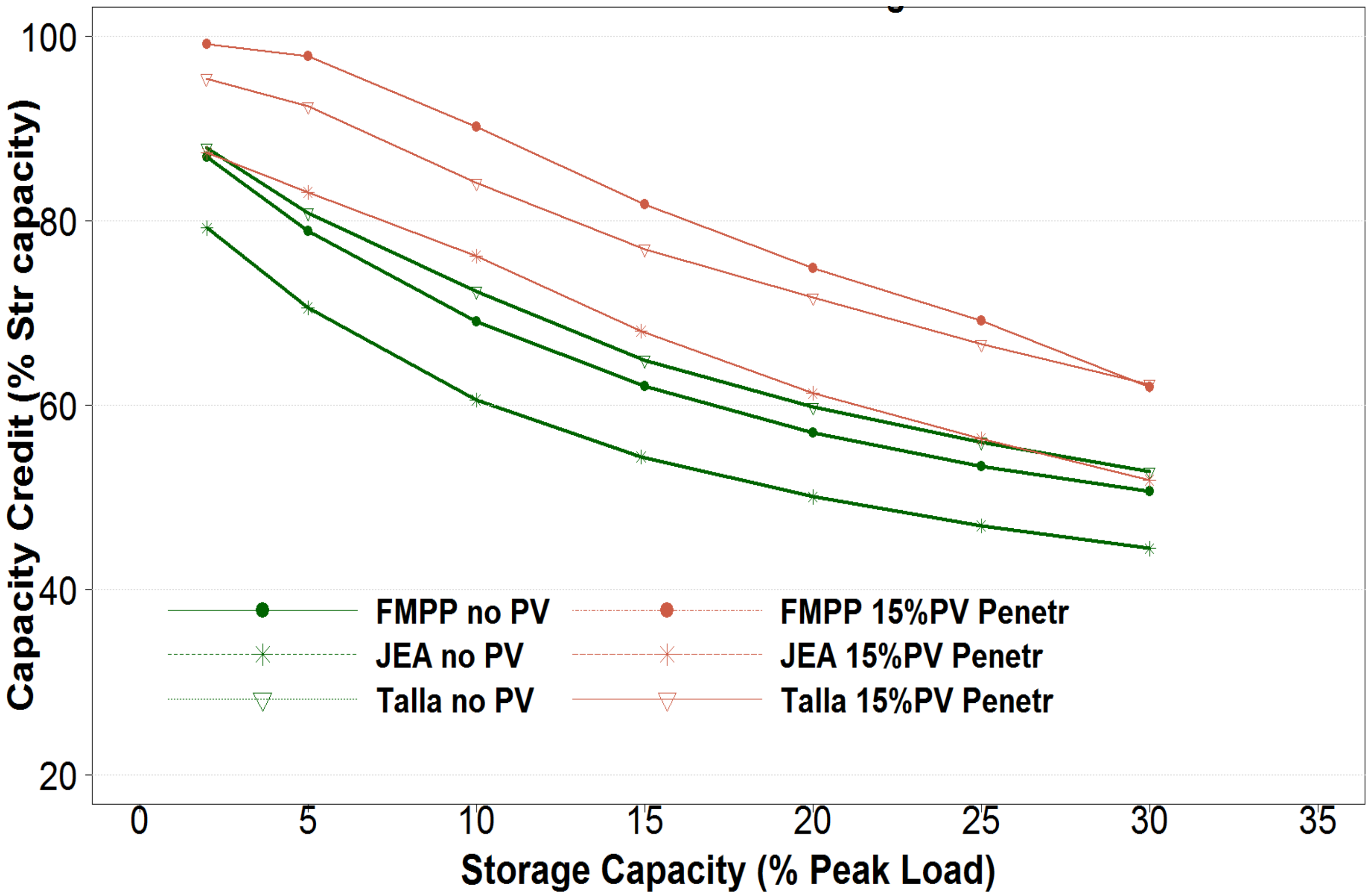
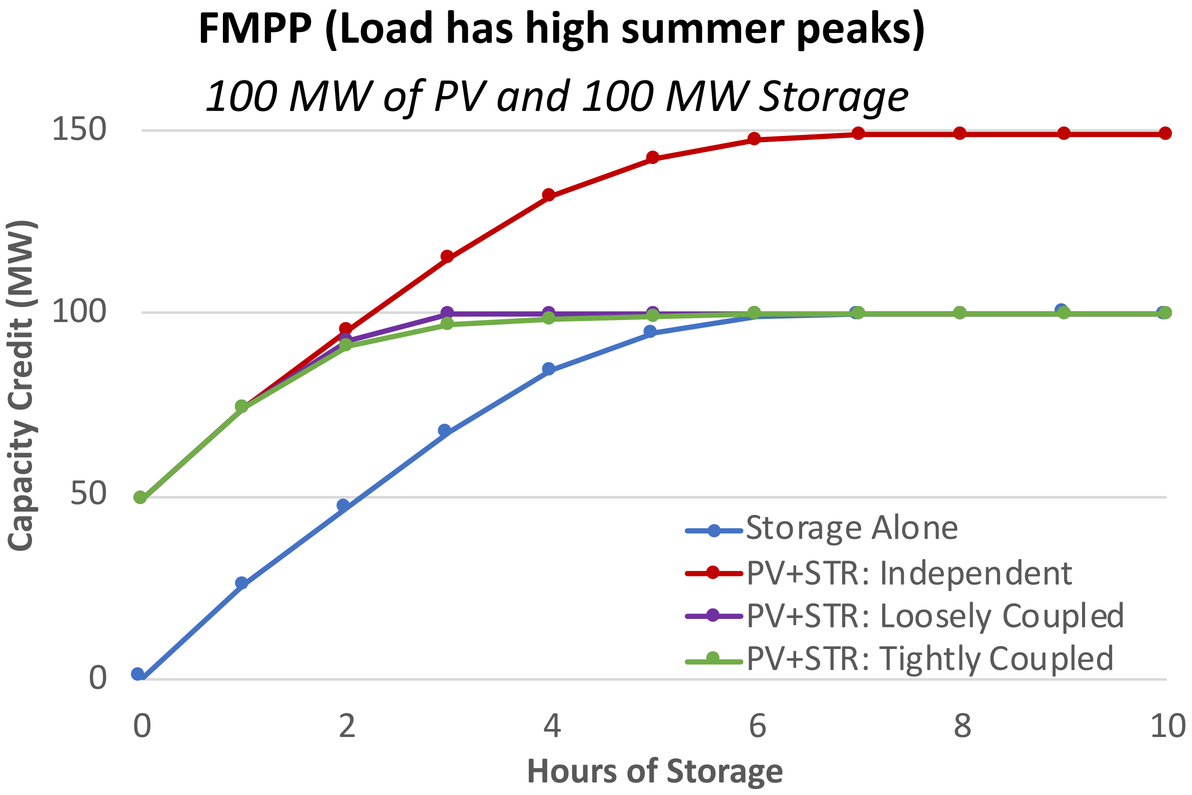
For a Fixed Storage Duration (4 hours), Capacity Credit Declines As More and More Storage is Deployed

