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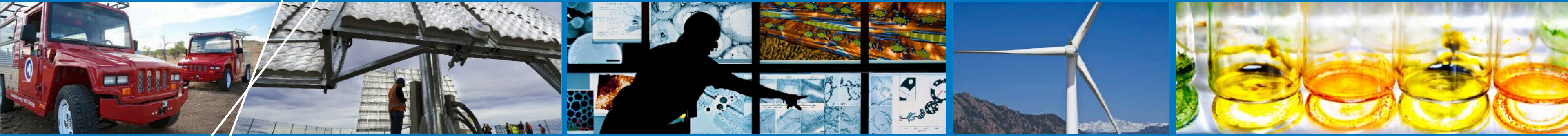
Overgeneration from Solar Energy in California – A Field Guide to the Duck Chart



Report Summary

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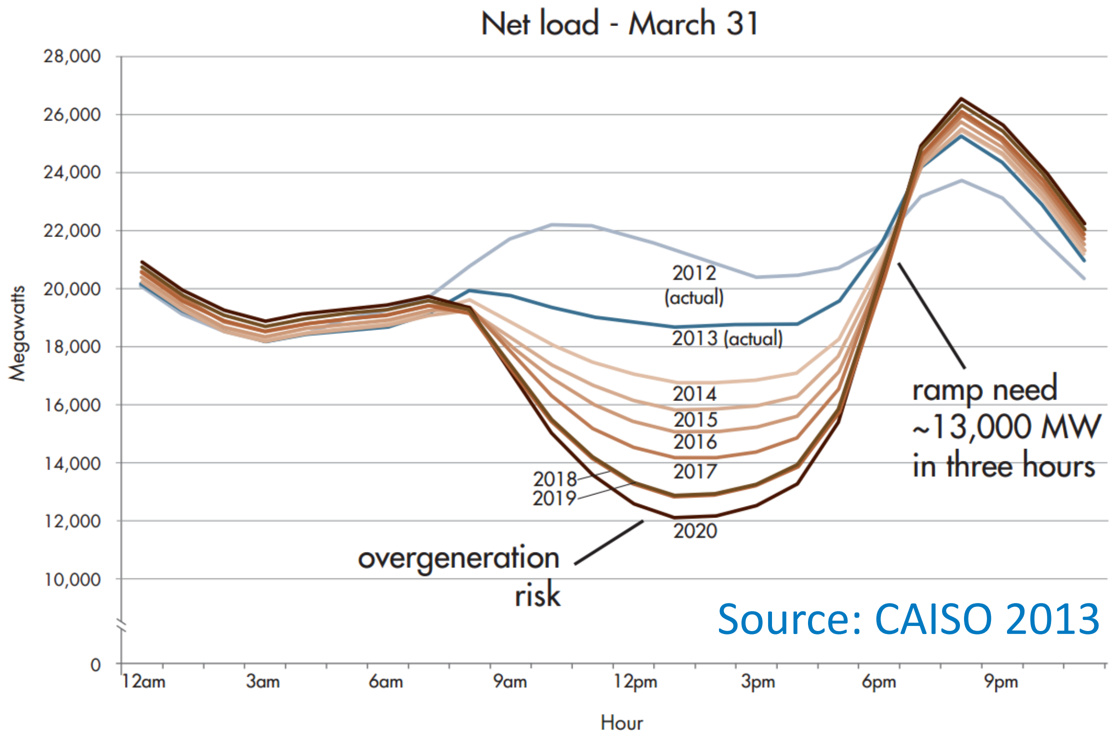
The Duck Chart



- **The challenge: How will this net load shape impact successful integration of renewable (mainly solar) energy?**
- **A big concern is overgeneration.**

Sources of overgeneration

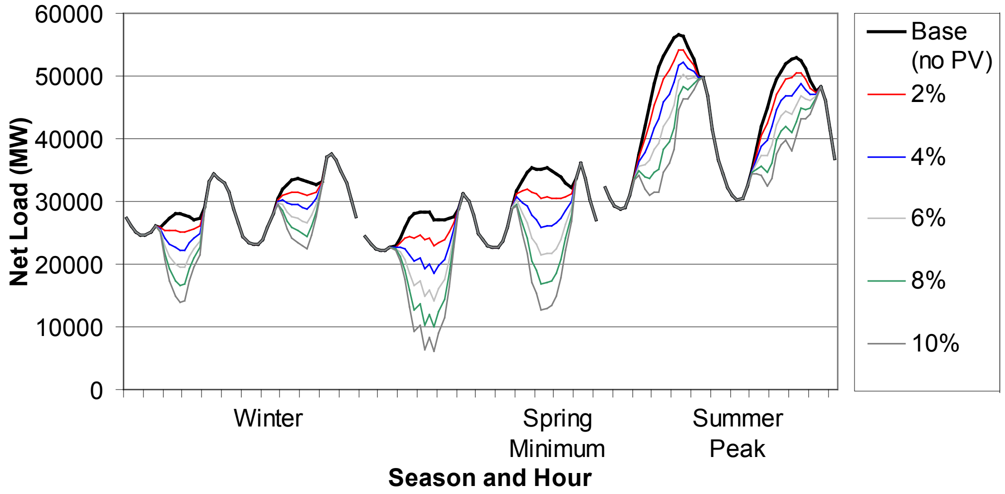
Too much supply, not enough demand, when considering:

- **Ramp constraints**
- **Minimum output levels from hydro and thermal generators**
  - This includes technical, institutional, and economic constraints
  - This also includes the need to operate partially loaded capacity to maintain system reliability

Overgeneration results in RE curtailment

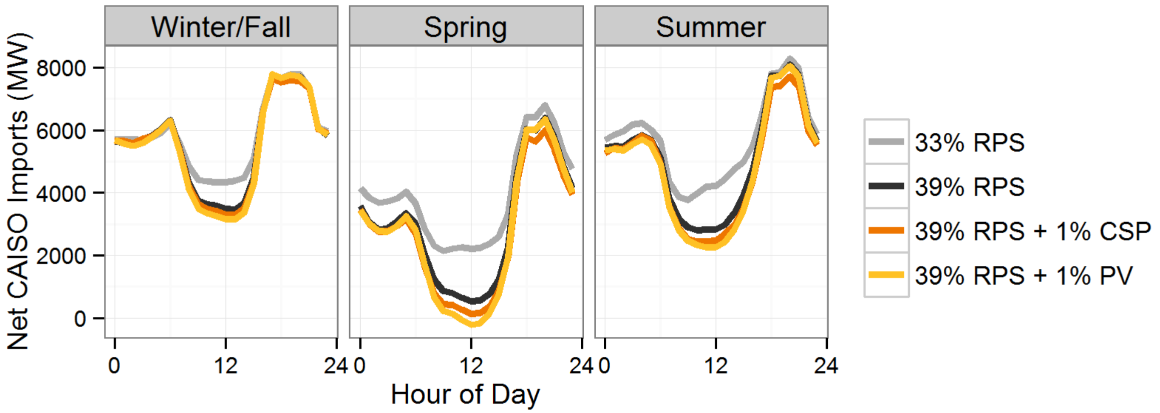
- Technically easy to do (at least on utility-scale renewable energy generation)
- But reduces economic benefits and increases the cost of meeting renewable portfolio standards or carbon-reduction goals

