NATIONAL RENEWABLE ENERGY LABORATORY

Energy Storage Requirements for Achieving 50% Penetration of Solar Photovoltaic Energy in California

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September 2016

NREL/PR-6A20-66970

Background

- Solar photovoltaic (PV) costs are declining.
- PV deployment is increasing, particularly in California.
- Stakeholders are increasingly aware of the economic limits to PV deployment based on supply/demand imbalance and resulting PV curtailment.
- Substantial use of enabling technologies and strategies might be needed to control curtailment and maintain the economic competitiveness at PV penetrations beyond 20%–25%.
  - What impact would various enabling technologies and strategies have on PV curtailment and economics?
  - What magnitude of these technologies and strategies would need to be deployed?
  - When would that deployment need to occur?

Project Goals

- Analyze the challenges of generating up to 50% of annual energy requirements with PV in California by 2030 (while generating up to 70% of annual energy requirements with all renewable sources)
- Examine various technologies and strategies that could increase grid flexibility, reduce PV curtailment, and maintain competitive PV economics
- Determine the amount of energy storage that might be needed to enable very high PV penetration under different flexibility scenarios

Methods: Modeling High-PV Scenarios in California

- We use NREL's Renewable Energy Flexibility (REFlex) model to simulate high-PV scenarios in California.
- REFlex is a reduced-form dispatch model that focuses on minimum-generation constraints.
- It performs chronological dispatch of storage, demand response, and electric vehicle charging.

Methods: Net Levelized Cost of Energy (LCOE) Metric

- Determining the optimal mix of renewables, storage, and other flexibility options will require detailed cost-benefit analysis.
- Because this is a scoping study, we need a simple metric to frame the overall requirements.
- Flexibility requirements are based on keeping PV curtailment to an acceptable level.
- The acceptable level is based on the net levelized cost of energy (LCOE).
  - Net LCOE is the cost of PV energy after considering curtailment and storage losses.
  - Net LCOE = base LCOE/(1 – curtailment rate)
  - Net LCOE does not include the cost of storage, which is largely recovered through providing resource adequacy capacity.
- Our target net LCOE is the variable cost of a combined-cycle generator in 2030: 7 cents/kWh
  - We use only the variable cost because PV will have zero marginal capacity credit beyond about 20% penetration.
  - Combined-cycle gas turbine assumptions in 2030 are 7,500 BTU/kWh, \$6.3/MMBTU, and \$52/ton CO_2.

Methods: Current (2014) California Generation Mix

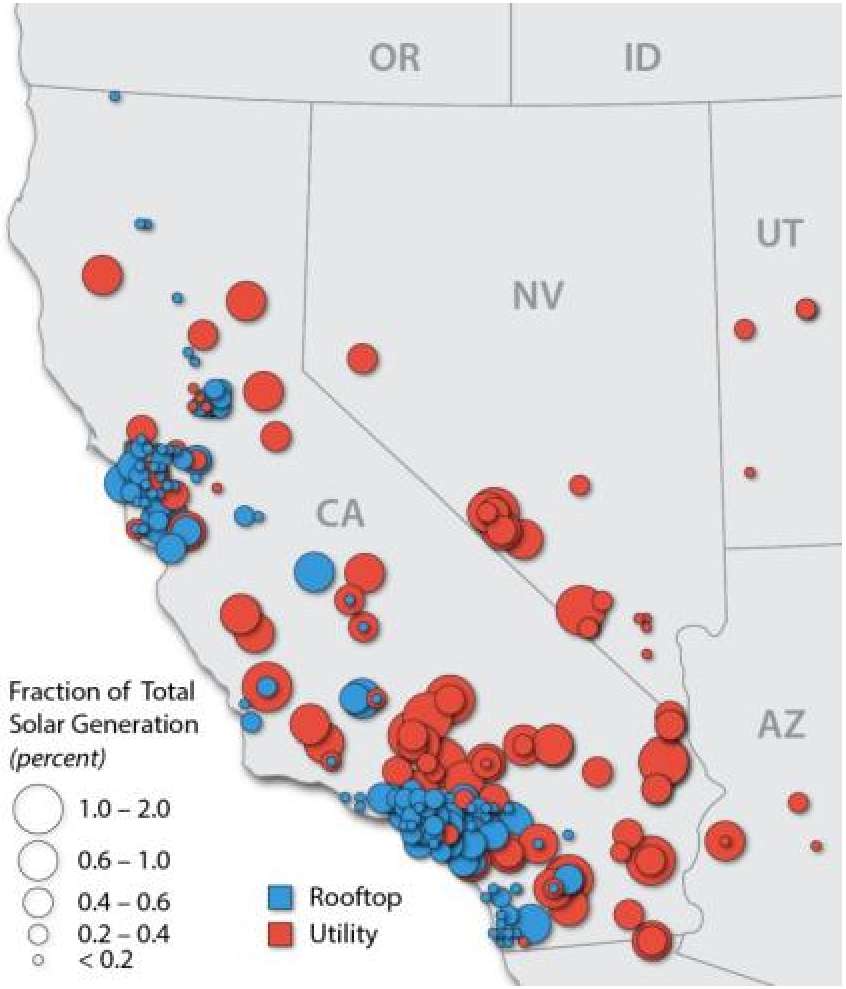
	California Annual Generation in 2014	
	(Gigawatt-hours) GWh	Percentage
Biomass	7,507	2.5%
Concentrating solar power (CSP)	1,619	0.5%
Fossil	151,037	50.0%
Geothermal	13,030	4.3%
Large hydro	16,350	5.4%
Nuclear	25,220	8.4%
PV (rooftop)	5,115	1.7%
PV (utility scale)	10,932	3.6%
Small hydro	2,787	0.9%
Wind	23,913	7.9%
Other (unspecified imports)	44,433	14.7%
Total	**301,943**	**100.0%**

Sources

- Rooftop PV: GTM Research and Solar Energy Industries Association. 2015. *U.S. Solar Market Insight Q2 2015*.
- Other technologies: California Energy Commission. 2014. California electricity statistics and data. http://energyalmanac.ca.gov/electricity/system_power/2014_total_system_power.html. Imports are included in the respective generator category as described in this source.

Methods: Creating a 2030 Scenario

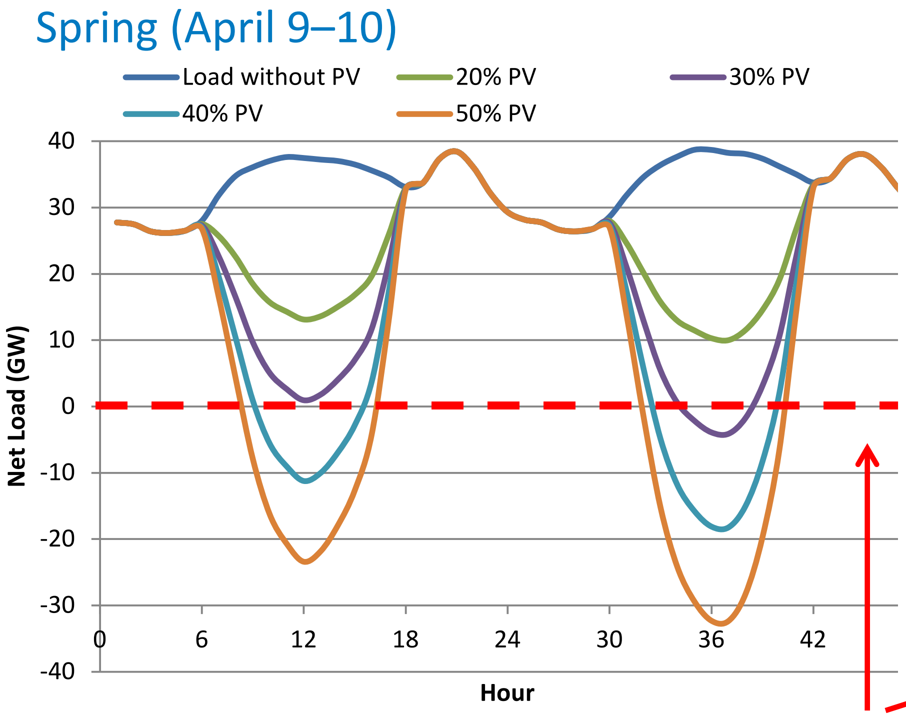
- Add enough wind to meet 11% of annual demand.
- Add PV to meet up to 50% of annual demand.
  - 60%/40% mix of utility/rooftop PV
  - Utility-scale PV is 60% tracking, 40% fixed
- Use PV and wind profiles from NREL Low-Carbon Grid Study http://www.nrel.gov/docs/fy16osti/64884.pdf

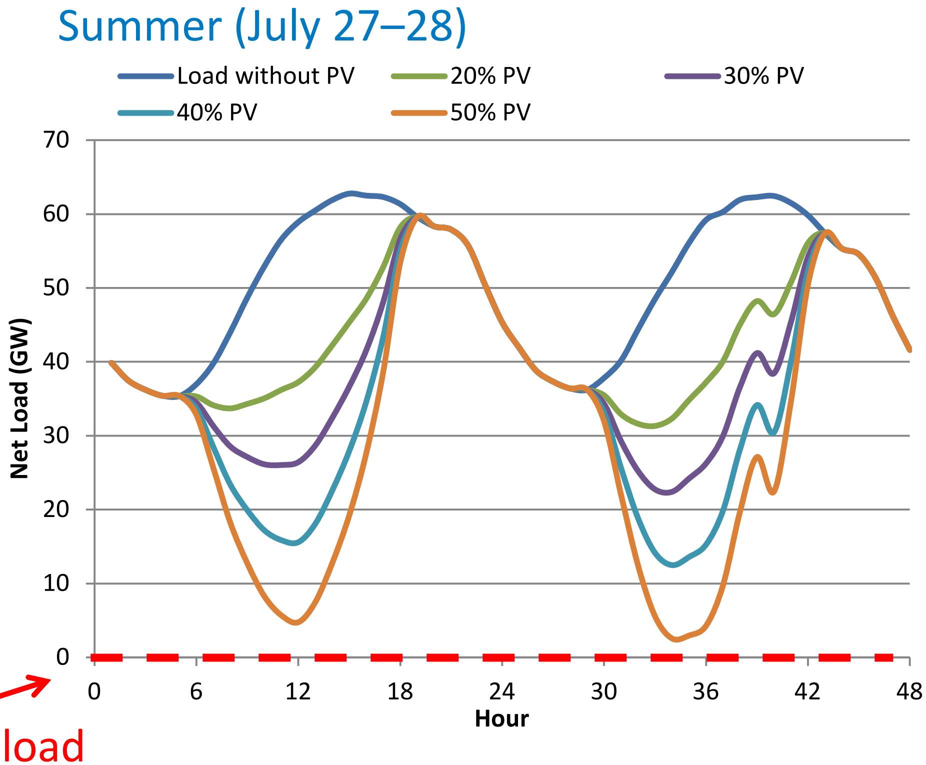


Locations of PV capacity

Why is 50% PV Challenging?