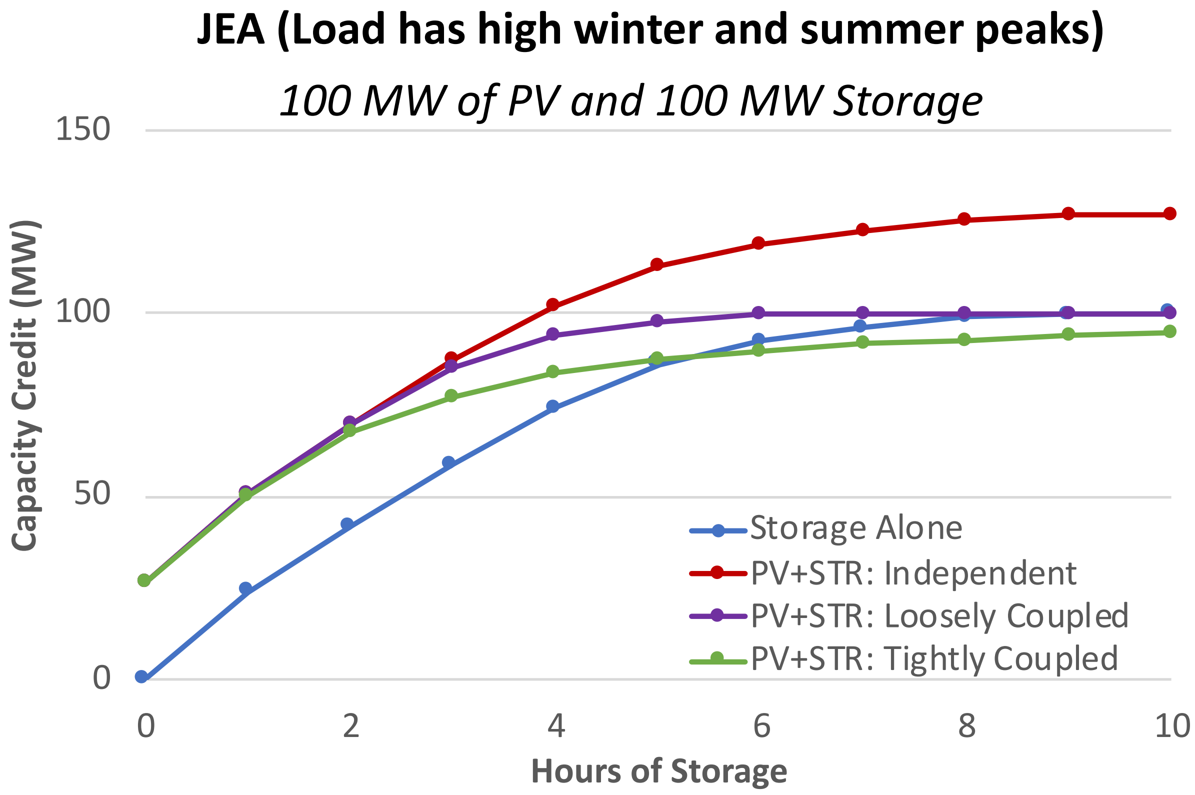


PV + Storage Configurations

Configuration	Description	Share Equipment?	Source of Electricity for Storage
Independent	PV and storage do not share equipment and storage is charged from the grid	No	Grid
Loosely Coupled	PV and storage both connect on the DC side of shared inverters, but storage can charge from storage or the grid	Shared Inverter	Grid or PV
Tightly Coupled	PV and storage connect on DC side of shared inverters, and storage can only charge from PV	Shared Inverter	Only PV

Capacity Credit of Solar+Storage Systems With Large Batteries Depends on Configuration

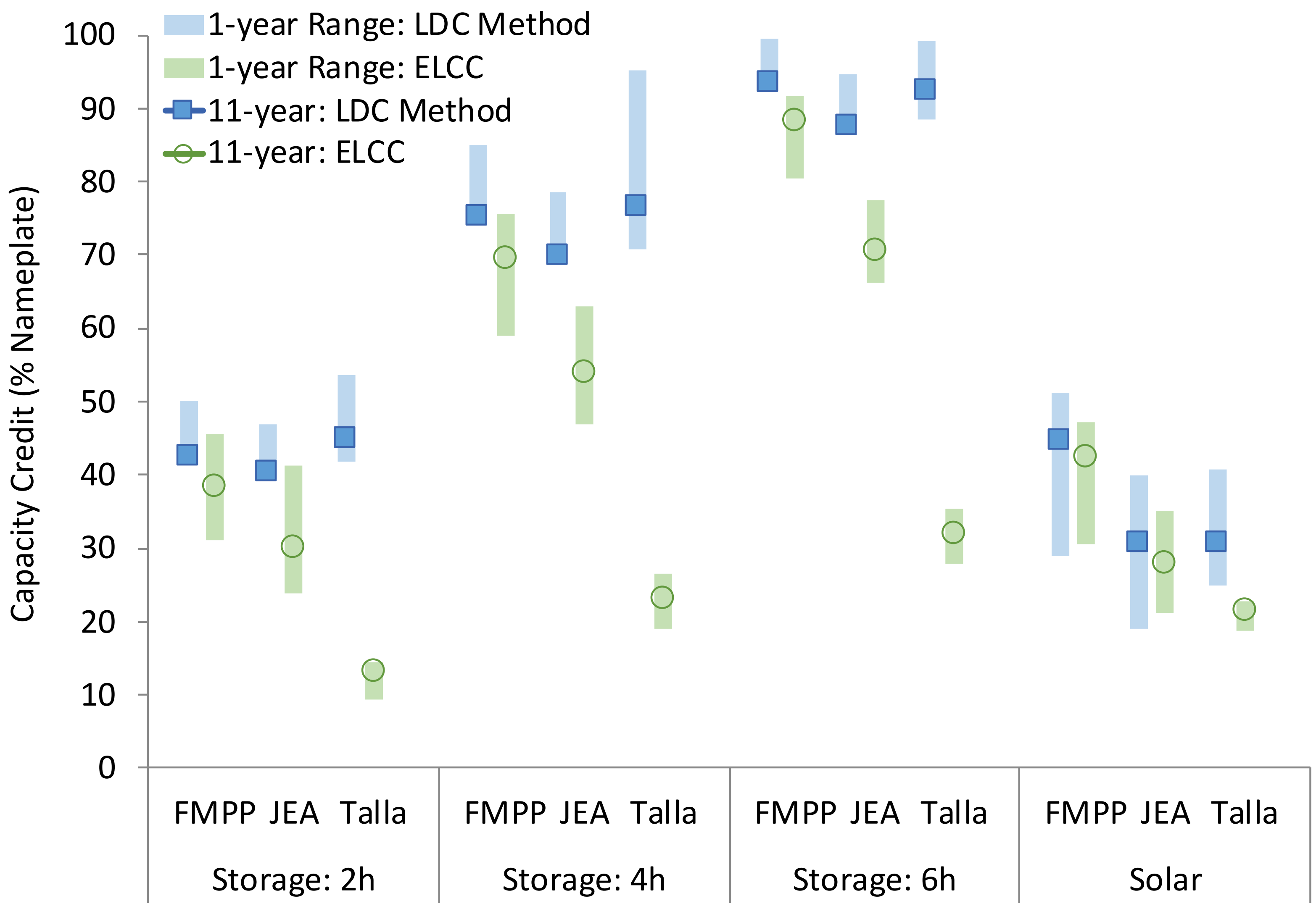




- Capacity credit of PV+Storage can be limited by the shared inverter when DC coupled
- No significant difference for loosely vs. tightly coupled

- For a load with high winter peaks, differences between loosely and tightly coupled are more important
- Restricting storage to charge only from solar can lead to a lower capacity credit than storage alone

Capacity Credit Calculated with Simplified Method is Consistent with Probabilistic Benchmark Except for Very Small Utilities