The duck chart shape has been noted previously



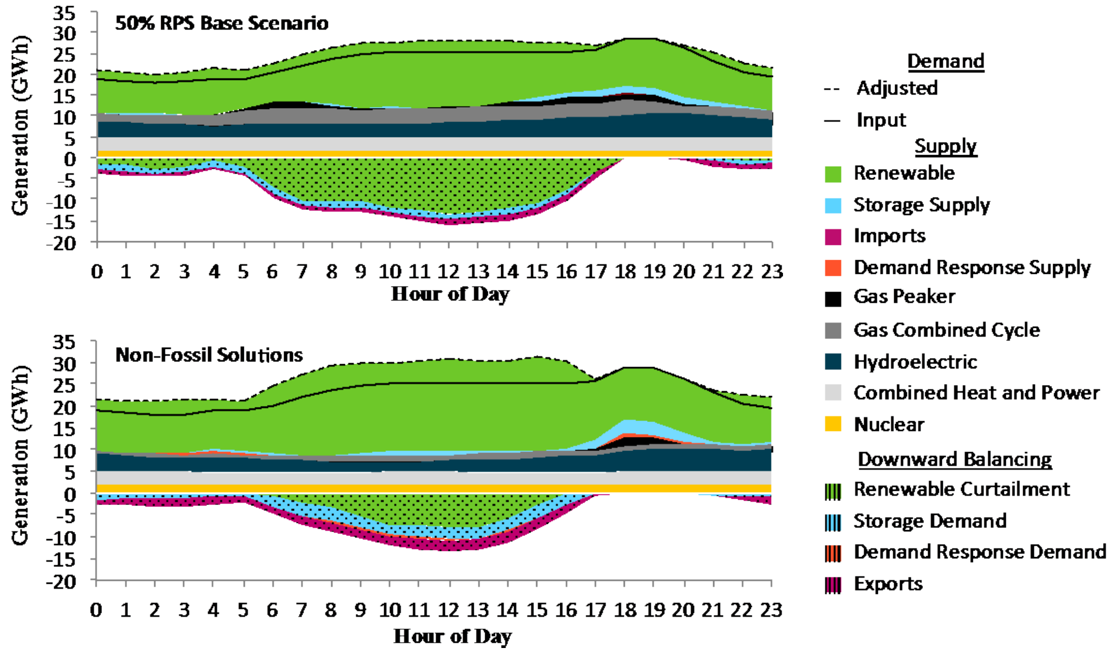
"Proto-duck" chart of California net load with increased penetration of PV (from Denholm et al. 2008)

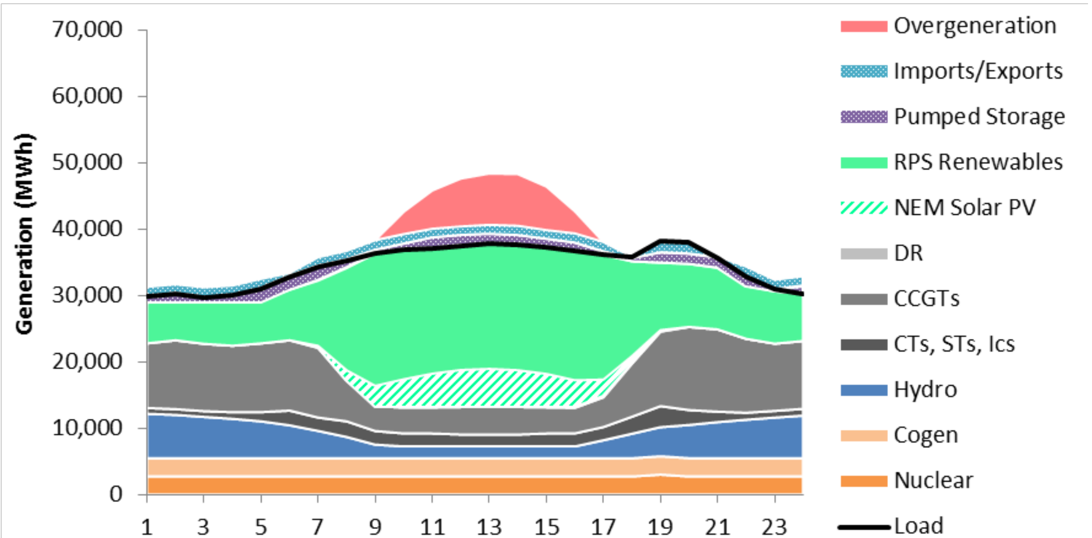
Example of an analysis of the impact of concentrating solar power (CSP) on the duck chart shape (from Jorgenson et al. 2014)



And there has been analysis of its impact on curtailment

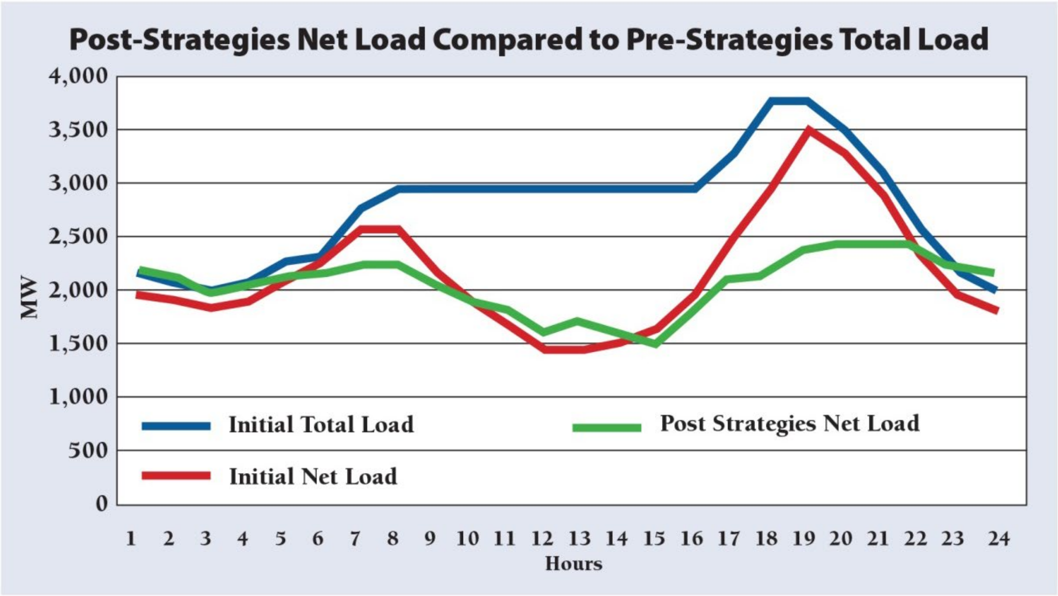
Example of an analysis of the impact of changing system flexibility on demand shape and curtailment from an analysis from Nelson and Wisland (2015)





Example of an analysis of the impact of high variable generation on net load shape and resulting overgeneration from E3 (2014)

These previous analyses also suggest mitigation measures



Example of an analysis of how the duck chart shape can be modified to minimize overgeneration (from Lazar 2014)

Goals of this work

- Provide a general overview of the duck chart and solar curtailment
- Examine how much curtailment will result as a function of solar penetration
- Examine the impact of mitigation options

Analysis framework

- **Use an industry-vetted simulation tool (PLEXOS)**
- **Use data from publically available sources (2024 TEPPC Common Case and 2014 LTPP)**
- **Modify for increased photovoltaic penetration**

Scenarios

Start with 11% wind and add increasing amounts of solar PV

Solar Pre-Curtailment Potential Scenario (%)	Total Solar (PV + CSP) Potential (GWh)	Total Pre-Curtailment RPS Potential (%)	Annual Regulation Up Requirement (GWh)	Annual Flexibility Up Requirement (GWh)
11	35,331	36.0%	3,499	10,590
15	46,473	39.6%	3,671	11,089
18	56,438	42.7%	3,947	11,651
21	66,155	45.8%	4,282	12,240
24	77,329	49.4%	4,718	12,947
31	98,964	56.3%	5,652	14,361
37	119,682	62.9%	6,607	15,746