- Figures show load and theoretical net load profiles for California during two days in the spring and summer when PV provides up to 50% of annual electricity, assuming no PV curtailment is required.
- Extreme changes in net load are well beyond what can be accommodated in the current power system (net load < 0 for ~2,200 hours per year).
- In remainder of presentation, we explore how 50% PV could be achieved.





Base Scenario
(Low Flexibility, Low Storage)

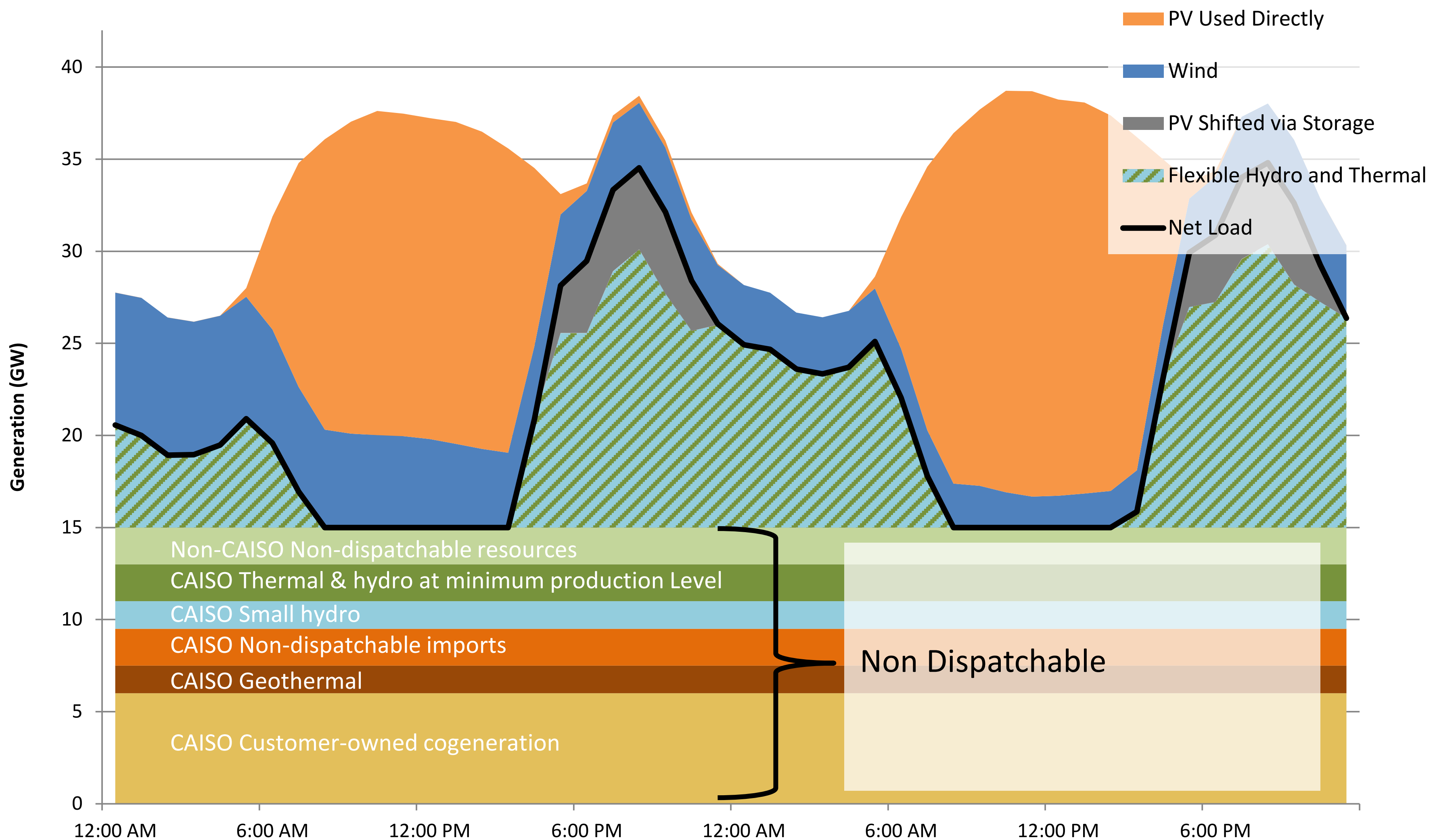
Base Scenario Characteristics

The base scenario assumes limited changes in grid operations between now and in 2030.

- 15-GW minimum generation level on hydro and thermal capacity
- Retirement of Diablo Canyon nuclear plant before 2030
- No new demand response
- No electric vehicles (EVs)
- No exports of solar generation to surrounding states
- No demand shifting
- 4.4 GW of storage (based on existing + mandated new storage in California)
- Load grows to 320 TWh, 64.7 GW peak demand

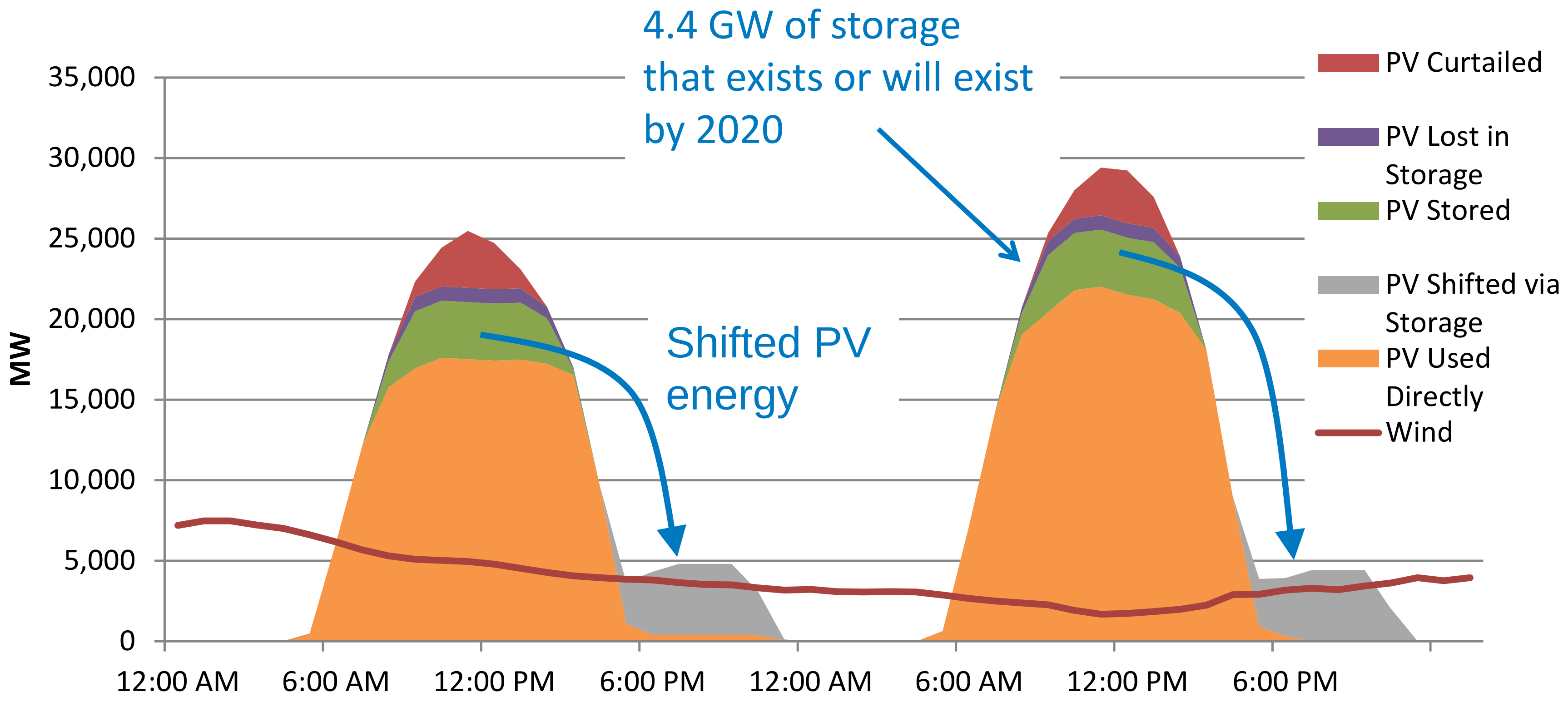
Base Scenario: System Dispatch at 20% PV, April 9–10

Midday wind and solar exceed what can be accommodated at 15-GW minimum generation, resulting in “overgeneration” and curtailment



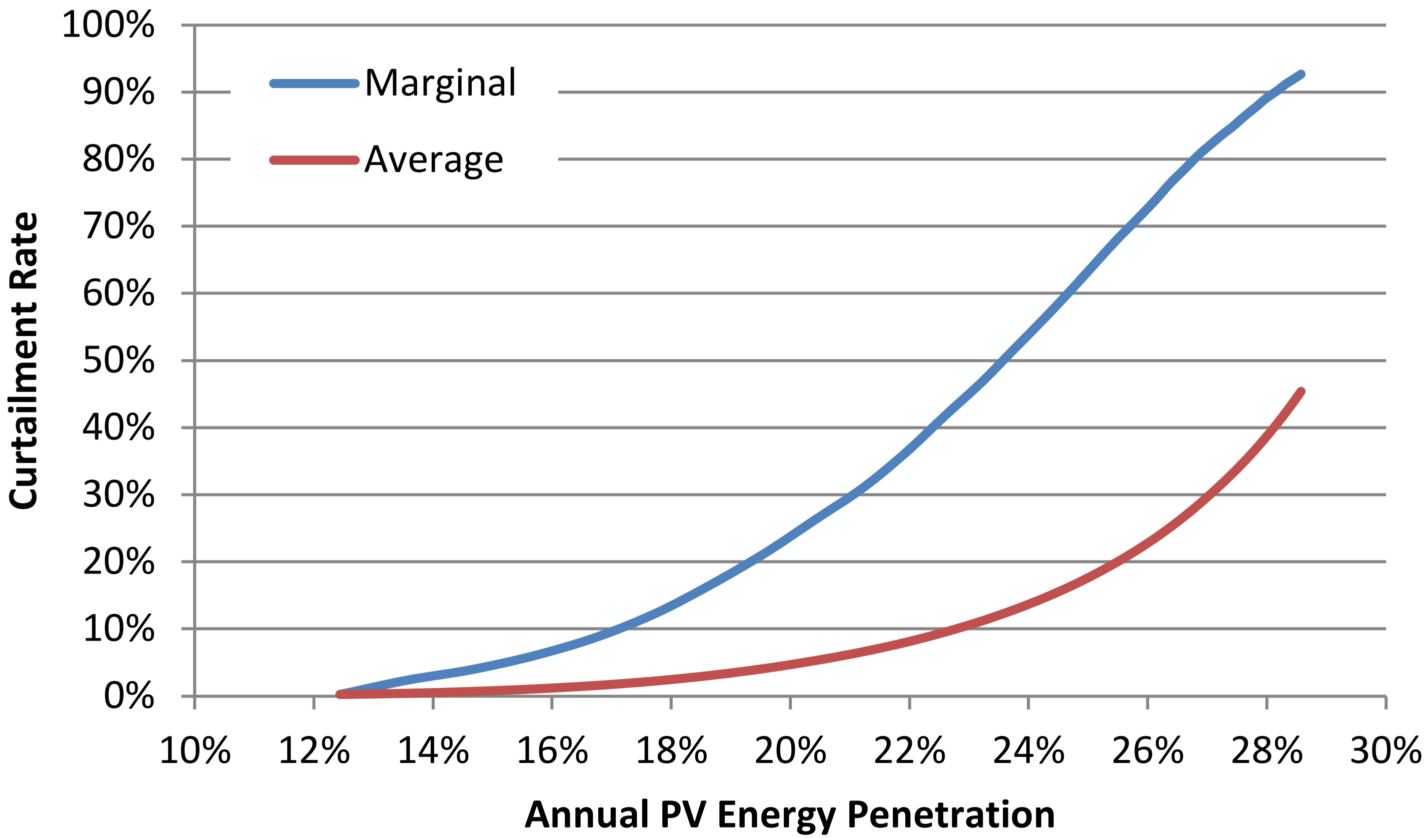
Base Scenario: PV Dispatch at 20% PV, April 9–10