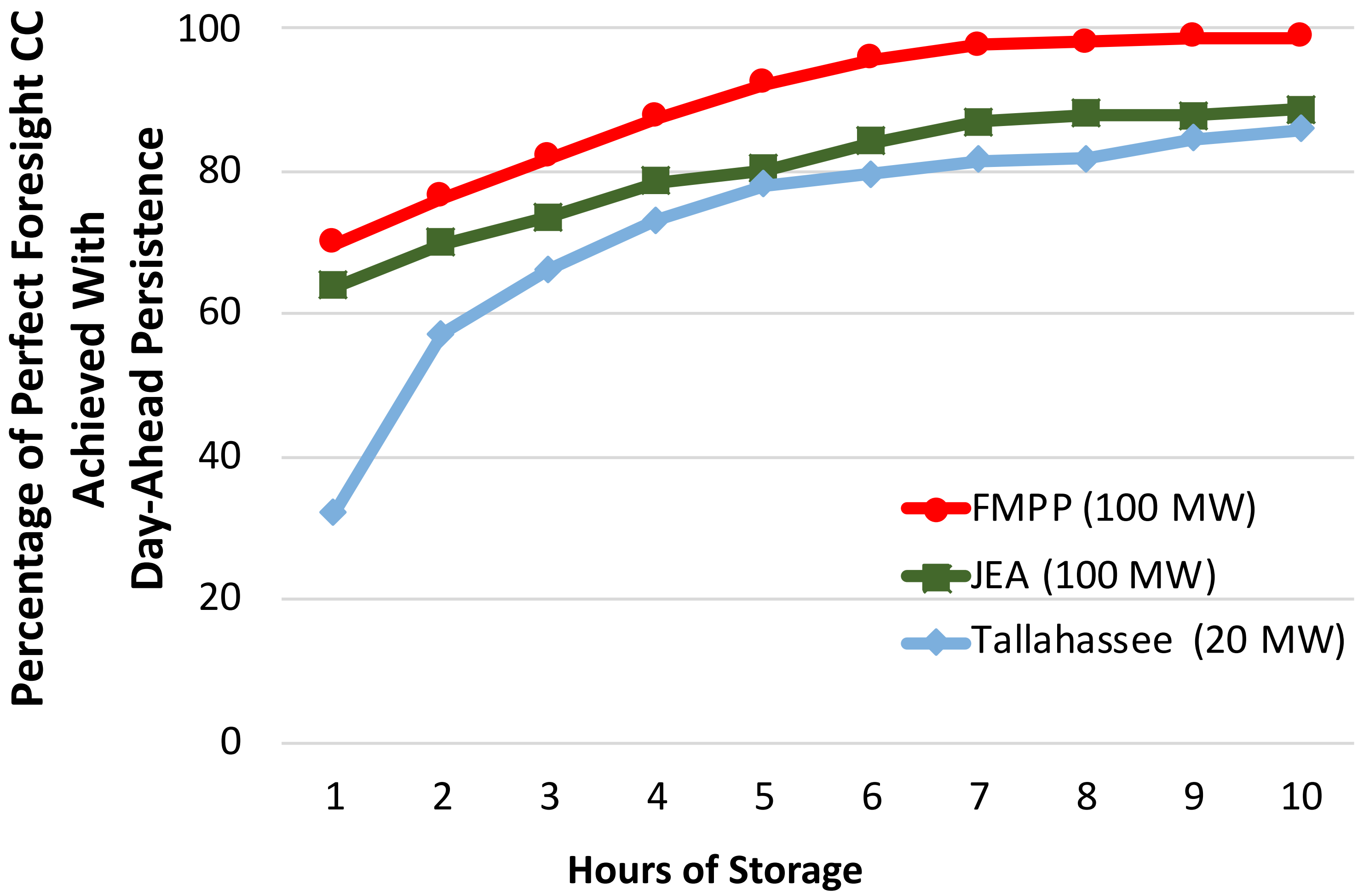


Probabilistic benchmark is a simple Loss of Load Probability Model.

The Effective Load Carrying Capability (ELCC) represents the amount that the demand can be increased after a resource is added to the generation mix while maintaining the same level of overall reliability.

Approximation method (LDC) does poorly for a small utility with a large generator.

Forecasting Matters for Storage Capacity Credit, Particularly for Short Duration

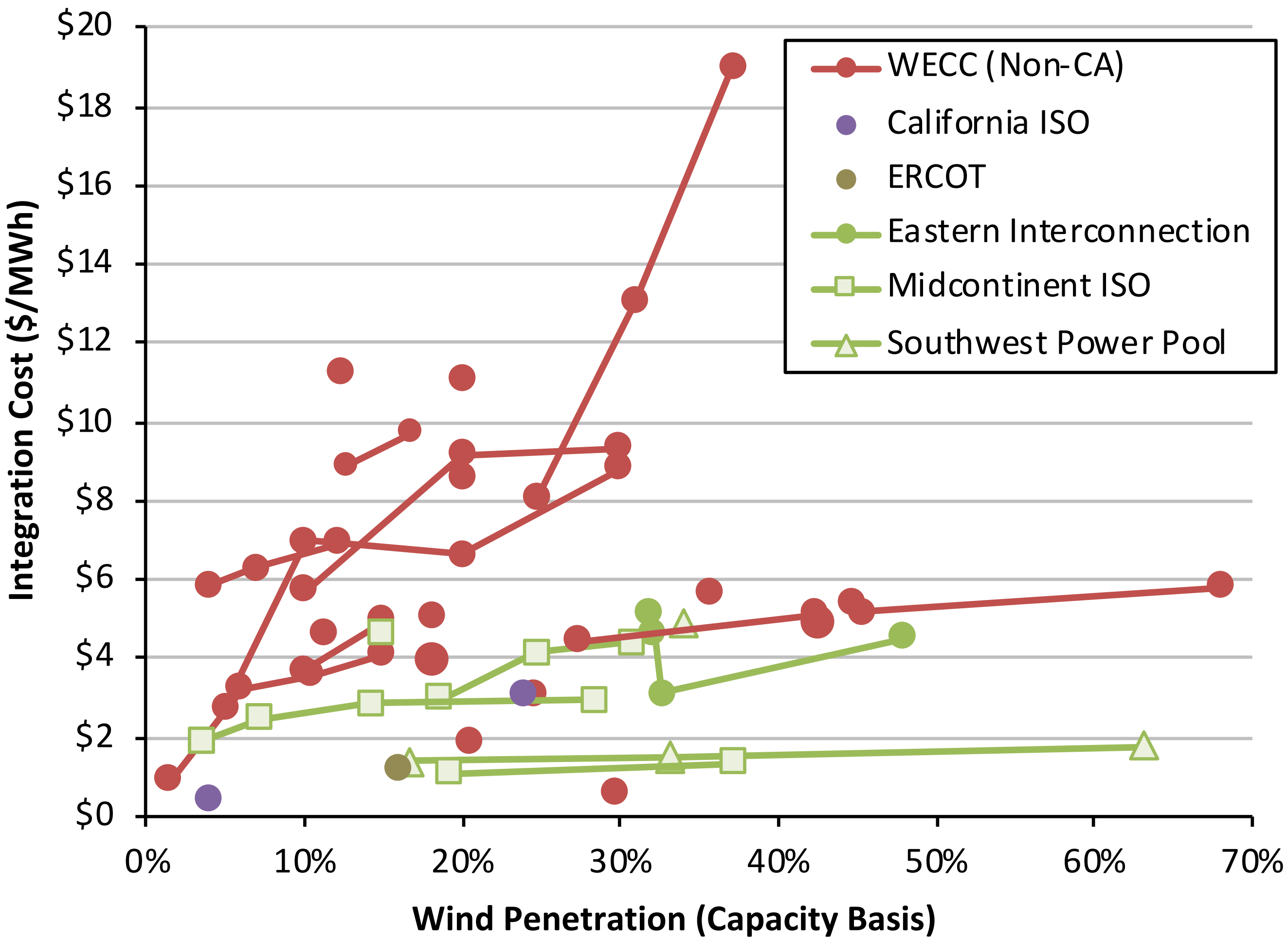


Solar Variability and Integration Costs

Survey of Integration Cost Studies

- Numerous entities conduct studies to estimate integration costs of wind and solar
- Integration cost estimates vary from study to study, due in part to differences in:
  - Resource mix
  - Institutional setting
  - Definitions of integration costs and calculation methodology
- Some methods are better suited to the context of an IRP than others:
  - What aspects of variable renewables are already captured in standard grid planning tools, and what aspects need to be separately estimated via an integration cost?