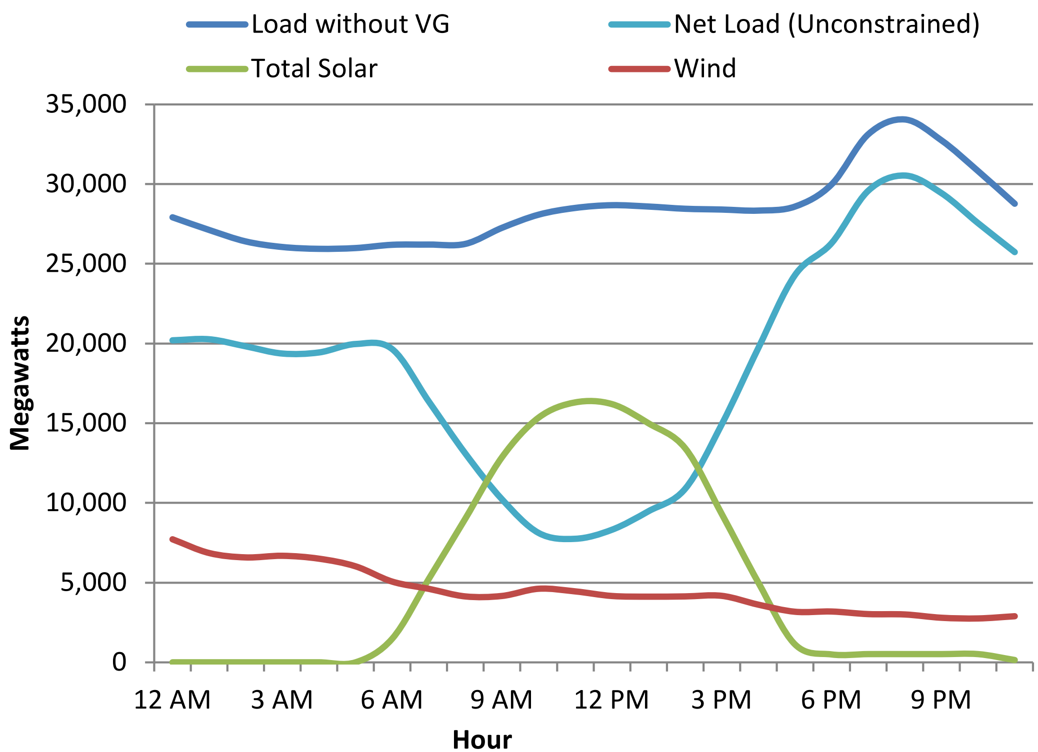
Initial (most conservative) case

Designed to approximate current grid conditions

- Wind and solar cannot provide upward reserves.
- No net exports of electricity from California are allowed and at least 70% of California-owned or contracted generation (including Hoover, Palo Verde, and certain renewable generation) from outside of the state must be imported.
- Up to about 1.3% of peak demand (as much as ~900 MW during periods of peak demand) can be shifted via economic demand response programs.
- No new storage is installed beyond what is in service in 2015.
- 25% of all generation within certain zones must be met with local thermal or hydro generation.
- Diablo Canyon remains online as a baseload (non-dispatchable) generator. The plant does not contribute to the 25% local generation requirement.
- Instantaneous penetration of variable generation (including PV, wind, and CSP without thermal energy storage) is limited to 60% of the normal load.

Net load on March 29

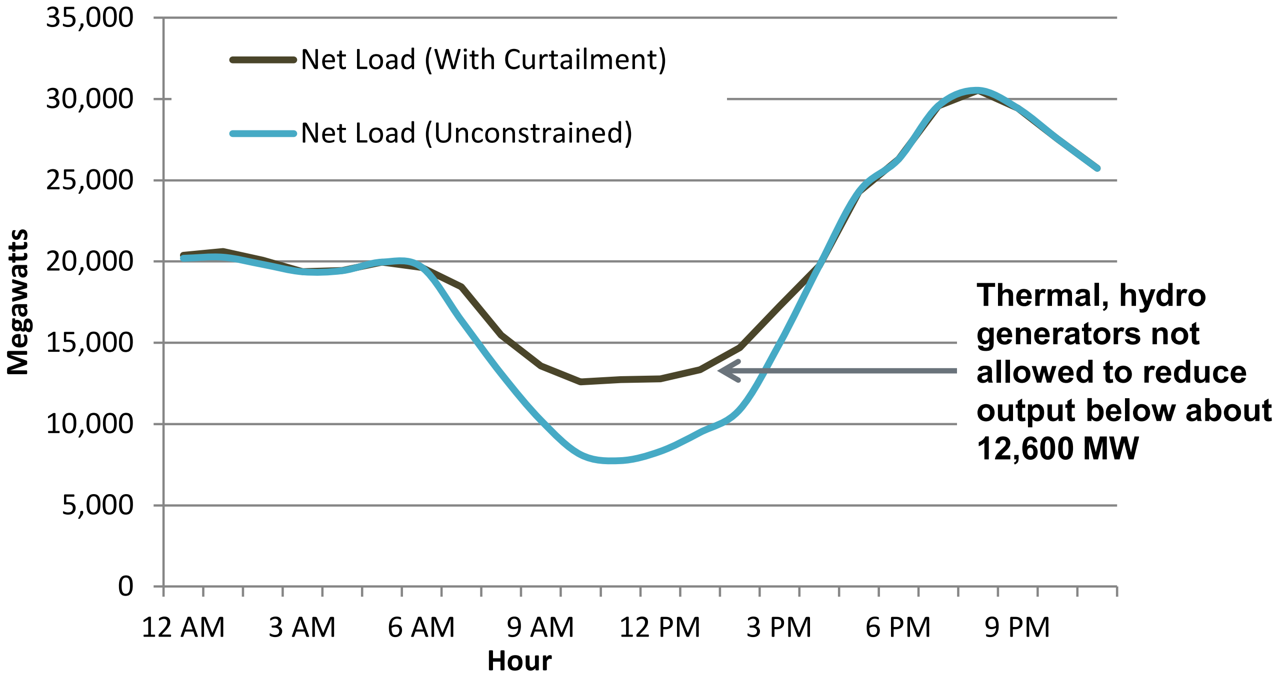
The worst day for potential overgeneration



Load, solar, and wind profiles for California on March 29 in a scenario with 11% annual wind and 11% annual solar assuming no curtailment

But not all PV can be used

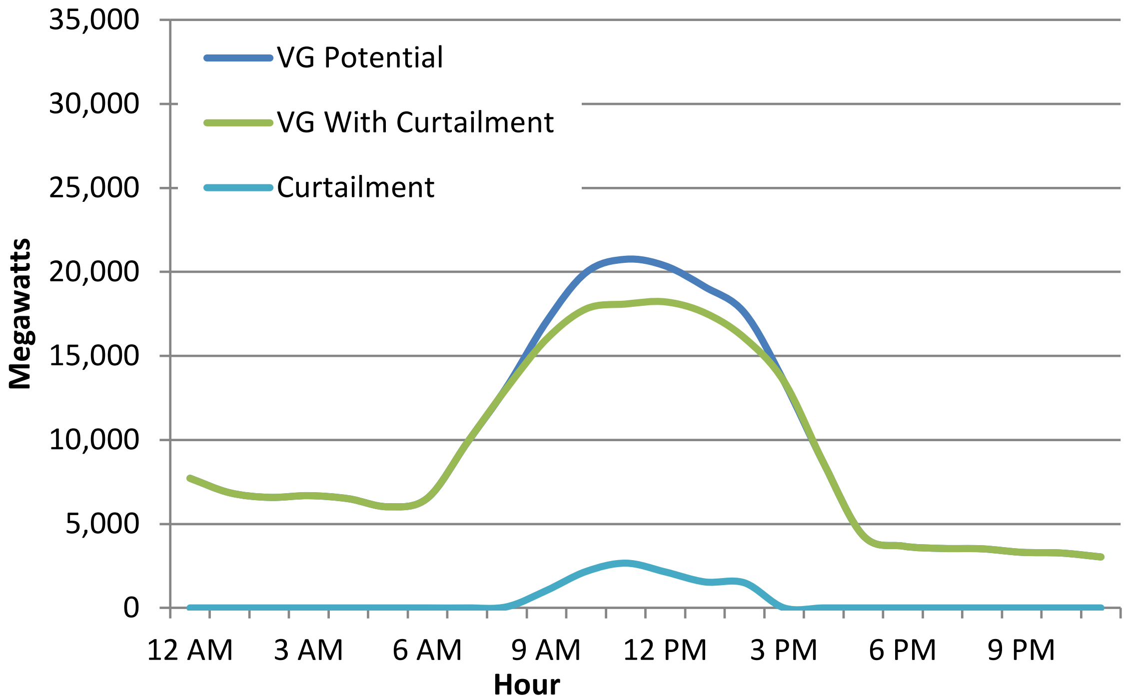
System constraints do not allow reduction in net load beyond a certain point…



