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 CO₂.

<table>
<thead>
<tr>
<th>Source/Technology</th>
<th>Gigawatt-hours (GWh)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>7,507</td>
<td>2.5%</td>
</tr>
<tr>
<td>Concentrating solar power (CSP)</td>
<td>1,619</td>
<td>0.5%</td>
</tr>
<tr>
<td>Fossil</td>
<td>151,037</td>
<td>50.0%</td>
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<tr>
<td>Geothermal</td>
<td>13,030</td>
<td>4.3%</td>
</tr>
<tr>
<td>Large hydro</td>
<td>16,350</td>
<td>5.4%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>25,220</td>
<td>8.4%</td>
</tr>
<tr>
<td>PV (rooftop)</td>
<td>5,115</td>
<td>1.7%</td>
</tr>
<tr>
<td>PV (utility scale)</td>
<td>10,932</td>
<td>3.6%</td>
</tr>
<tr>
<td>Small hydro</td>
<td>2,787</td>
<td>0.9%</td>
</tr>
<tr>
<td>Wind</td>
<td>23,913</td>
<td>7.9%</td>
</tr>
<tr>
<td>Other (unspecified imports)</td>
<td>44,433</td>
<td>14.7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>301,943</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

Sources

- Other technologies: California Energy Commission. 2014. California electricity statistics and data. [http://energyalmanac.ca.gov/electricity/system_power/2014_total_system_power.html](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.
  o 60%/40% mix of utility/rooftop PV
  o Utility-scale PV is 60% tracking, 40% fixed

• Use PV and wind profiles from NREL Low-Carbon Grid Study

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.

Spring (April 9–10)

Summer (July 27–28)

Zero net load
Base Scenario
(Low Flexibility, Low Storage)
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
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.

4.4 GW of storage that exists or will exist by 2020

Shifted PV energy

4.4 GW of storage that exists or will exist by 2020
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%.
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.
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.
• 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.
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.
  o 35.4 miles/day and 0.34 kWh/mile

• Load profiles depend on charging pattern.
  o At-home charging: Vehicle charging only occurs at the end of the day when the vehicle is at home.
  o Opportunity charging: Vehicle charging begins whenever the vehicle arrives at its destination, which assumes widespread availability of charging stations.
  o 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

<table>
<thead>
<tr>
<th></th>
<th>Low Flexibility</th>
<th>Mid Flexibility</th>
<th>High Flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum generation level (GW)</td>
<td>10</td>
<td>8.75</td>
<td>7.5</td>
</tr>
<tr>
<td>Export capacity (GW)</td>
<td>2.5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Demand response availability (GW peak/avg. daily GWh)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.4/2.2</td>
<td>2/10</td>
<td>4/21</td>
</tr>
<tr>
<td>EV penetration (% of California light-duty vehicles)</td>
<td>5%</td>
<td>15%</td>
<td>25%</td>
</tr>
<tr>
<td>EV charging profile (optimized-opportunity-at home)</td>
<td>33%-33%-33%</td>
<td>50%-25%-25%</td>
<td>75%-15%-10%</td>
</tr>
</tbody>
</table>

<sup>a</sup> 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.
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%.
With 50% PV penetration and 30 GW of storage, the marginal curtailment rate approaches 20%.
• 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.

![Diagram showing additional storage needed for different scenarios.](image-url)
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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Full report available at:
http://www.nrel.gov/docs/fy16osti/66595.pdf