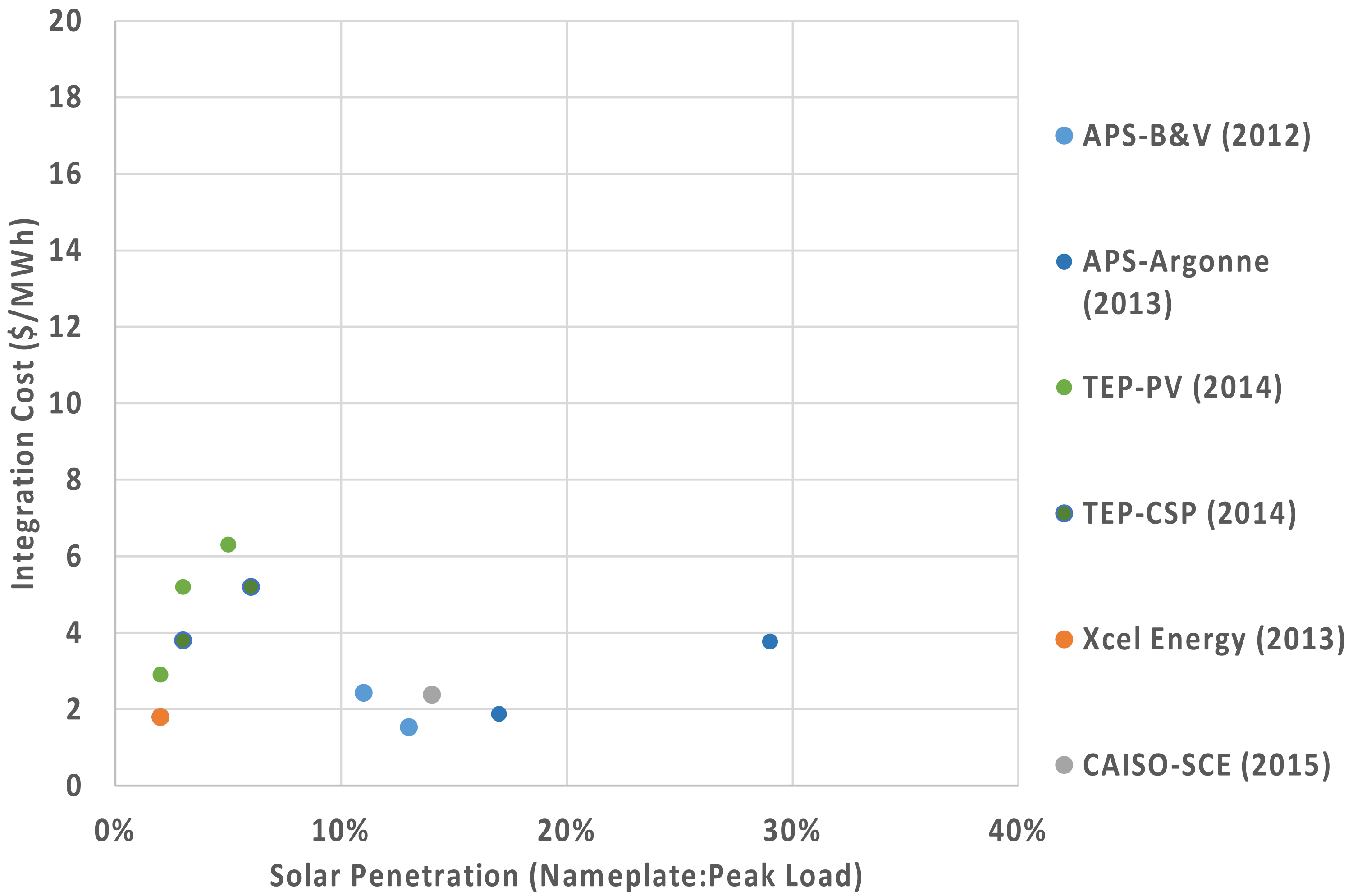
US Wind Integration Cost Estimates



Notes: All studies categorized as WECC (Non-CA) are from individual utilities within WECC. Studies in California and ERCOT are all regional. Many of the studies in the Eastern Interconnect (inclusive of those in MISO and SPP) are regional, but some are from individual utilities. Studies that assessed multiple wind energy penetrations using a common methodology are depicted with connecting lines.

US Solar Integration Cost Estimates

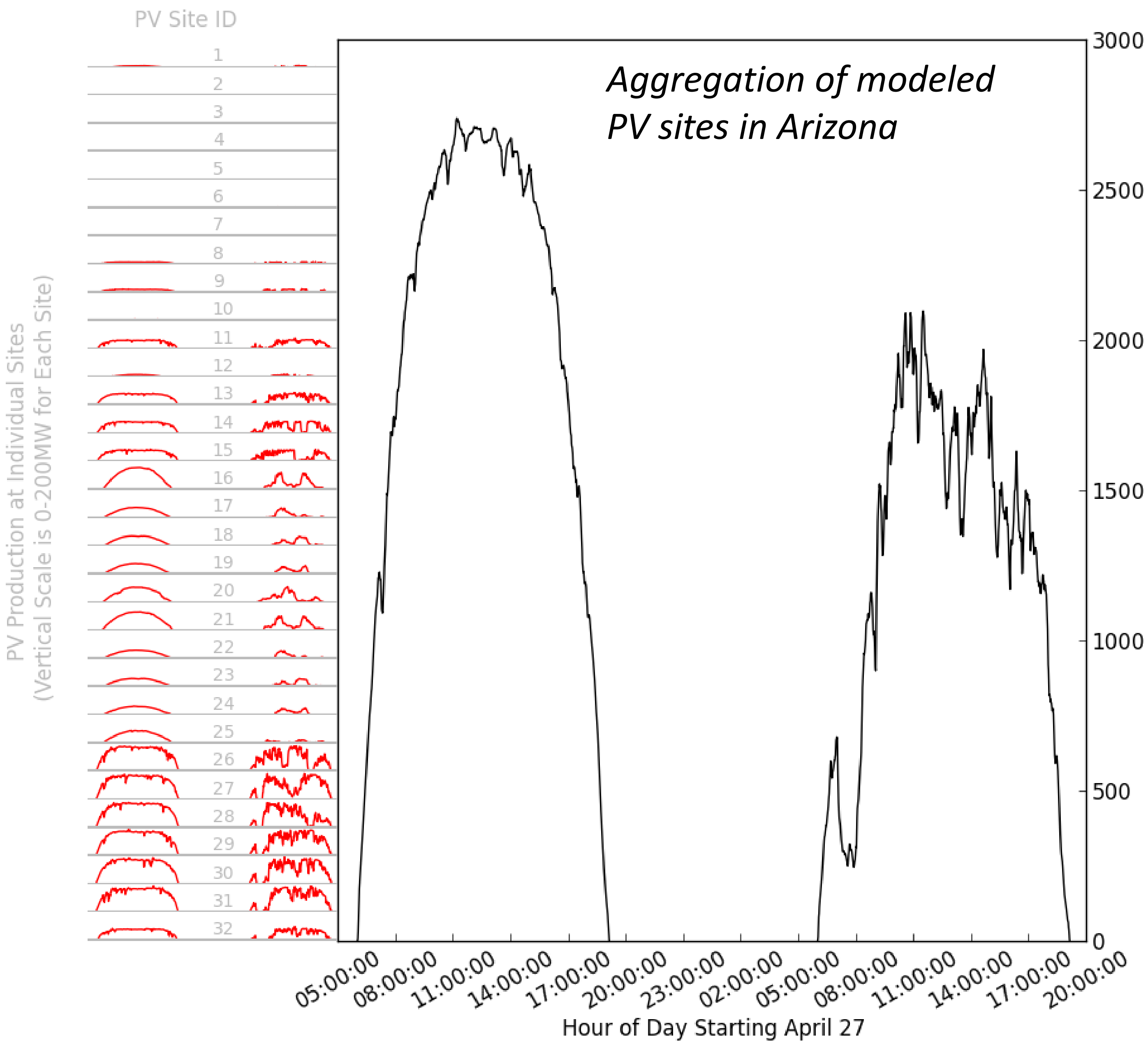
Figure 5. Solar integration costs by level of penetration