Modeled net load in California on March 29 in a scenario with 11% annual wind and 11% annual solar in a system with a 60% instantaneous penetration constraint

Resulting variable generation curtailment

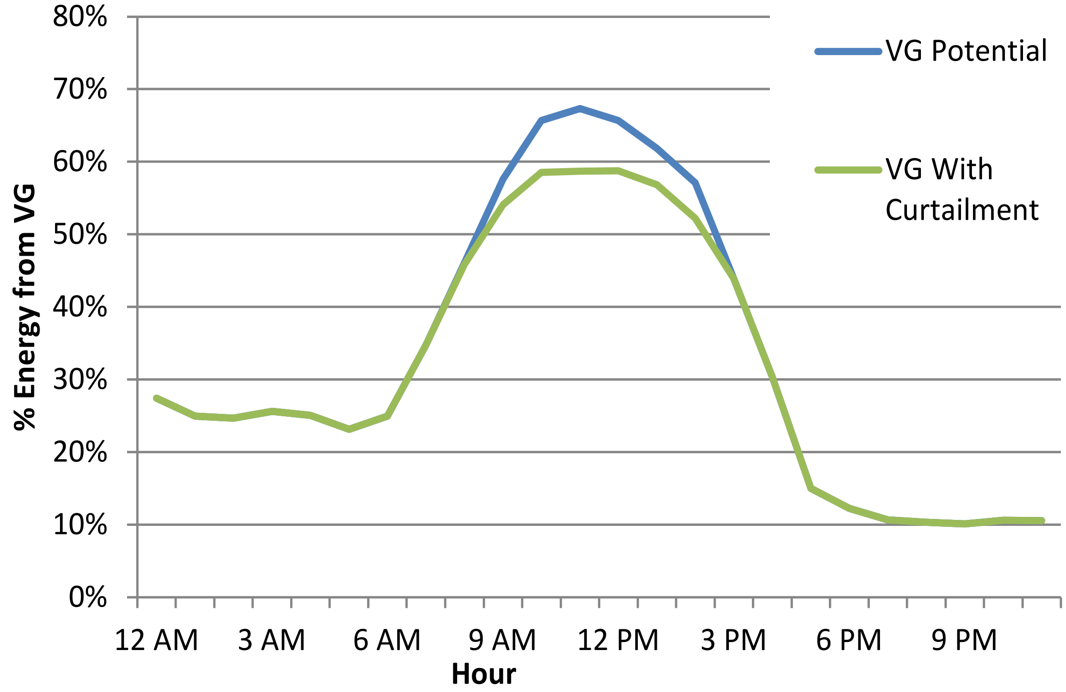
About 5% of the potential VG is curtailed on this day



Used and curtailed VG in California on March 29
in a scenario with 11% annual wind and 11% annual solar

Most curtailment due to 60% limit

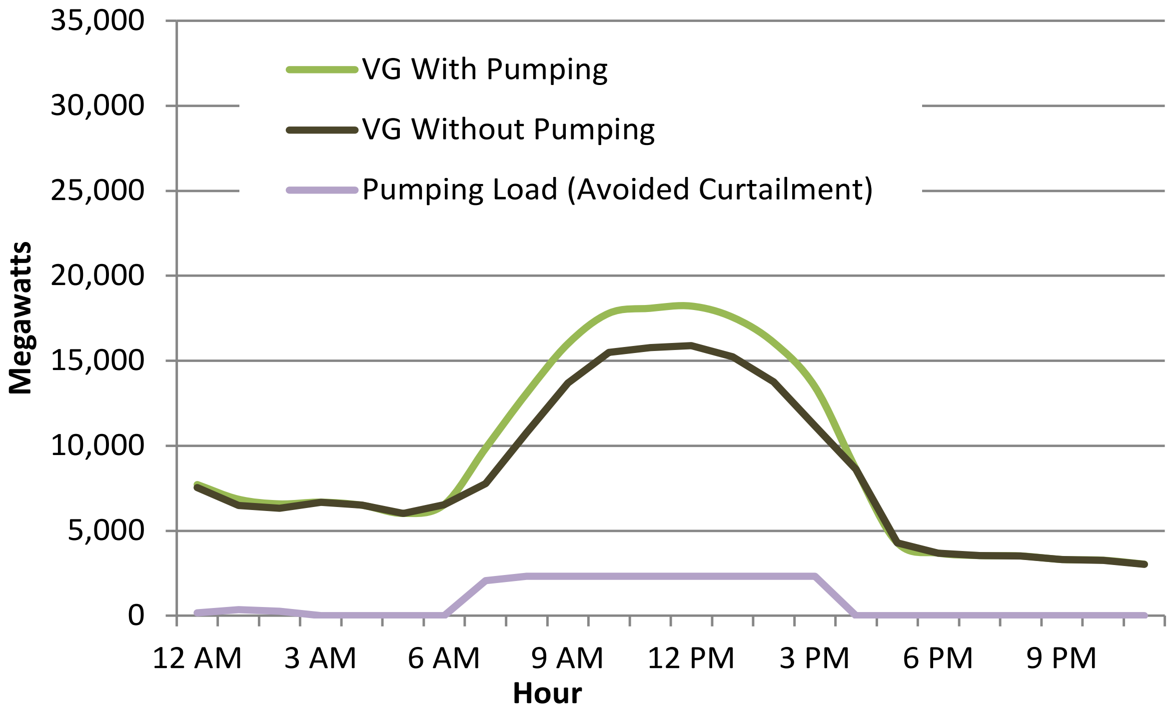
PV could potentially provide up to nearly 70% of the total demand in California at noon on this day



Instantaneous penetration of VG on March 29 with and without curtailment in a scenario with 11% annual wind and 11% annual solar