- Existing and projected storage eliminates most curtailment.
- About 5% of potential PV is curtailed annually, including storage losses.



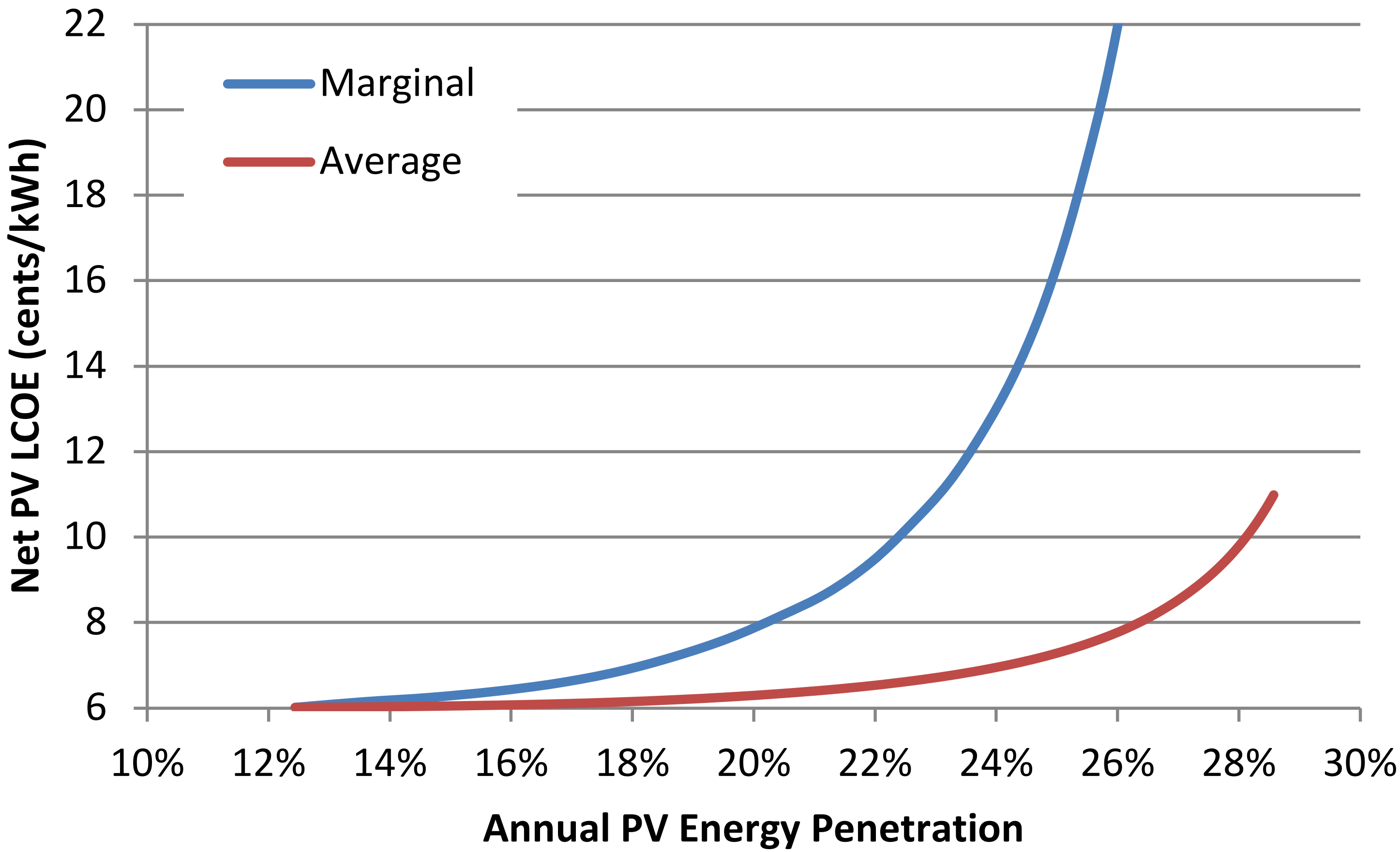
Base Scenario: Curtailment Rate at Various PV Levels

- Marginal curtailment rates can indicate the threshold at which PV becomes uncompetitive with alternative resources.
- Under the base scenario, PV's marginal curtailment rate increases rapidly once PV penetration rises above 20%.



Base Scenario: Net PV LCOE at Various PV Levels

- We calculate net LCOE assuming a base PV LCOE of 6 cents/kWh.
- Reducing the base PV LCOE would help maintain cost competitiveness, but the shape of the marginal curve means even very low-cost PV would require additional grid flexibility to achieve penetrations beyond 25%.



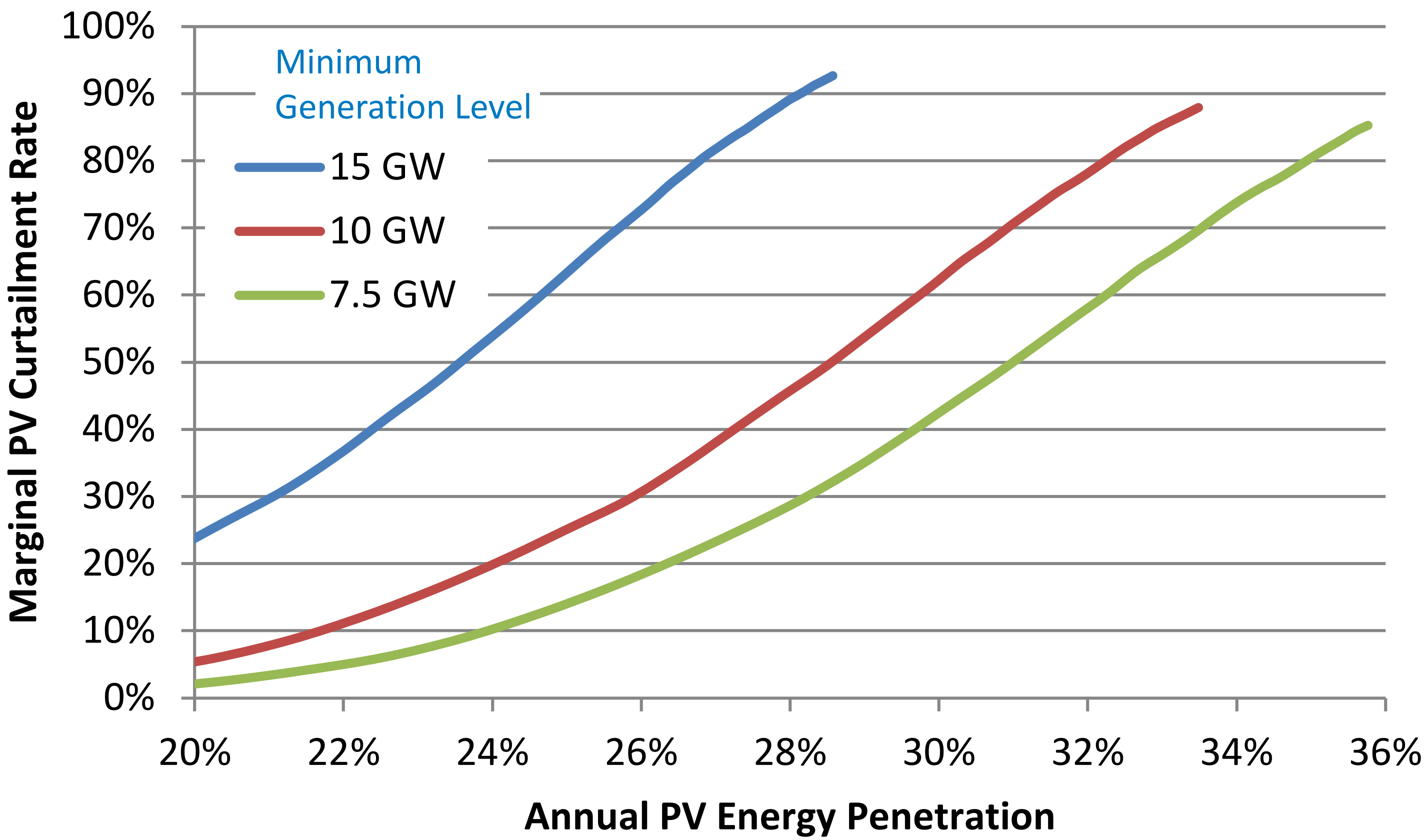
Scenarios with Non-Storage Flexibility Options

Flexibility Options

- Flexible Generation/Lower Minimum Generation Levels
  - Changing long-term contracts with combined heat and power plants and other thermal generators
  - Learning the true costs of frequent thermal plant cycling
  - Incorporating improved forecasting
  - Using curtailed variable generation for reserves
- Electricity Exports
  - Expanding footprint of day-ahead and real-time exports
- Demand Response and Shiftable Load
  - Increasing the number of consumers using real-time pricing, time-of-use pricing, and/or utility-controlled loads
- Additional Load from Electric Vehicles (EVs)
  - Adding EVs to California's fleet and optimizing EV charging