Source: Synapse 2015

Aggregation of PV Smoothes Production

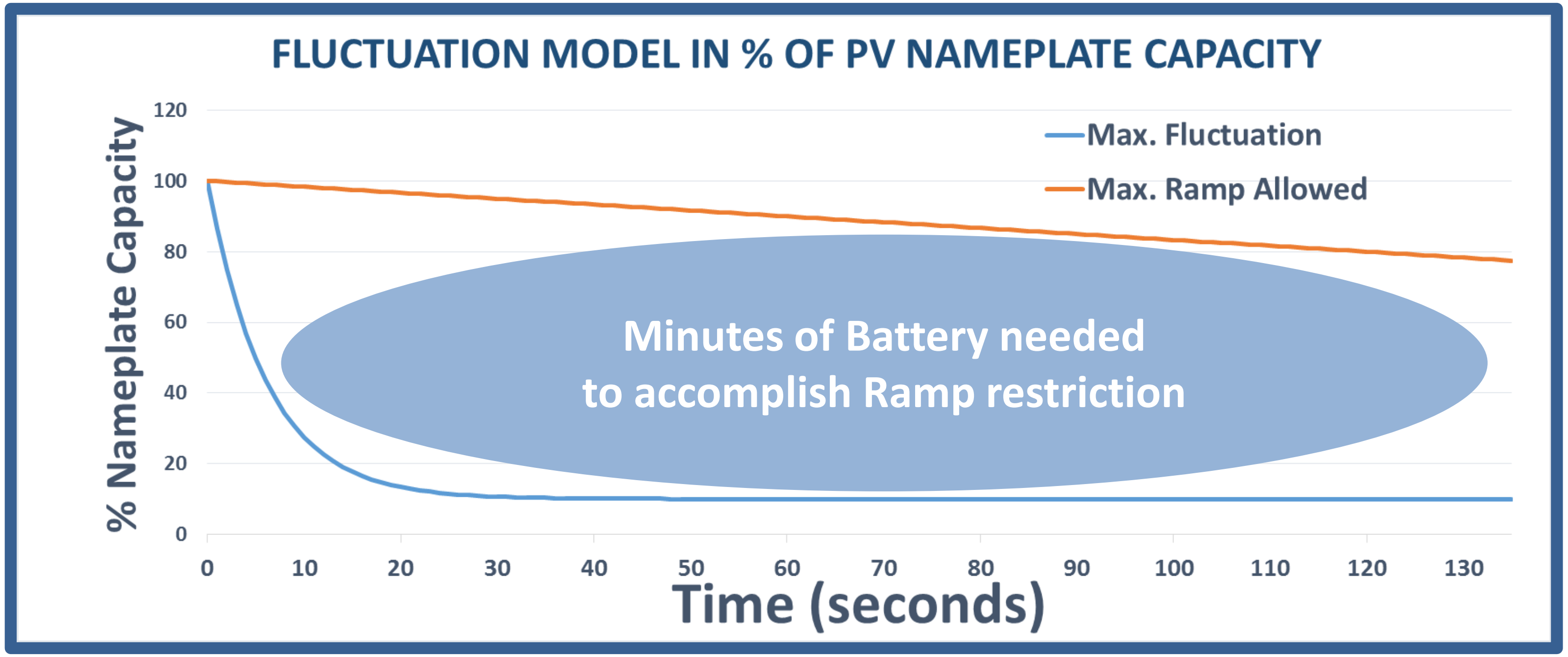
- Aggregate output of multiple sites is smoother than individual sites
- Degree of smoothing depends on the time-scale of variability (e.g., minutes to hours) and the distance between sites
- Costs of managing short-term variability are considerably lower with aggregation