Existing storage is important

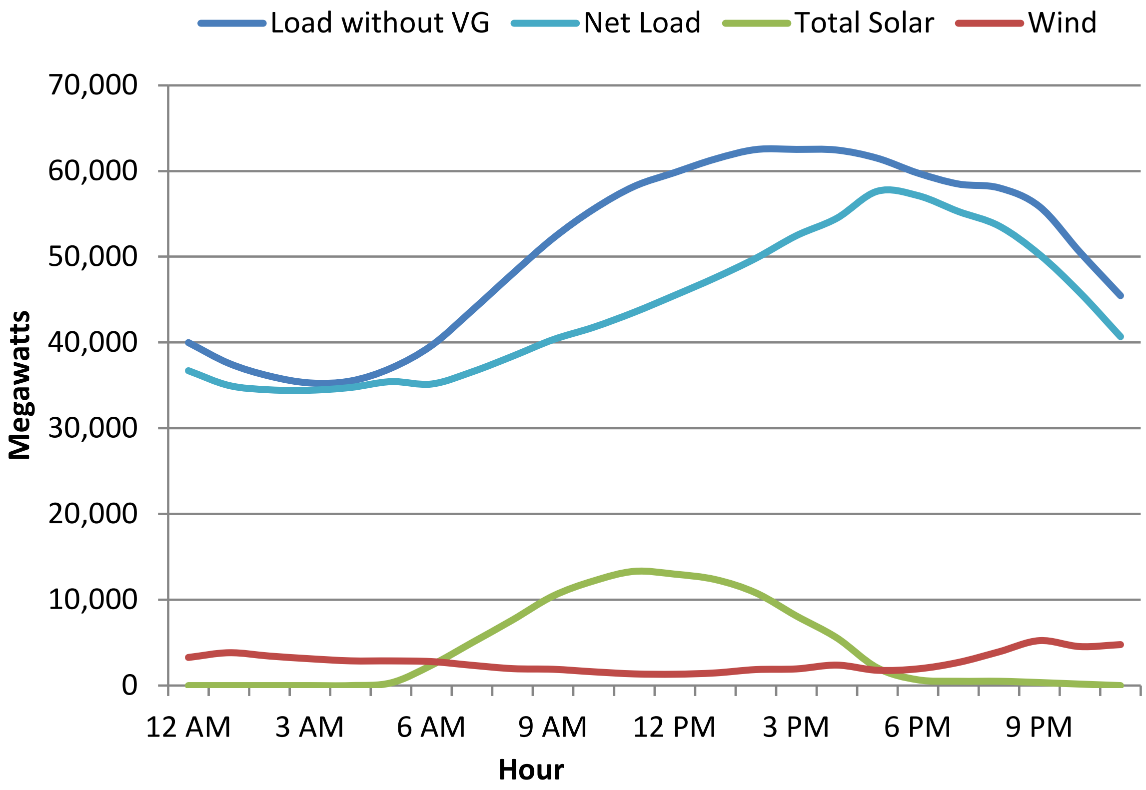
Larger amount of PV would be curtailed without the existing pumped hydro storage in California



Increase in VG use resulting from schedulable pumped storage in a scenario with 11% annual wind and 11% annual solar

Little curtailment during the summer

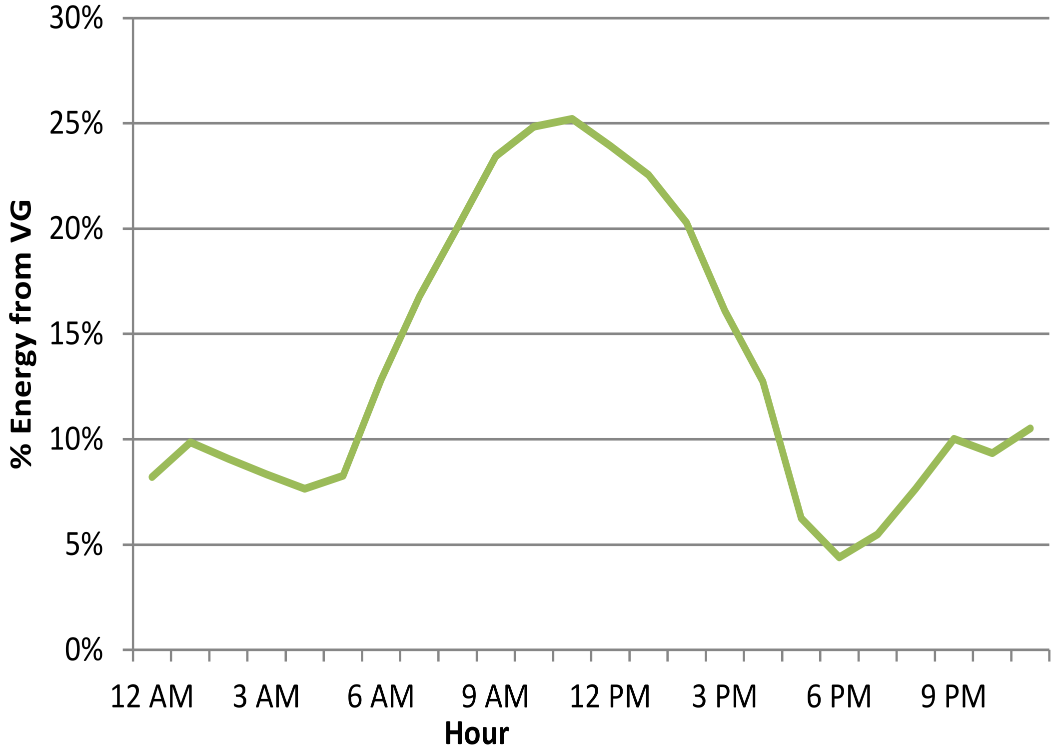
During peak demand days, there is sufficient demand to absorb all the potential VG



Load, solar, and wind profiles for California on July 27 in a scenario with 11% annual wind and 11% annual solar

Lower summer VG penetration

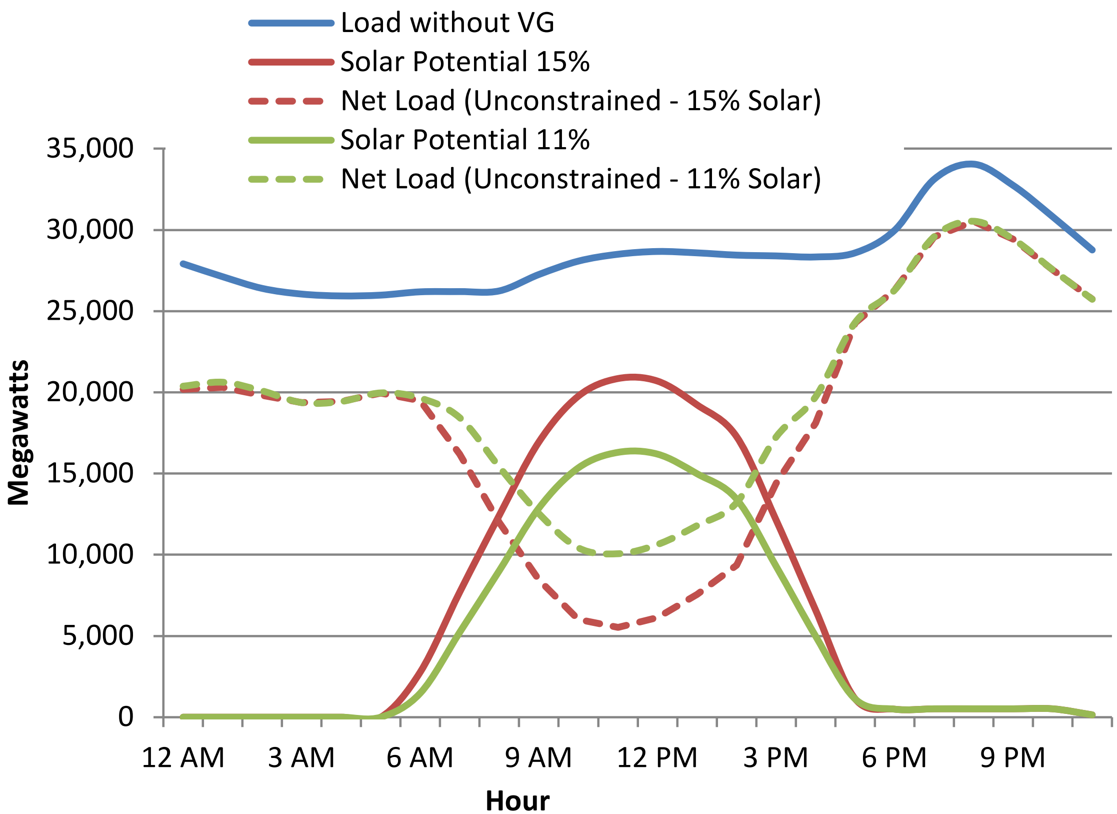
VG contribution is much smaller on the day with the greatest demand