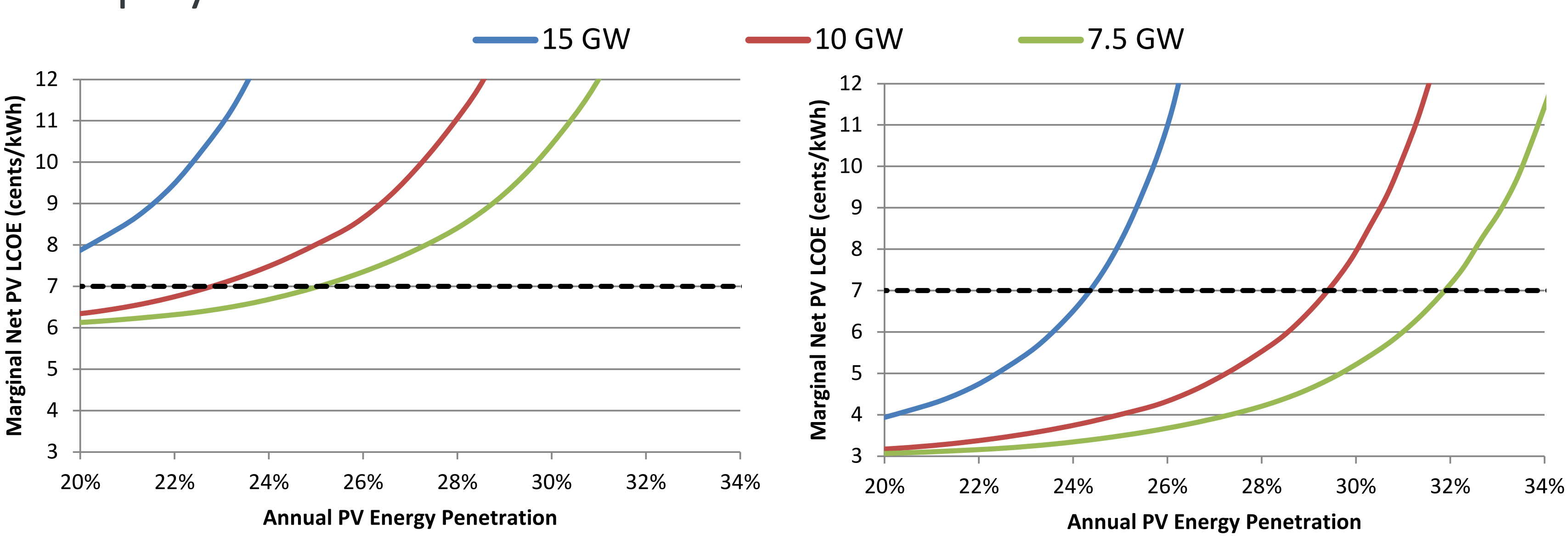
Flexible Generation: Curtailment Rate at Various PV Levels

- Base minimum-generation level is 15 GW.
- Both reduced minimum-generation scenarios (10 GW and 7.5 GW) substantially reduce marginal curtailment rates.



Flexible Generation: Net PV LCOE at Various PV Levels

- At the lowest minimum generation, PV with a base LCOE of 6 cents/kWh achieves a marginal net LCOE of 7 cents/kWh dashed line, which is comparable to variable costs of a future combined-cycle gas generator) at greater than 25% PV penetration.
- However, even with a base LCOE of 3 cents/kWh and high flexibility, the marginal net LCOE of PV increases rapidly beyond 35% PV penetration, so additional measures likely are needed to enable such deployment.

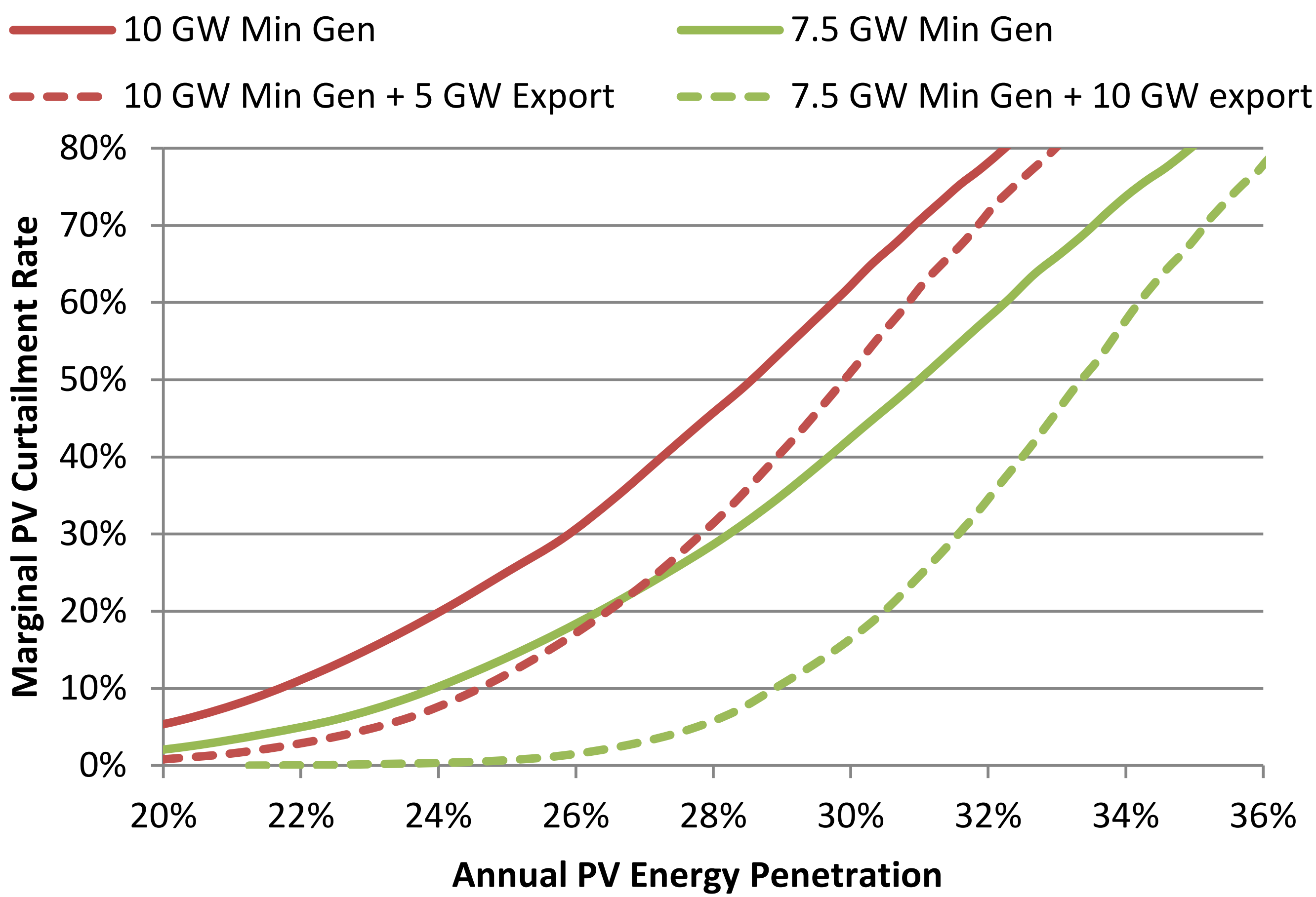


6 cents/kWh base PV LCOE

3 cents/kWh base PV LCOE

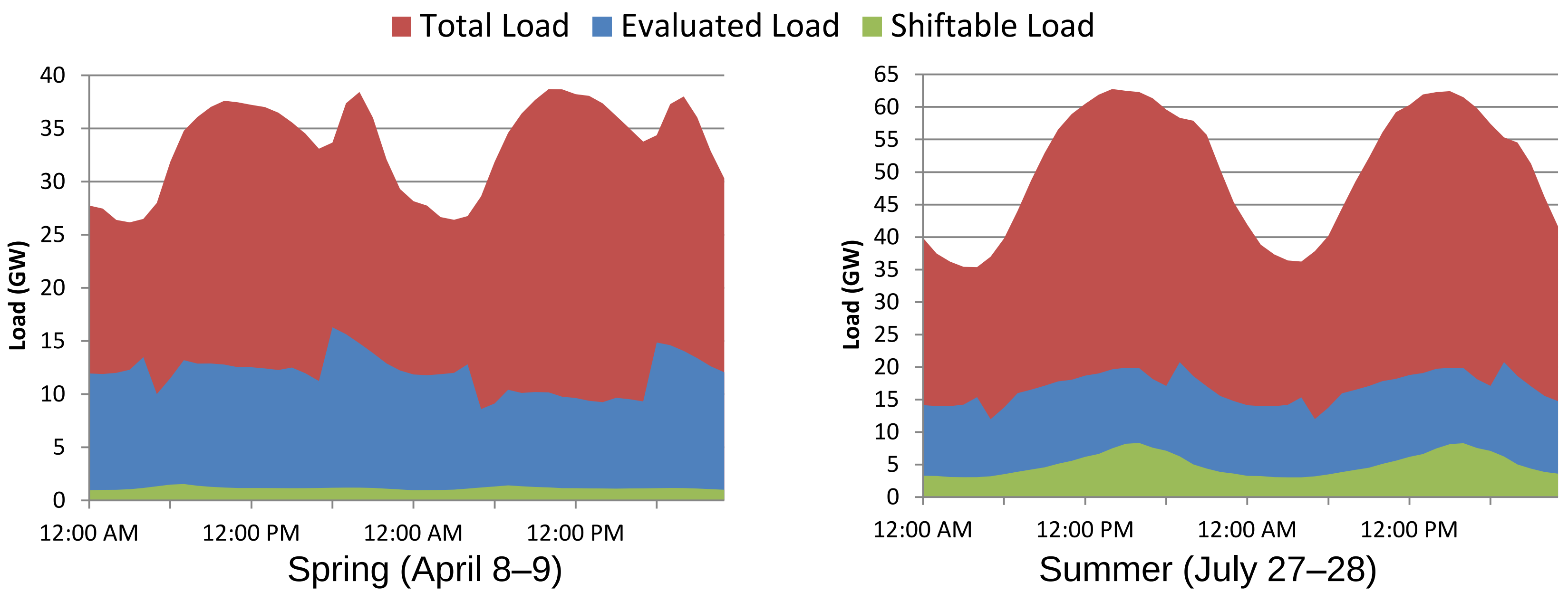
Increased Exports: Curtailment Rate at Various PV Levels

We assume exports from California to neighboring states do not count toward in-state generation. Thus, each gigawatt of export capacity is less effective at shifting the curtailment curves than each gigawatt of minimum generation reduction.