Source: Mills et al 2013

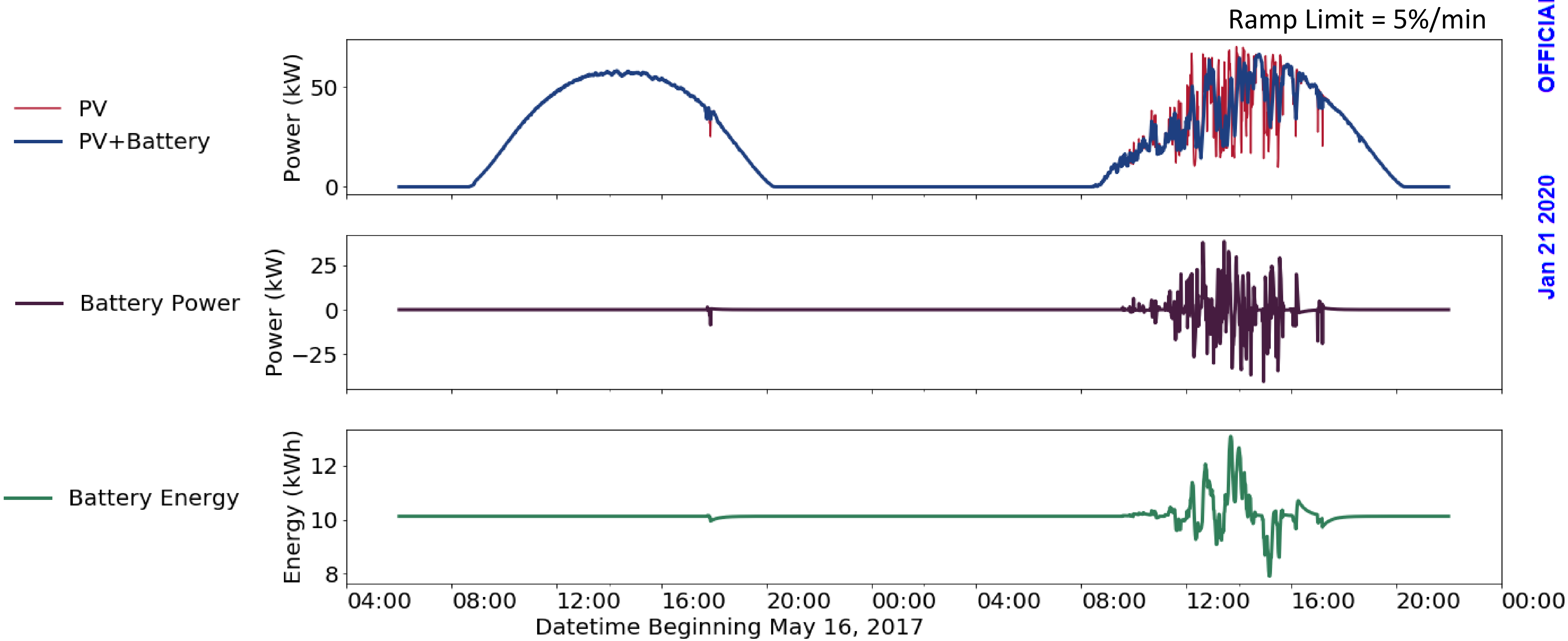
Solar + Storage Ramp Control

Size the Battery Using a "Worst Fluctuation" Model

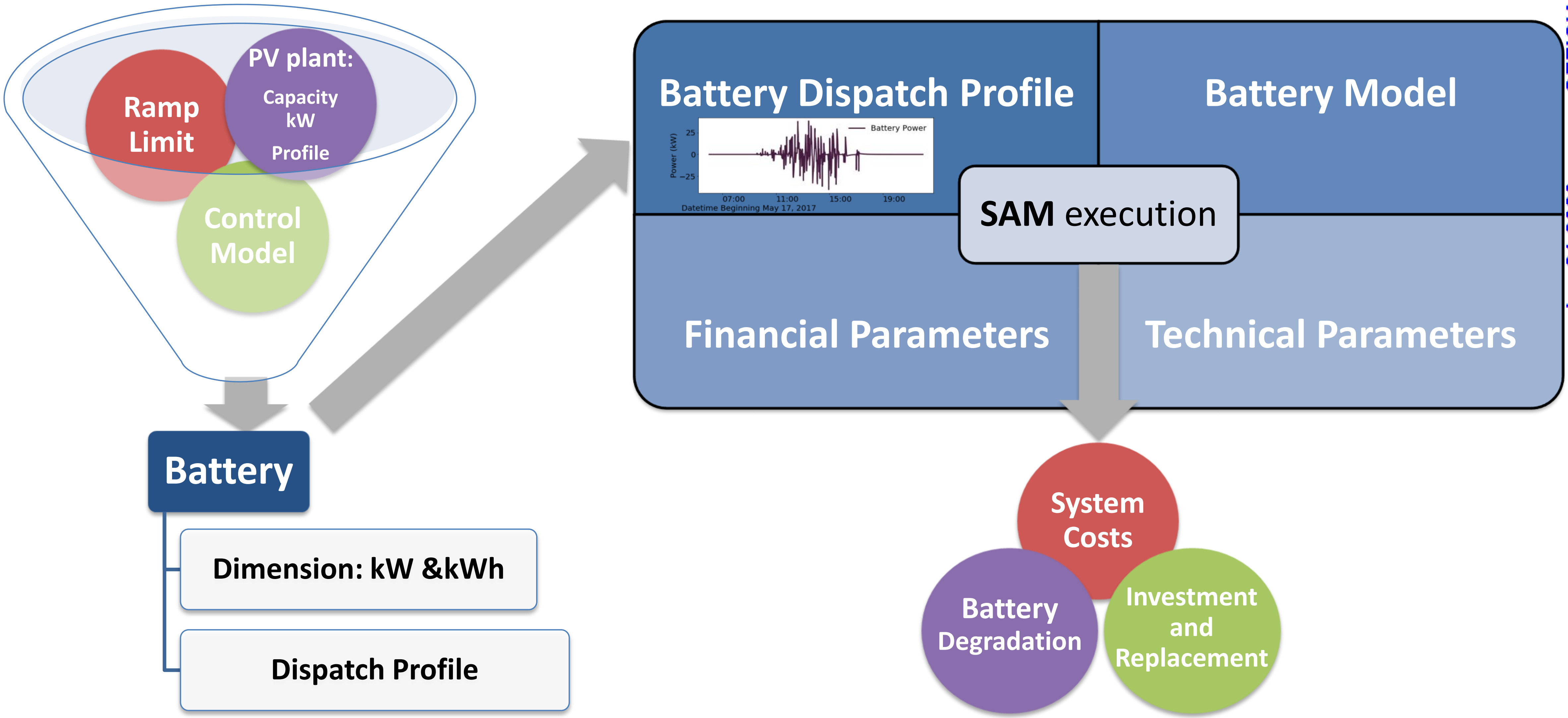


Maximum Ramp (%/min)	Battery Duration (Minutes at PV Nameplate capacity)	Battery Energy (kWh) Pn=75kW
1	81	101.2
2	41	50.6
3	27	33.8
4	20	25.3
5	16	20.3
6	14	16.9
7	12	14.5
8	10	12.7
9	9	11.3
10	8	10.1
11	7	9.2
12	7	8.4
13	6	7.8
14	6	7.2
15	5	6.8
16	5	6.3

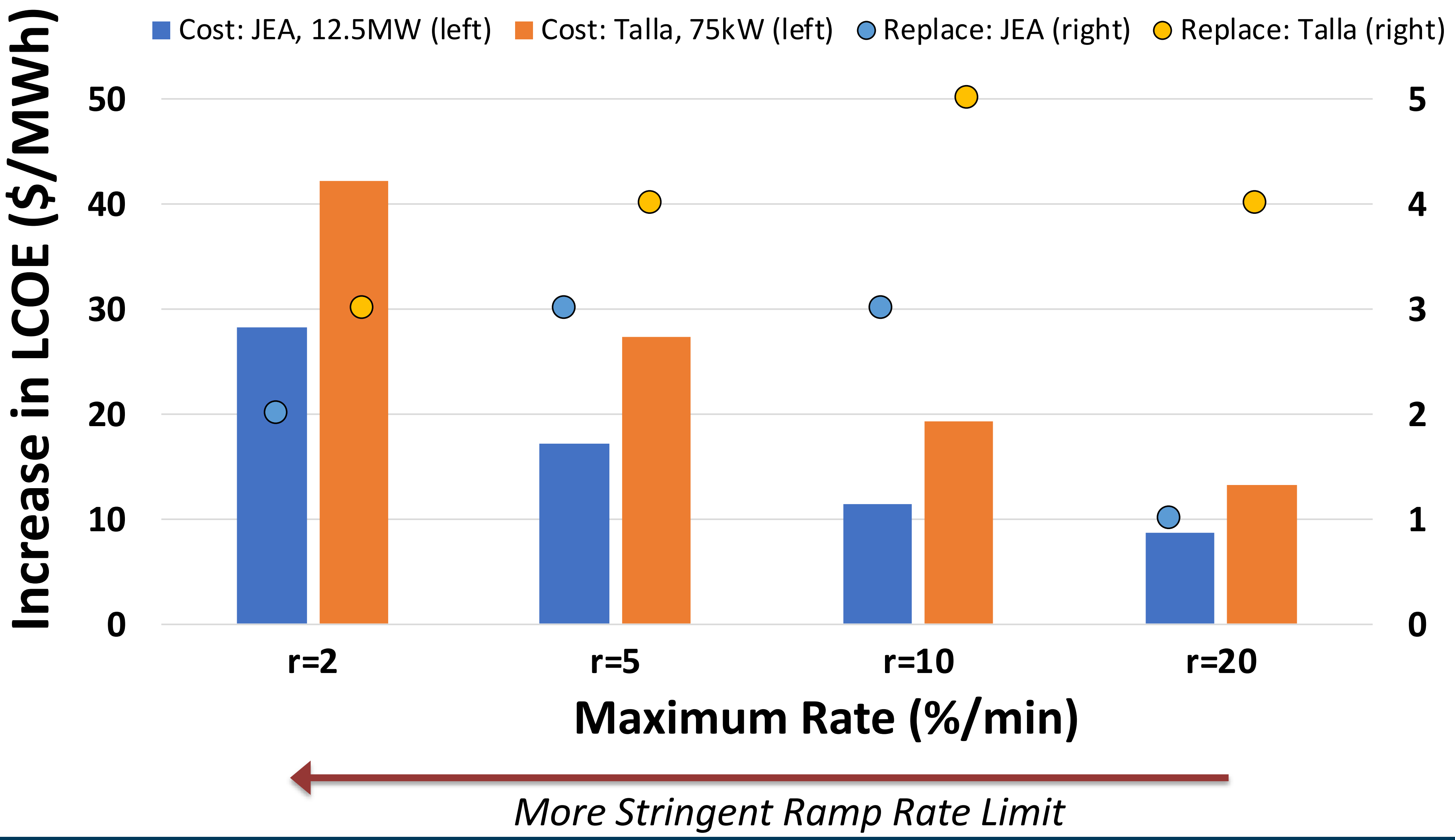
Dispatch Battery Using a Simple Daytime Charging Ramp Control Model



Use NREL's SAM to Analyze Battery Degradation and Costs for Different Ramp Rate Limits



Incremental Battery Costs Increase with Stringency of Ramp Rate Limits



Battery Costs (Fu 2018) = $285/kWh + $106/kW

Battery nameplate equal to solar nameplate

Discount rate of 6.4%

Replacement when battery degrades to 80% of energy capacity

Increase in LCOE represents incremental cost per unit of solar energy to meet ramp limit

Discussion

- Capacity credit of solar varies by utility due to differences in load patterns
- Capacity credit of storage varies with storage duration
- Capacity credit of solar+storage can be limited by shared inverter or interconnection when batteries are large
- Smoothing from solar aggregation lessens integration challenges
- Batteries can be added to solar plants to meet specific ramp-rate limitations, though there are additional costs
- Duration of battery storage and power rating requirements increase with more stringent ramp rate requirements. Larger batteries increase costs.
- Degradation of batteries is more severe with small batteries that are experience large charge and discharge cycles

Additional Directions to Explore

- How do battery size, degradation, and total costs change with various other ramp control strategies?
- How do the costs of ramp-rate limits compare to alternative approaches to managing variability?
  - Geographic diversity: smoothing over larger footprints suggests it may be less expensive to manage aggregate PV ramps rather than ramps at individual PV locations
  - Flexibility from PV curtailment and dispatch
  - Ramping and balancing reserves from dispatchable generators
- How can ramp-control costs be reduced by providing multiple services from the same battery?

Questions?