Instantaneous penetration of VG in California on July 27 in a scenario with 11% annual wind and 11% annual solar

Adding more PV makes the problem more challenging

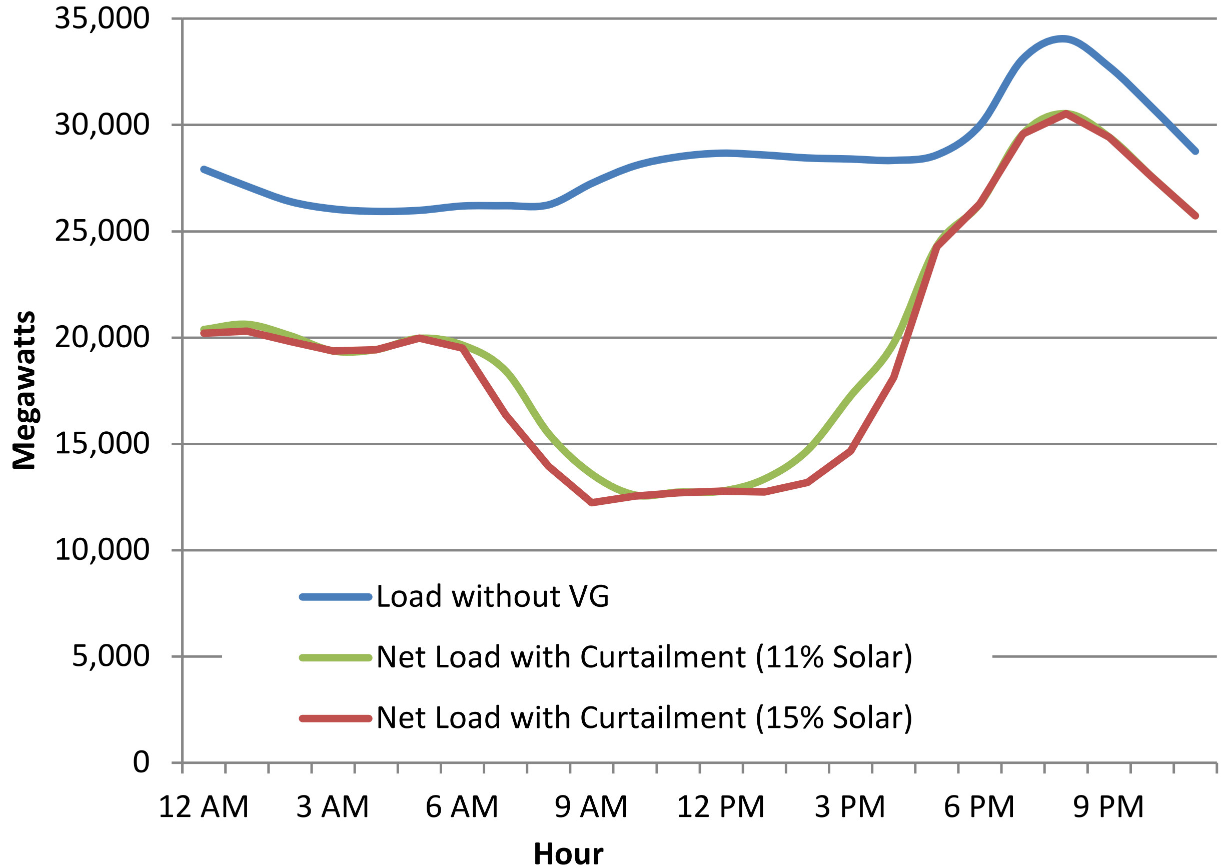
Additional PV increases the size of the duck "belly" and requires even greater flexibility



Load in California and VG profiles on March 29 in a scenario with 11% and 15% annual solar assuming no curtailment

Without greater flexibility, the net load cannot be reduced

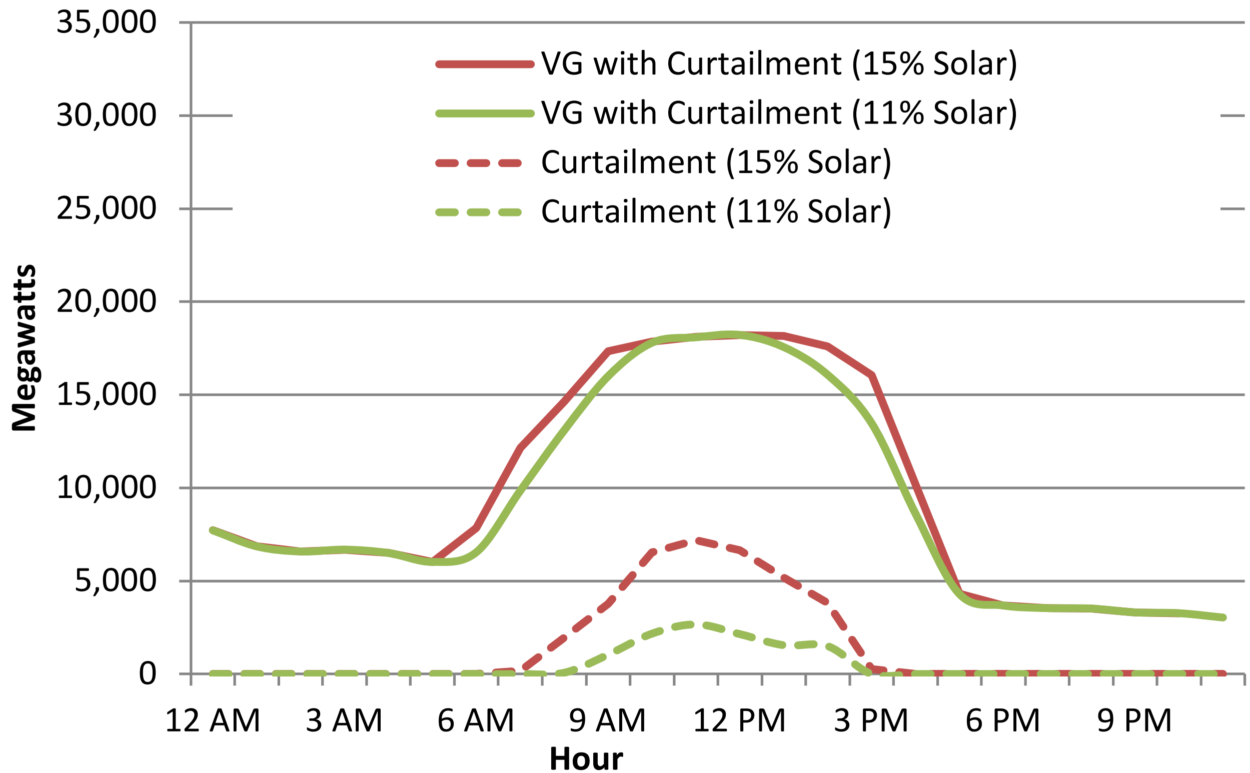
Without reducing the minimum generation level, adding PV does not change the shape of the duck



Net load on March 29
in a scenario with 11% and 15% annual solar
considering operational constraints

And PV curtailment increases

Most (65%) of additional PV is curtailed on this day (5% over the entire year)