Demand Response Availability

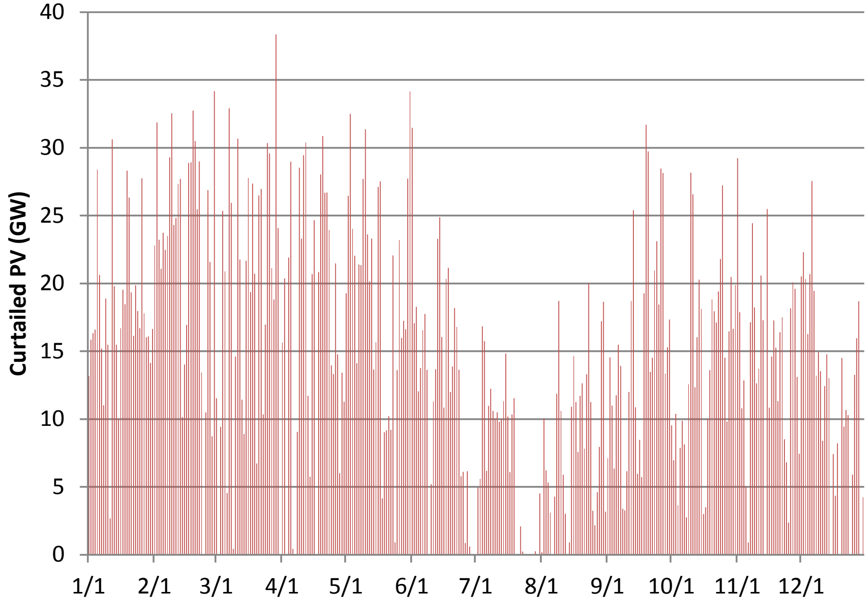
- The ability to shift load varies hourly, daily, and seasonally.
- We use demand-shifting assessments from the Lawrence Berkeley National Laboratory (LBNL) and the Oak Ridge National Laboratory (ORNL).
- Both assessments show relatively little ability to shift loads during the spring, when curtailment is highest.
- Only a fraction of existing loads is evaluated; future work could consider the full potential for load shifting and fuel switching.



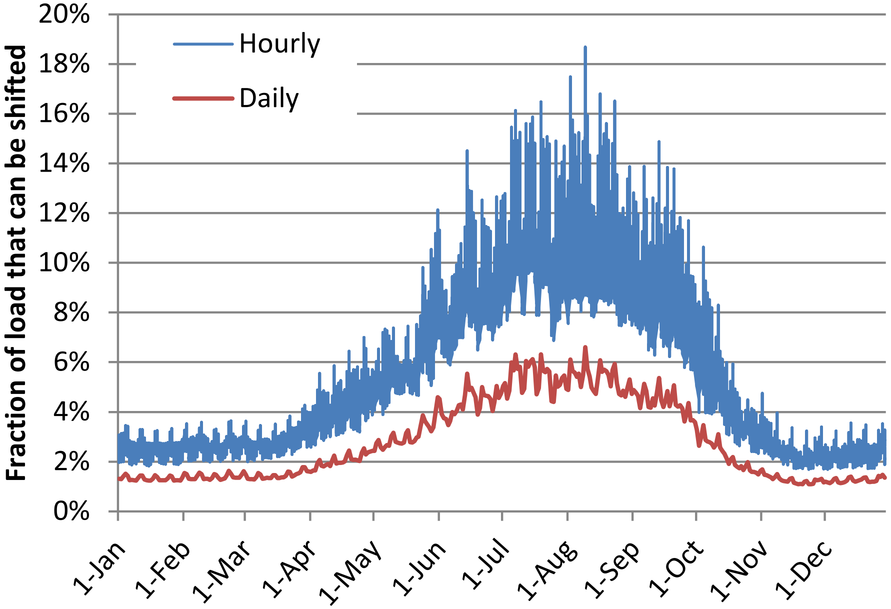
Load-reduction potential in the LBNL technical potential resource data set.

Demand Response: Load-Shifting Potential (LBNL and ORNL Data)

- Load shifting depends on the ability to reduce load during low solar output and increase load during high solar output.
- In a system with 50% PV, curtailments peak in the spring and are low in the summer, largely because this is the period of highest load (left figure).
- Yet load shifting availability peaks in the summer and is low during the spring, when only about 2% of demand is assumed to be shiftable (right figure).
- This mismatch of high-curtailment periods and shiftable-demand periods limits the curtailment-reduction potential of demand response.



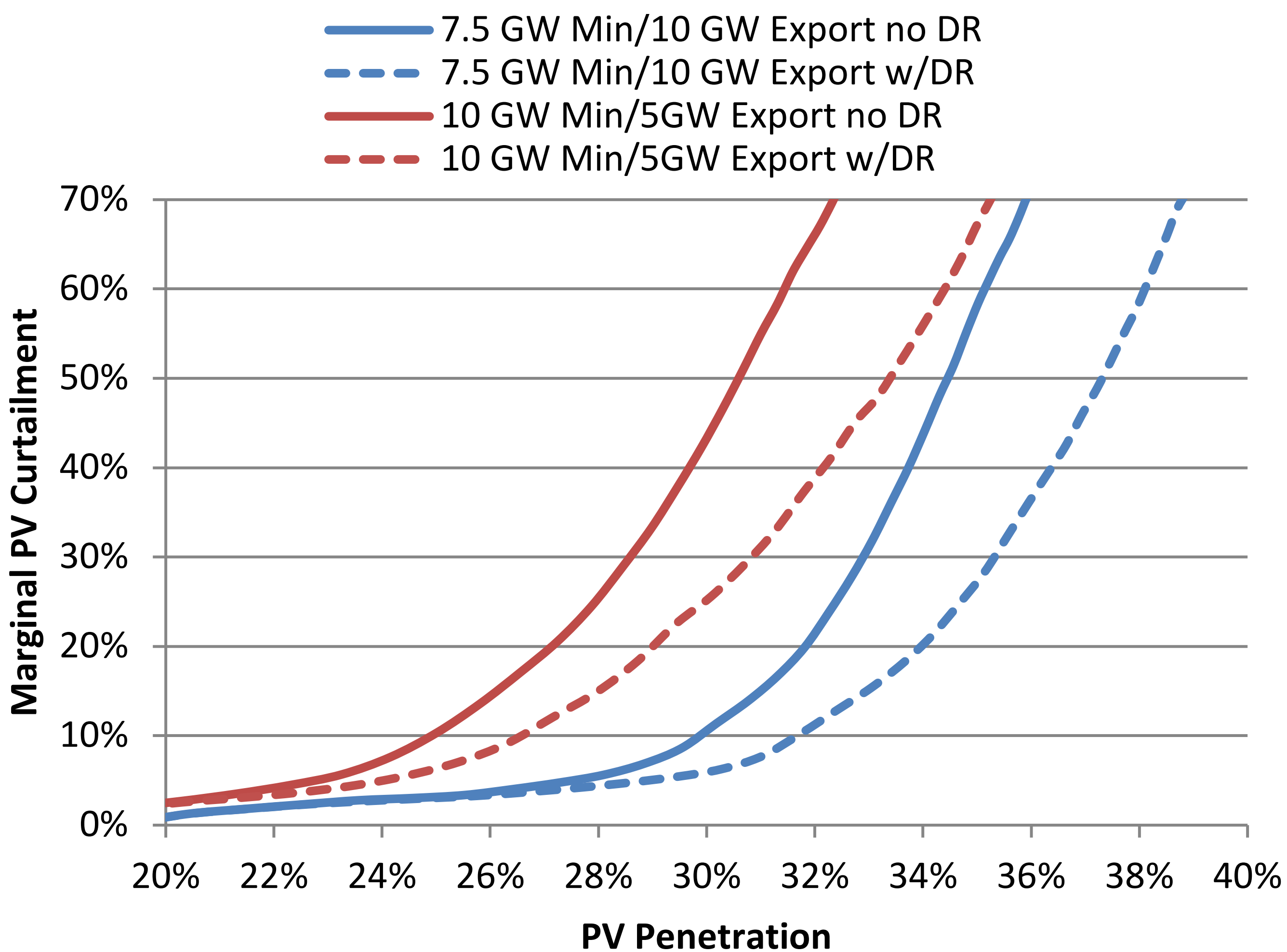
Hourly curtailment in a system with enough PV to achieve 50% PV with a 7.5-GW system minimum-generation level and a 5-GW export capacity



Fraction of total hourly and daily load that can be shifted using the LBNL and ORNL technical potential

Demand Response: Curtailment Rate at Various PV Levels

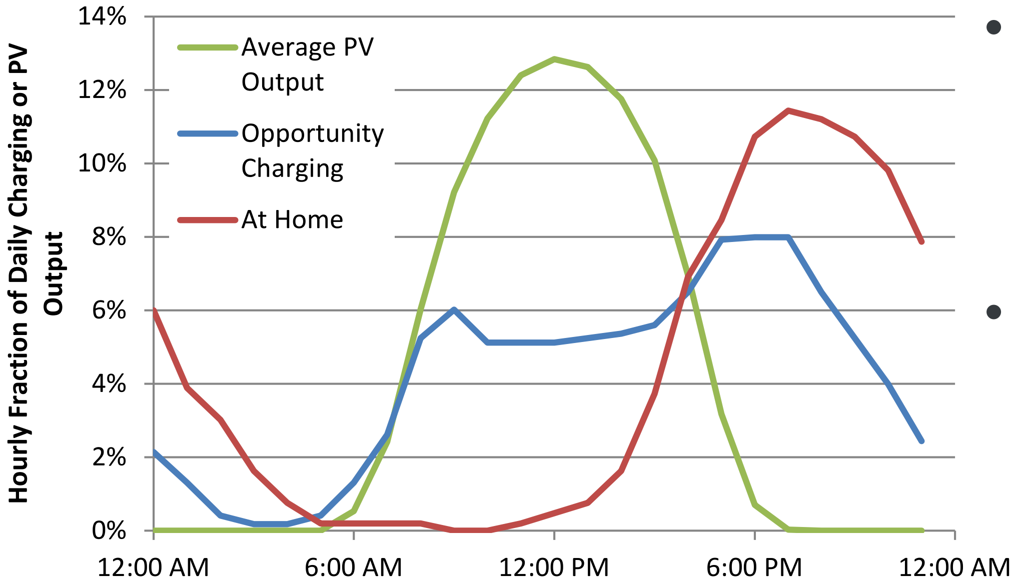
Adding demand response shifts the curtailment curves by as much as about two percentage points.