- Contact information

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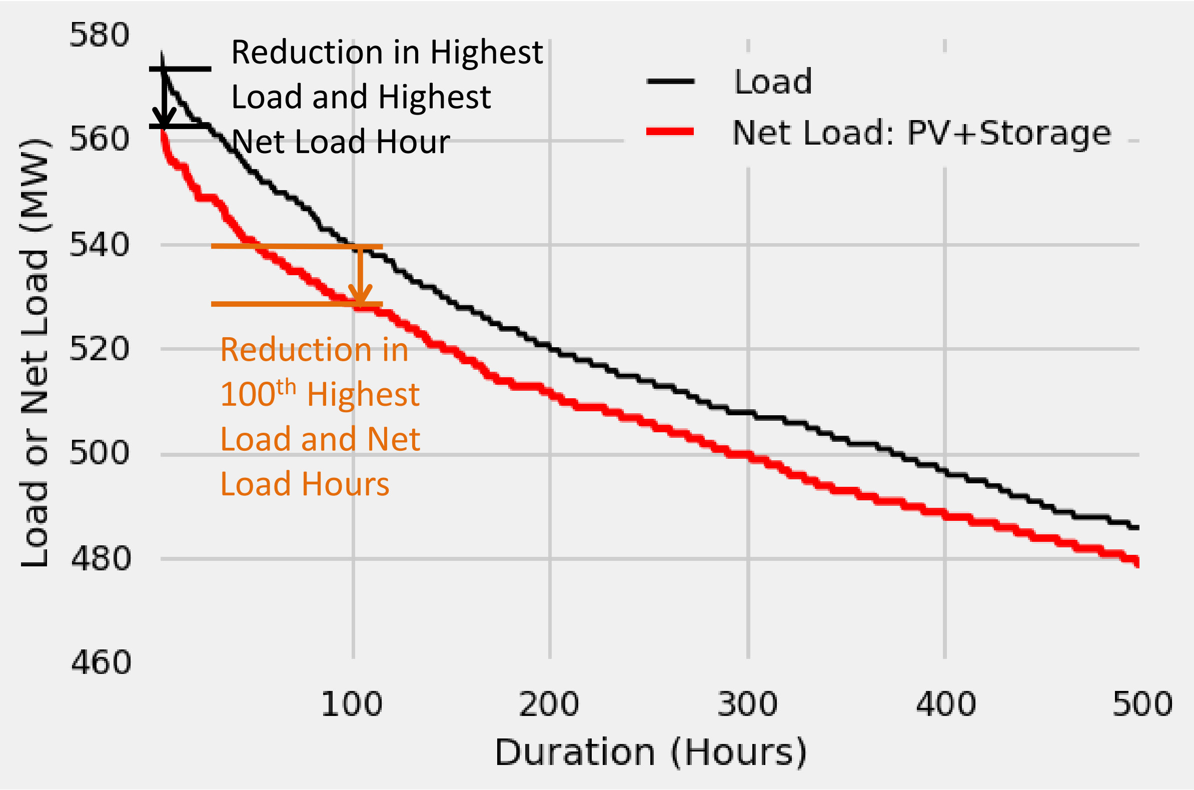
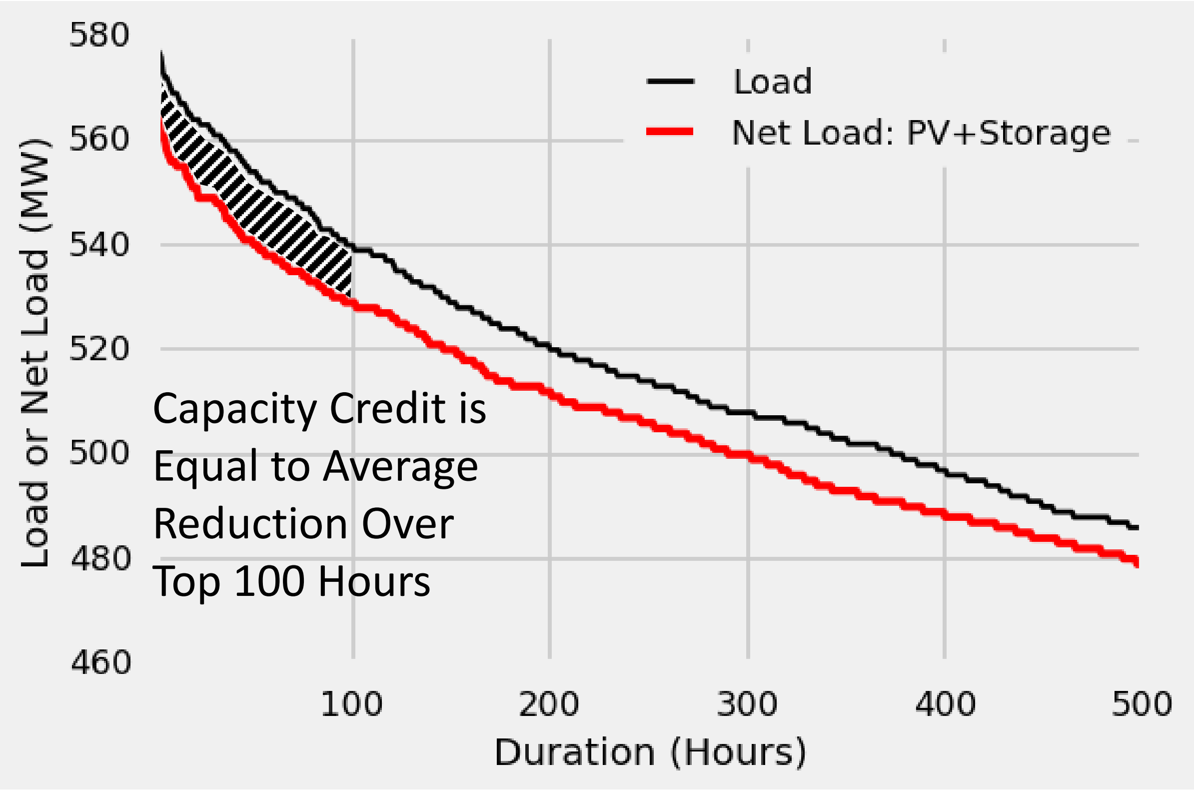
APPENDIX

Resources

- Mills and Rodriguez 2019:
  - Mills, Andrew D., and Pía Rodriguez. "Drivers of the Resource Adequacy Contribution of Solar and Storage for Florida Municipal Utilities." Berkeley, CA: Lawrence Berkeley National Laboratory, October 24, 2019. https://escholarship.org/uc/item/9xz19063.
- Mills et al. 2013:
  - Mills, A., A. Botterud, J. Wu, Z. Zhou, B. M. Hodge, and M. Heaney. "Integrating Solar PV in Utility System Operations." Argonne, IL: Argonne National Laboratory, October 2013. http://www.osti.gov/scitech/biblio/1107495.
- Mills and Wiser 2010:
  - Mills, Andrew, and Ryan Wiser. "Implications of Wide-Area Geographic Diversity for Short-Term Variability of Solar Power." Berkeley, CA: Lawrence Berkeley National Laboratory, September 2010. https://emp.lbl.gov/publications/implications-wide-area-geographic.
- 2018 Wind Technologies Market Report:
  - Wiser, R., and M. Bolinger. "2018 Wind Technologies Market Report." Washington D.C.: U. S. Department of Energy, August 2019. https://emp.lbl.gov/wind-technologies-market-report.
- Synapse 2015:
  - Luckow, P., T. Vitolo, and J. Daniel. "A Solved Problem: Existing Measures Provide Low-Cost Wind and Solar Integration." Cambridge, MA: Synapse Energy Economics, Inc., August 25, 2015. http://synapse-energy.com/sites/default/files/A-Solved-Problem-15-088.pdf.

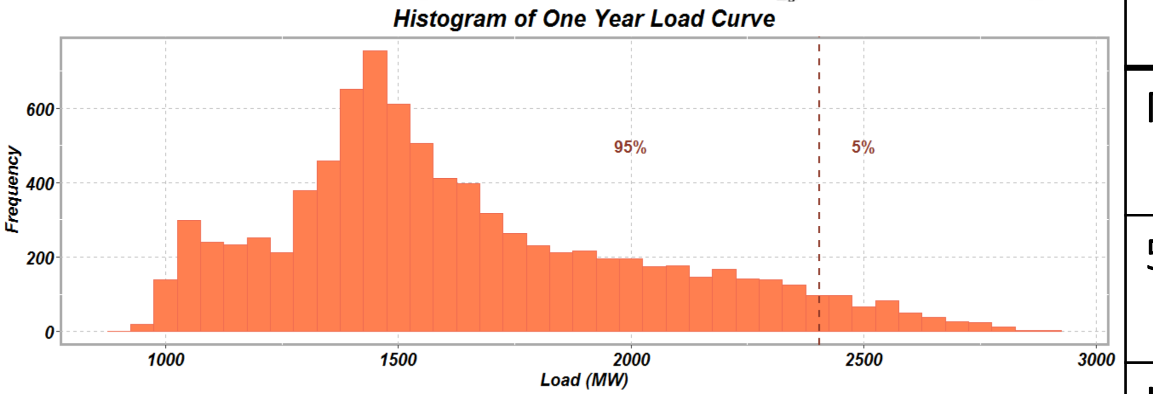
Capacity Credit Based on Method Used in NREL's Resource Planning Model