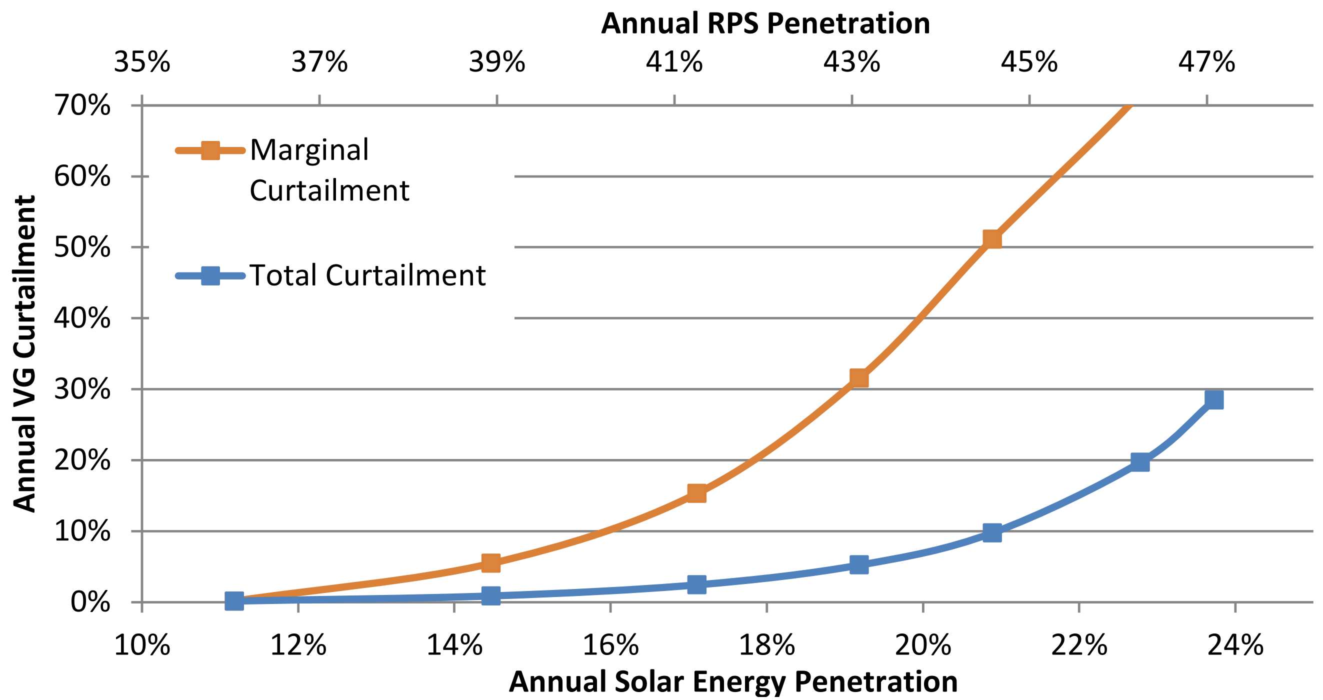


Usable and curtailed VG on March 29 in a scenario with 11% and 15% potential annual solar

Impact of VG penetration in the base case

Marginal curtailment = curtailment of all incremental VG moving from one penetration level to the next

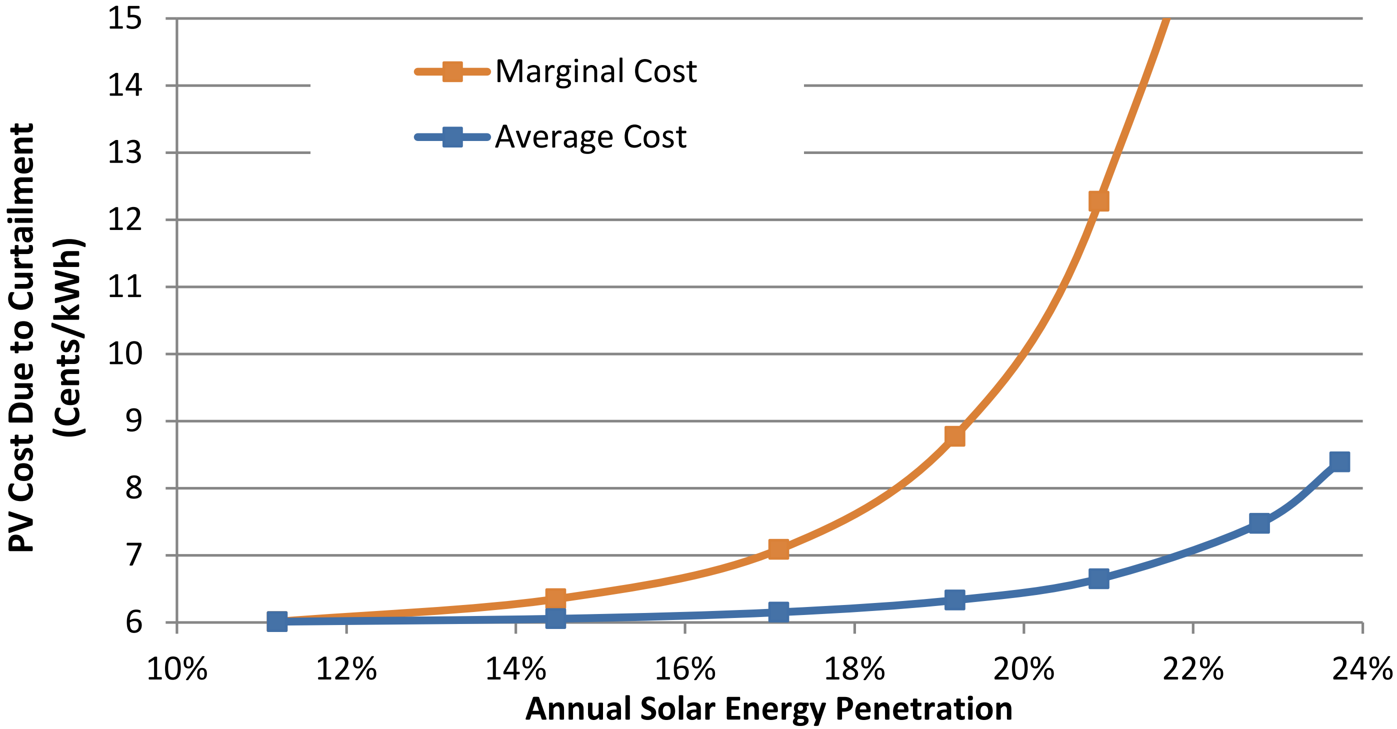
Total curtailment = curtailment rate of all PV installed on the system at a certain penetration level



Marginal and average curtailment due to overgeneration under increasing penetration of PV in California with a 60% instantaneous penetration limit

Impact of VG curtailment on LCOE

Curtailed energy means less can be sold and incremental costs of additional PV rise dramatically



Marginal and average PV LCOE (based on SunShot goals) due to overgeneration under increasing penetration of PV in California with a 60% instantaneous penetration limit