Electric Vehicles: Assumptions and Load Profiles

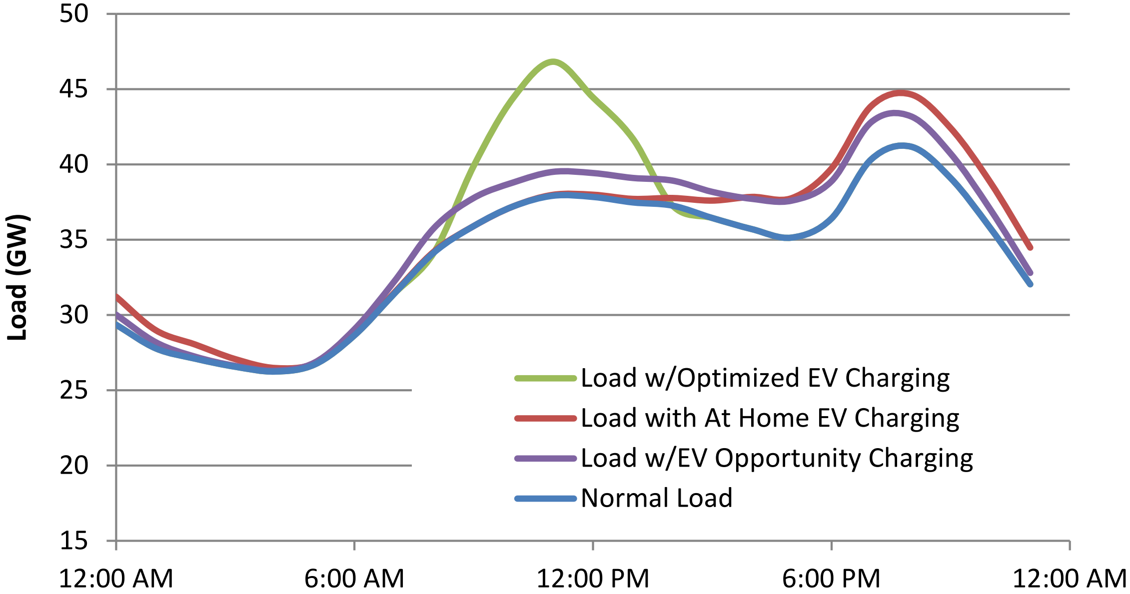
- We assume vehicles require 12.1 kWh/day.
  - 35.4 miles/day and 0.34 kWh/mile
- Load profiles depend on charging pattern.
  - At-home charging: Vehicle charging only occurs at the end of the day when the vehicle is at home.
  - Opportunity charging: Vehicle charging begins whenever the vehicle arrives at its destination, which assumes widespread availability of charging stations.
  - Optimized charging: Vehicle charging uses as much PV output as possible that would otherwise be curtailed.

Electric Vehicles: Charging Profiles



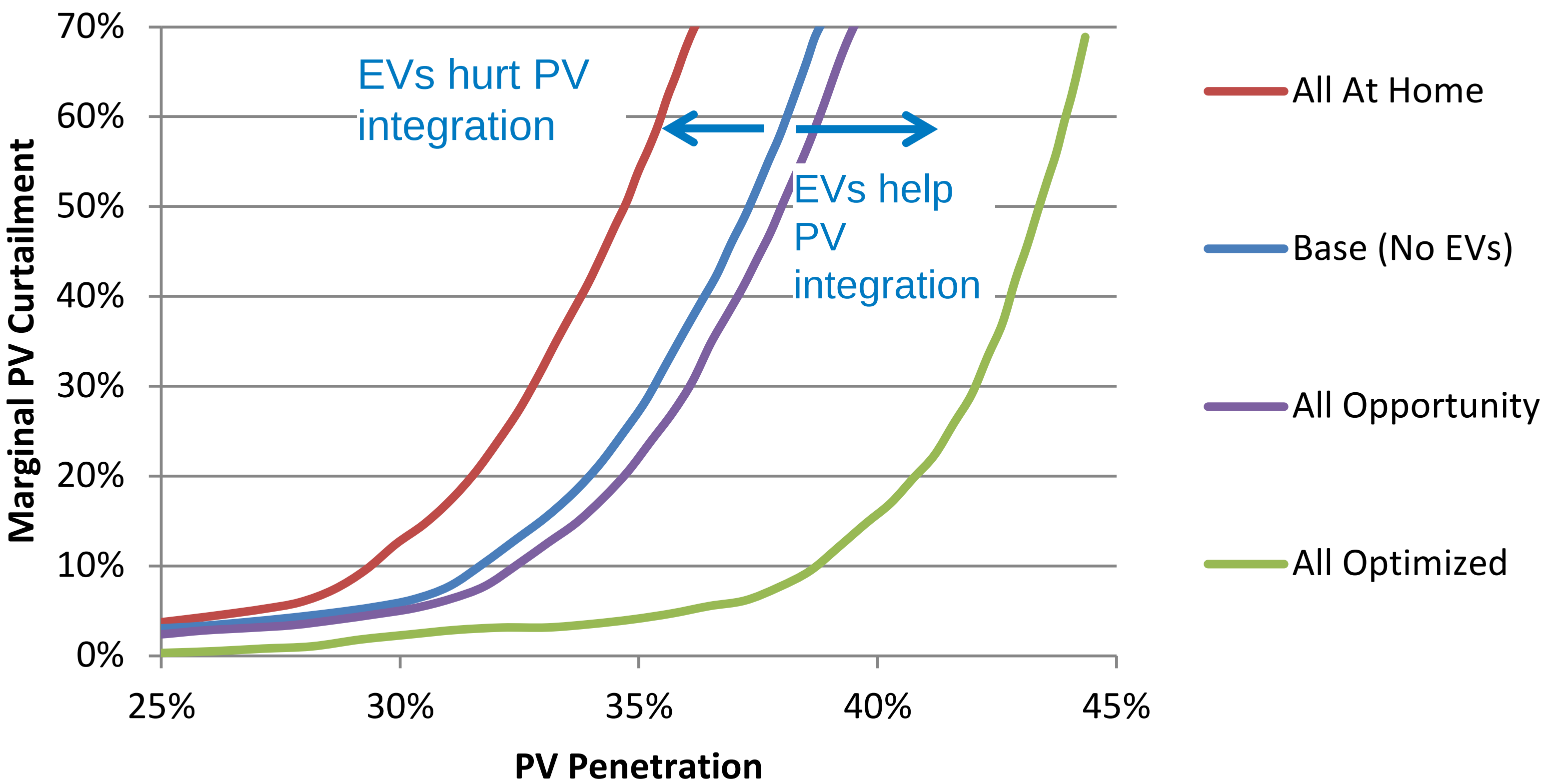
- Opportunity charging (blue line at left) is better for integrating PV, with about half of the demand occurring during periods of significant PV output (green line).
- But, peak charging demand occurs in early evening when PV output is declining rapidly.

- Optimization aligns EV charging load with high PV generation (green line at right) better than opportunity (purple line) or at-home (red line) charging.
- Scenario shown assumes 10% EV penetration on April 1.



Electric Vehicles: Impact of 25% EV Penetration on PV Curtailment

- We assume 6.4 million EVs (25% penetration), a 7.5-GW minimum-generation level, 10-GW export capacity, and full demand response availability.
- Optimized and opportunity charging help PV integration, whereas at-home charging hurts PV integration.



Energy Storage Scenarios

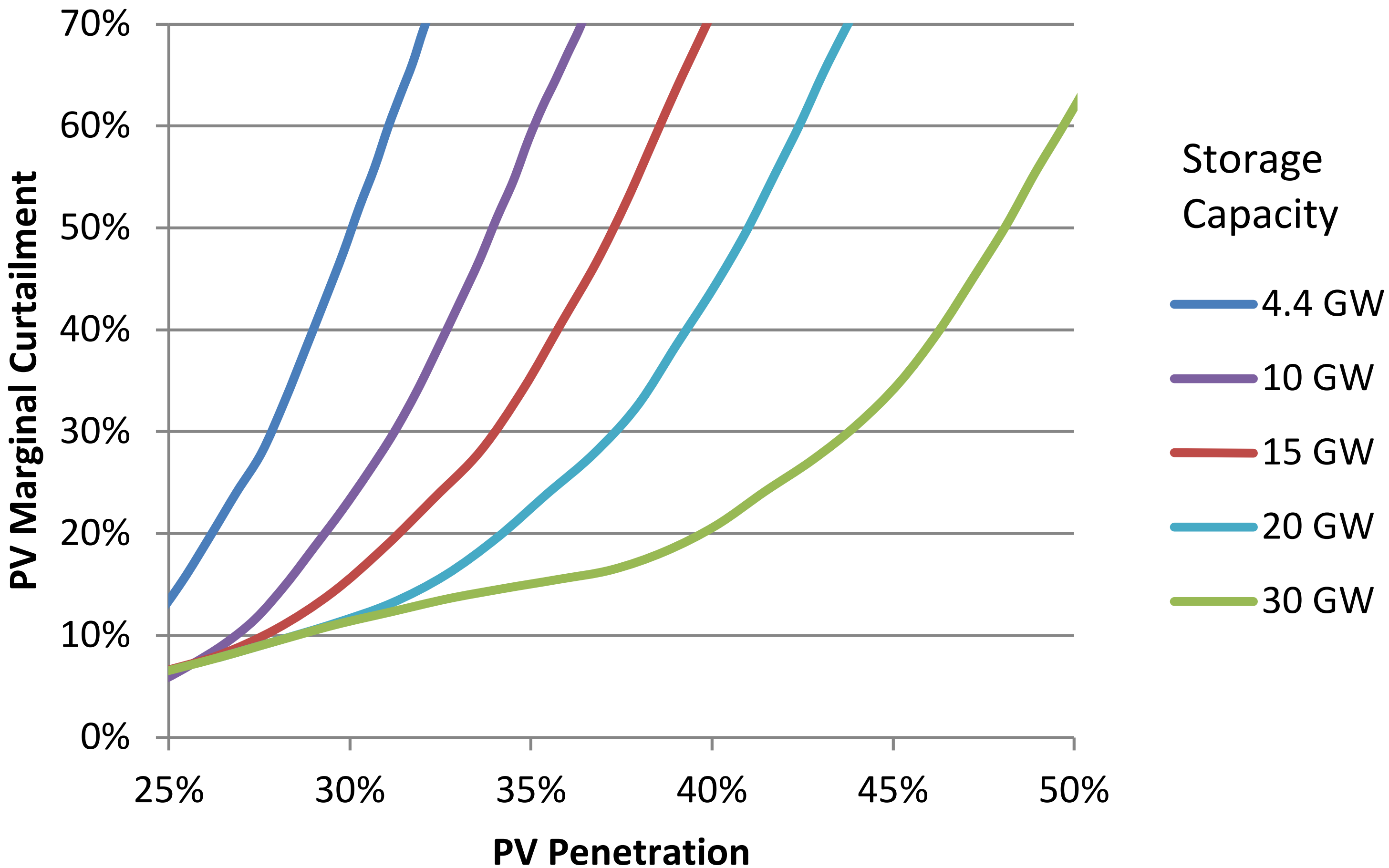
Energy Storage Scenarios Evaluated

	Low Flexibility	Mid Flexibility	High Flexibility
Minimum generation level (GW)	10	8.75	7.5
Export capacity (GW)	2.5	5	10
Demand response availability (GW peak/avg. daily GWh)[a]	0.4/2.2	2/10	4/21
EV penetration (% of California light-duty vehicles)	5%	15%	25%
EV charging profile (optimized-opportunity-at home)	33%-33%-33%	50%-25%-25%	75%-15%-10%

[a] These values represent the peak and average shiftable load during months of highest PV curtailment (March–May), with the high-flexibility scenario using the full LBNL technical potential, which assumes about 2% of the average daily demand is shiftable.