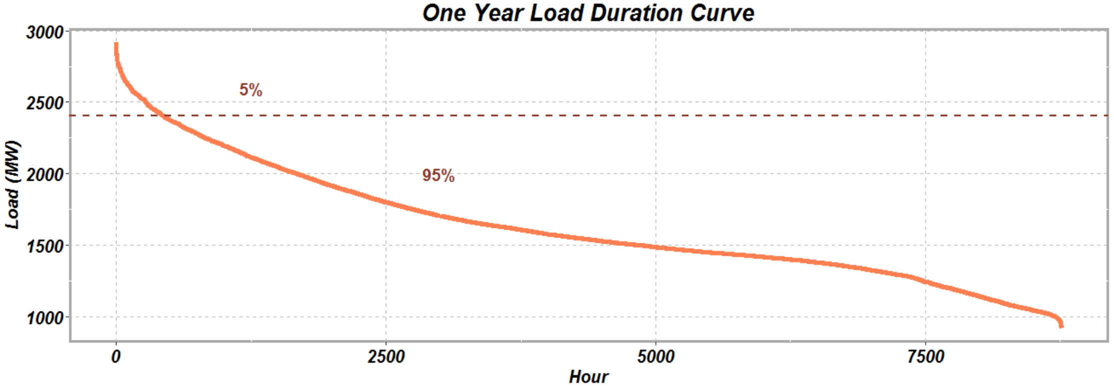




What Storage Dispatch Provides an Upper Bound on Storage Capacity Credit? Insight From CVaR

$$CVAR = min_{VAR,xi,Ls}\left\{VAR_{5\%} - \frac{1}{5\%\ observations}\sum_{\substack{s \\ L_s > VAR}} (L_s - VAR_{5\%})\right\}$$

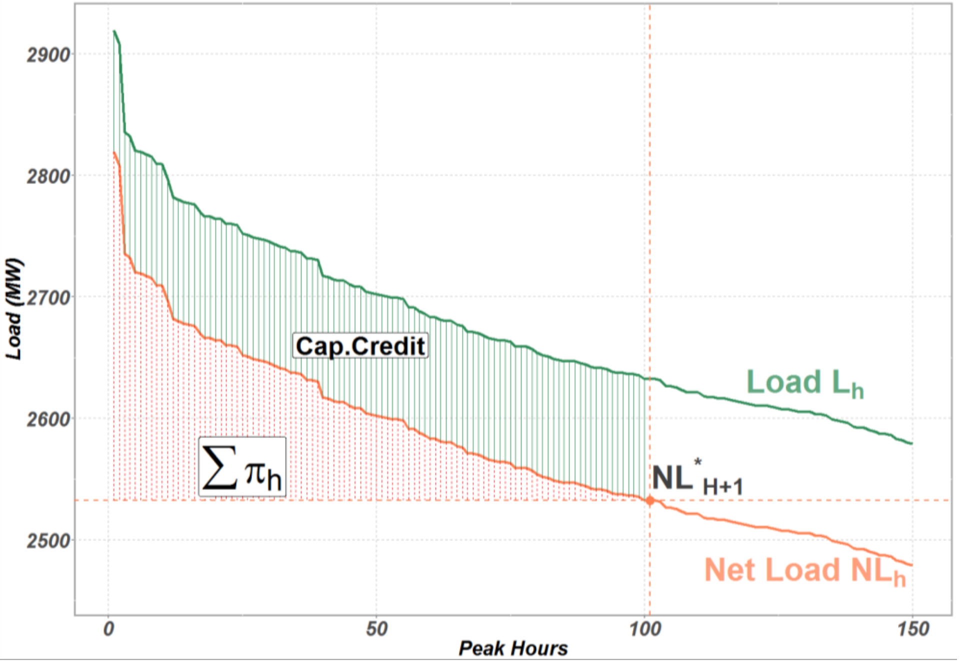




Typical CvaR Problem	Maximum Capacity Credit Dispatch of Storage
Min CVaR.................................	Min average peak net load
5th Percentile	100 highest hours
Losses	Net load
Portfolio of Stocks	Storage dispatch
VaR.....................................	Net Load in hour 101

Examples: Rockafellar et al. 2000. “Optimization of Conditional Value-at-Risk.” *Journal of Risk* 2: 21–42.
Conejo et al. 2010. “Risk Management.” In *Decision Making Under Uncertainty in Electricity Markets*

Storage Dispatch to Maximize Capacity Credit of Storage



Objective

$$\min\left\{NL^*_{H+1} + {}^{1}\!/_{H} \sum_h \pi_h\right\}$$

Operational Constraints

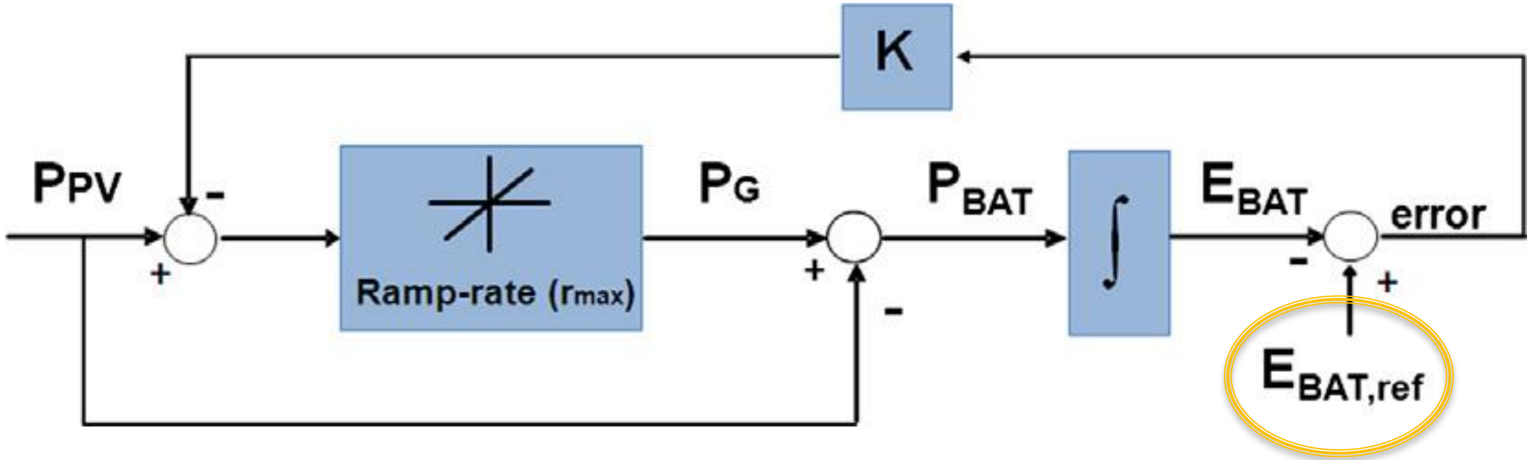
Load and Net Load	$NL_h = L_h + Bi_h - Bo_h$
Identify Peak Hours	$\pi_h \geq NL_h - NL^*_{H+1}$
Ignore Net Load in Non-peak Hours	$\pi_h \geq 0$
Storage Energy Balance	$Bl_h = Bl_{h-1} + \eta \cdot Bi_h - Bo_h$
Maximum Storage Level	$Bl_h \leq Bl_{Max}$
Maximum Storage Production	$0 \leq Bo_h \leq Bp_{Max}$
Maximum Storage Charge	$0 \leq Bi_h \leq Bp_{Max}$

Emerging Applications of PV Ramp-Rate Control

- In isolated systems, where broad aggregation of multiple resources is not possible, managing the intermittent nature of solar with conventional generators is challenging.
- In some cases, system operators have implemented interconnection requirements that establish a maximum allowed fluctuation within a certain time scope. System operators in Puerto Rico, for example, imposed a 10%/min limit on PV ramps.
- Different strategies for using energy storage to limit PV fluctuations are demonstrated in the literature. Each has advantages and disadvantages:
  - Ramp-Rate control strategies: daytime charging, inverter limitation, PV plant production model, step model
  - Moving Average Model
  - Constant production

Smoothing of Power Fluctuations with Energy Storage: Daytime Charging Ramp-Rate Control Model

- **Basic Control Model**
- Energy from the sun is used to keep battery level close to the reference value (half charge $E_{BAT,ref}$)



- Value of recovery constant *K*: too high or too low values will increase the risk of totally discharging the battery. Values between 2 and 8 are recommended.

Distances Required for Short Fluctuations to be Uncorrelated Are < 1km