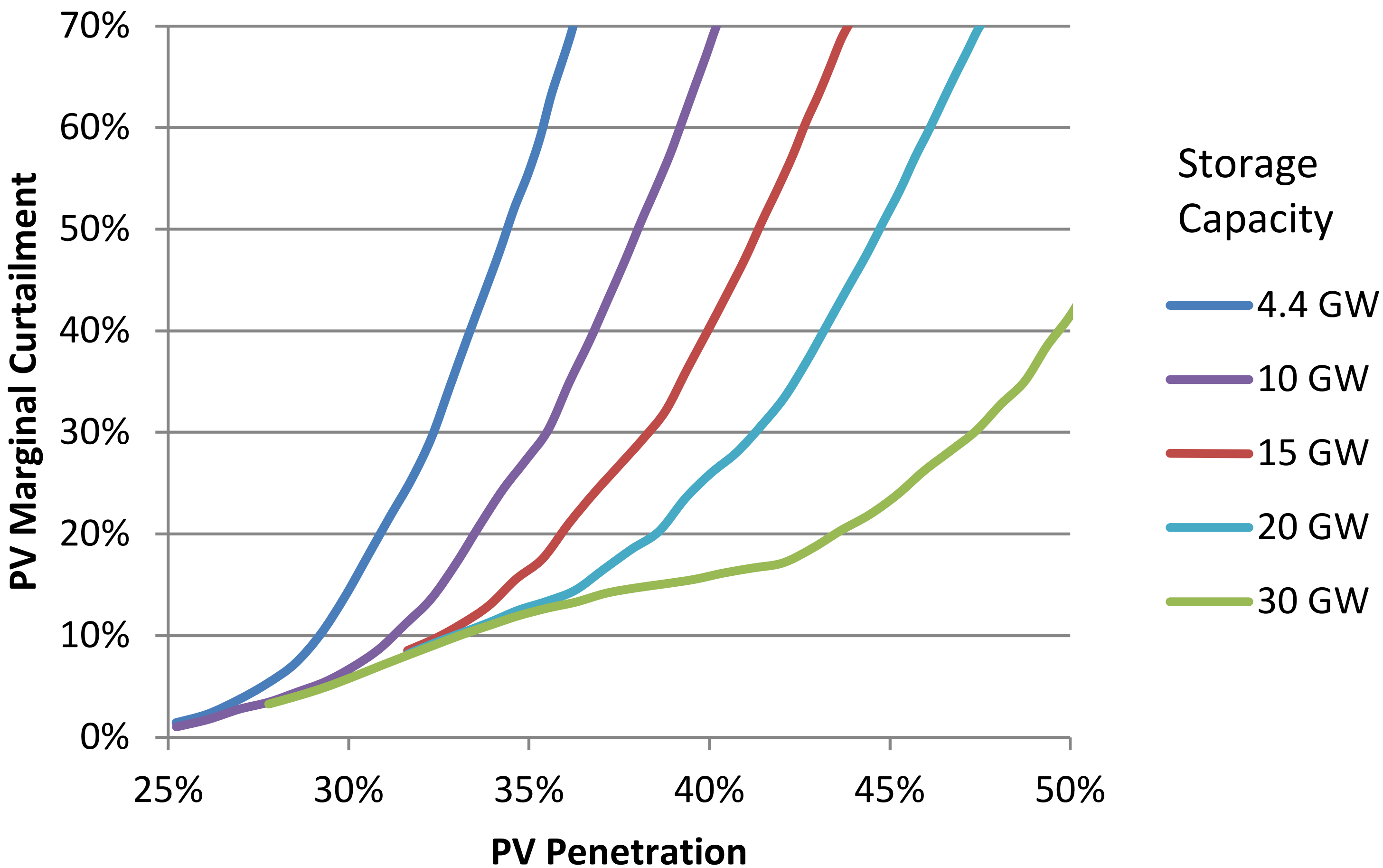
Low Flexibility: Curtailment Rate at Various PV Levels

Thirty (30) GW of storage and low flexibility result in marginal curtailment exceeding 60% at 50% PV.



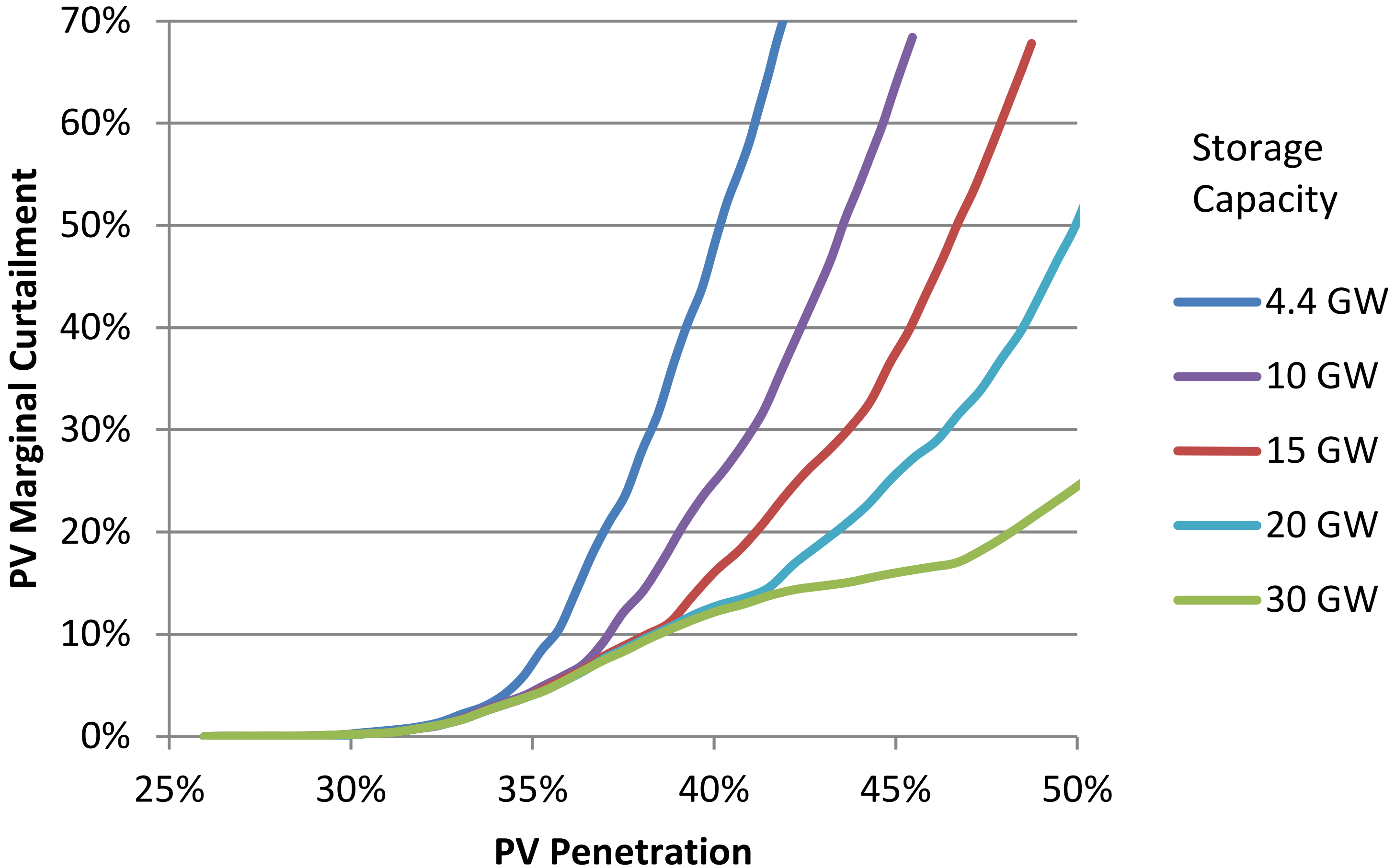
Mid Flexibility: Curtailment Rate at Various PV Levels

With 50% PV penetration and 30 GW of storage, the marginal curtailment rate drops to about 40%.



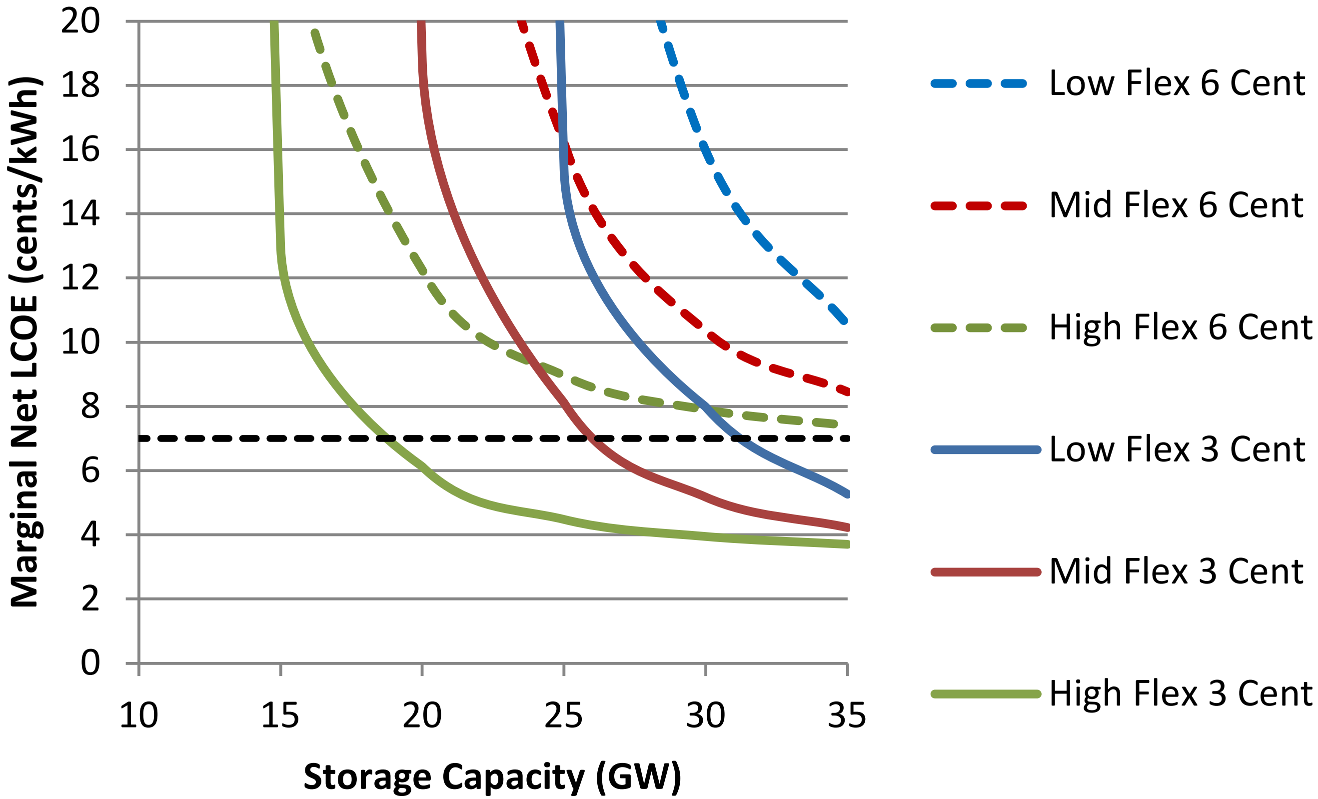
High Flexibility: Curtailment Rate at Various PV Levels

With 50% PV penetration and 30 GW of storage, the marginal curtailment rate approaches 20%.



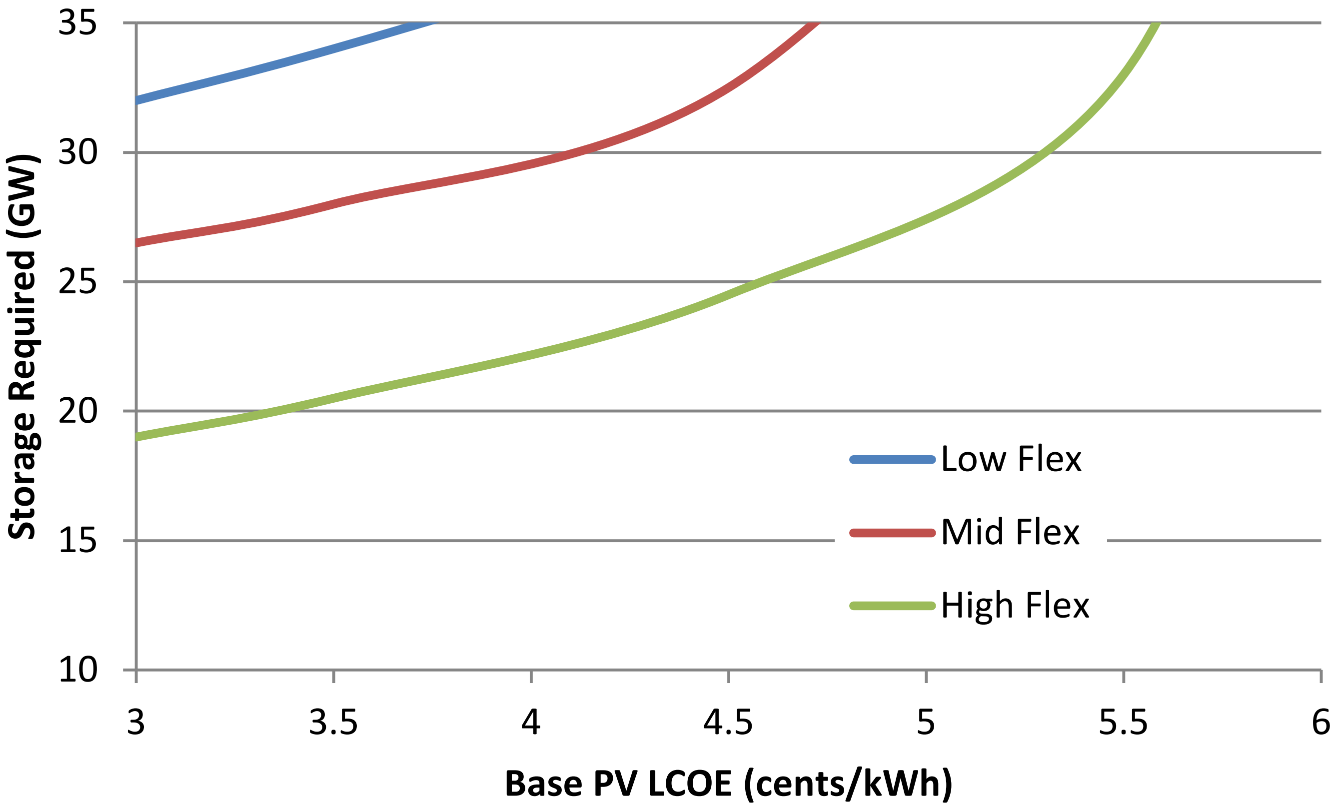
All Scenarios, Two Base PV Costs: Net LCOE at 50% PV

- Dashed marginal net LCOE target line (7 cents/kWh) approximates the variable cost of future combined-cycle gas turbines, including carbon costs.
- With lower-cost PV (3 cents/kWh) and high flexibility, achieving 50% PV with target net LCOE requires about 19 GW of storage.
- With lower-cost PV and less flexibility, reaching 50% PV could require 25–30 GW of storage.



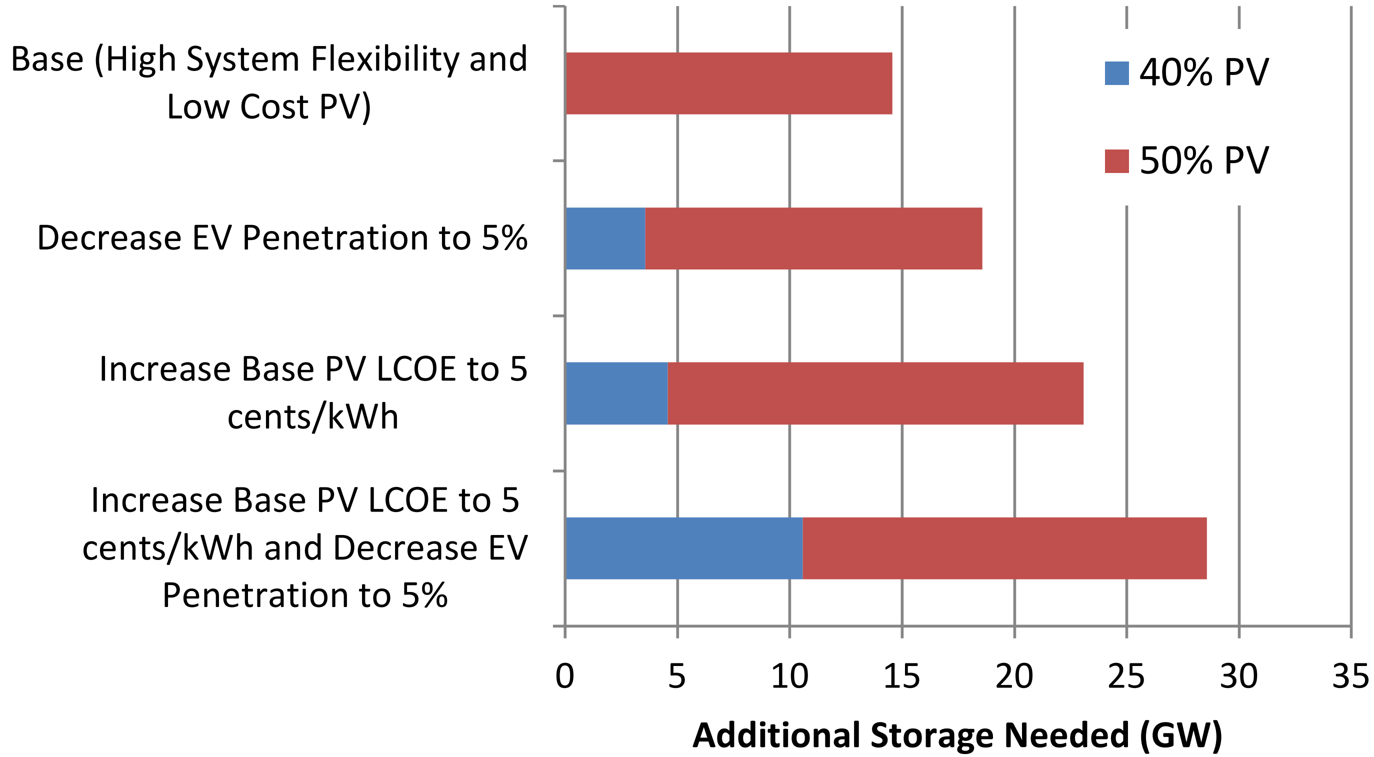
All Scenarios: Storage Required to Achieve 50% PV

- Figure shows energy storage required to achieve a marginal net PV LCOE of 7 cents/kWh as a function of base PV LCOE at 50% PV penetration and three levels of grid flexibility.
- Both grid flexibility and low-cost PV appear critical to reducing storage requirements.



High-Flexibility Scenario: Storage Sensitivity Analysis

- In the high-flexibility scenario with base PV cost of 3 cents/kWh, about 15 GW of additional energy storage are required to achieve 50% PV at a marginal net PV LCOE of 7 cents/kWh (top bar).
- Decreasing EV penetration, increasing the base PV cost, or doing both increases the additional storage requirements (other bars).
- Achieving only 40% PV penetration reduces the storage requirements substantially.



Conclusions

- **California would require at least 19 GW of total storage to support 50% PV at a marginal net PV LCOE comparable to projected variable costs of combined-cycle gas generators.**
  - This includes about 15 GW of new storage beyond the storage that already exists or is planned.
  - It would represent a substantial storage increase—in the entire United States, today's total installed storage capacity is only about 22 GW.
- **The 19 GW of storage requirement for 50% PV depends on very low-cost PV, high EV penetration, and other robust flexibility measures.**
  - Without these measures, total storage requirements can exceed 30 GW.
  - Storage requirements are much lower at 40% PV penetration.
  - Rapidly increasing storage requirements beyond 40% PV suggests the need to examine the feasibility of large-scale energy storage deployment and the optimal mix of low-carbon generation resources (e.g., with CSP, wind).
- **Declining storage costs could make large-scale storage competitive with deployment of new conventional peaking resources.**
  - California currently has about 22 GW of fossil-fueled peaking capacity, 14 GW of which is more than 25 years old.
  - Cost-competitive energy storage might be able to replace much of the retiring fossil-fueled peaking capacity.

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