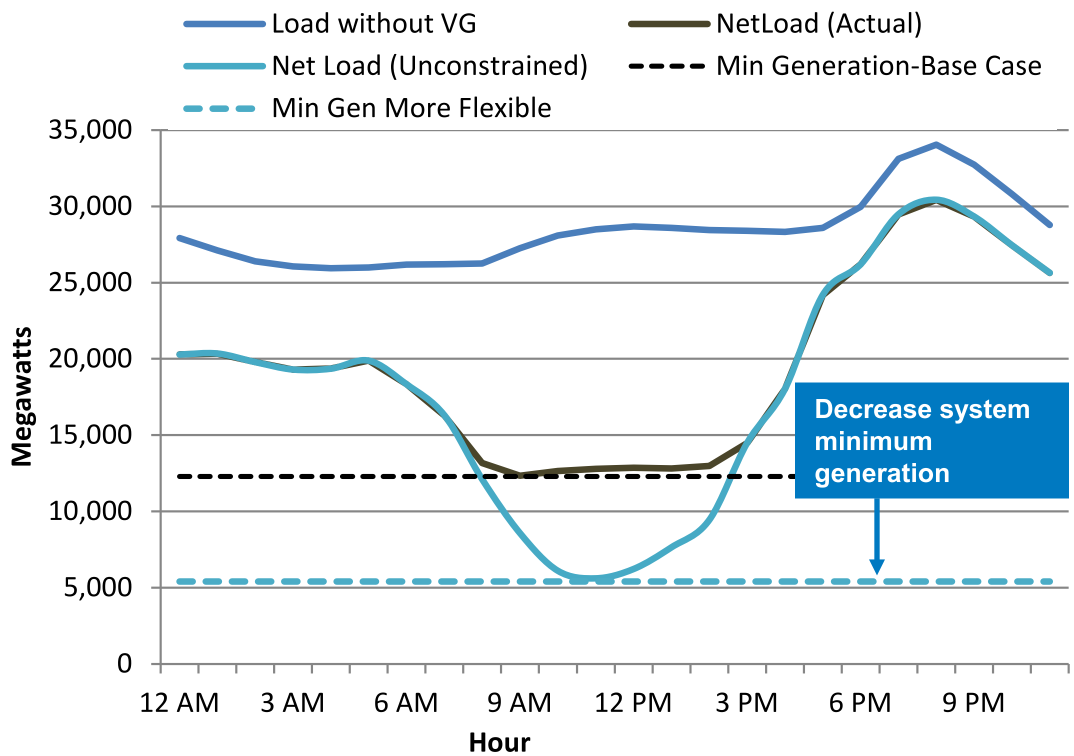
Enabling greater solar penetration

How can we accommodate or change the duck chart shape to increase VG penetration and reduce curtailment?

- **Fatten the Duck –** All approaches that increase the flexibility of the grid and allow greater instantaneous penetration of VG resources—includes changing operational practices to allow more frequent cycling, unit starts and stops, and minimizing the amount of thermal units held at part load.
- **Flatten the Duck –** Shrink the belly shape by shifting supply/demand patterns to allow solar energy to meet parts of the load that would not normally be provided in the middle of the day. Typically involves demand response or storage.

Option 1: Fatten the duck

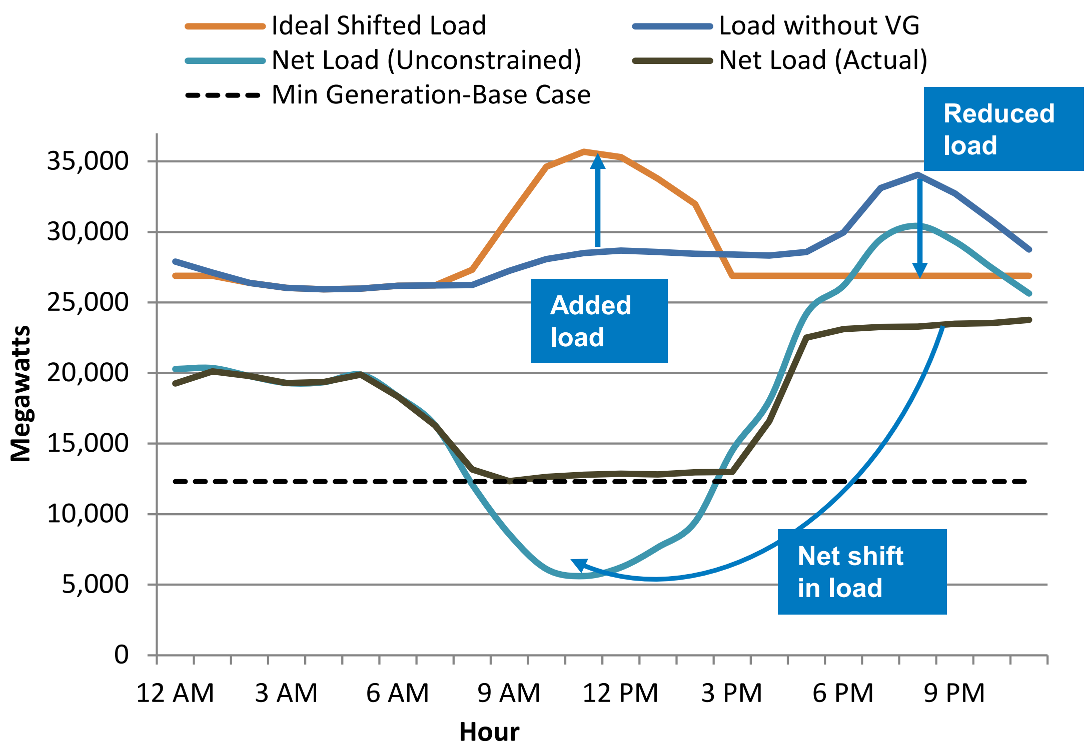
Make a bigger belly



Accommodate increased penetration of PV by reducing system minimum generation requirements and fattening the duck

Option 2: Flatten the duck

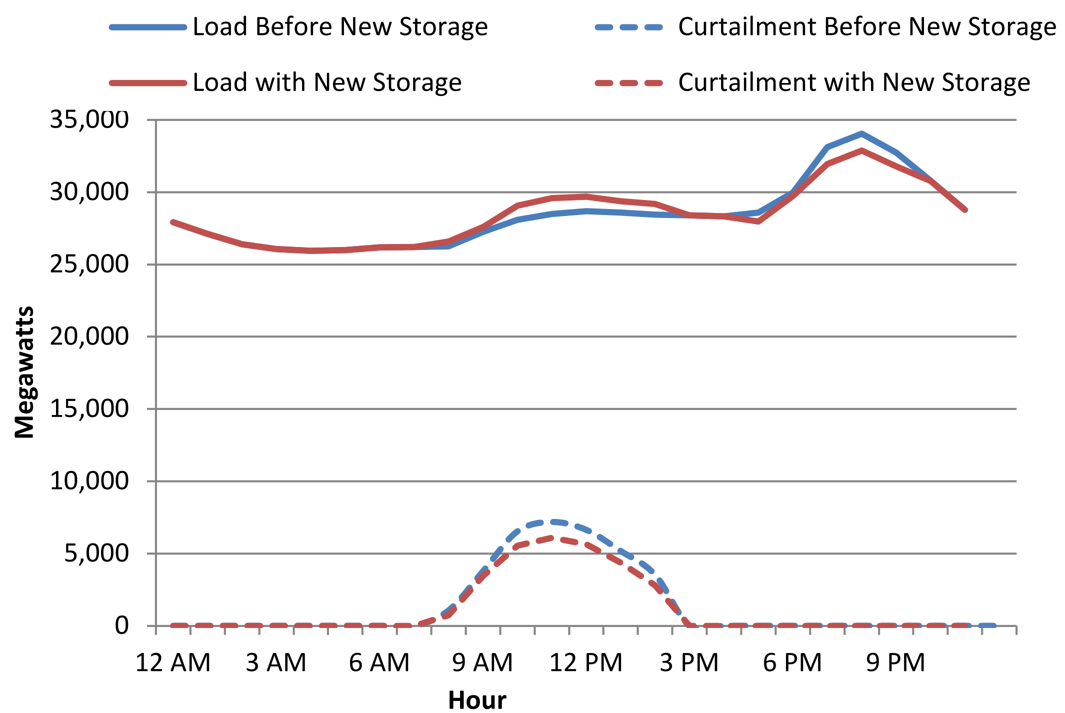
Or "streamline" the duck…by shifting demand



Accommodate increased penetration of PV by flattening the duck (increasing mid-day demand)

Example – New storage flattens the duck

New storage can provide shift load. Here is the additional load produced by the California storage mandate



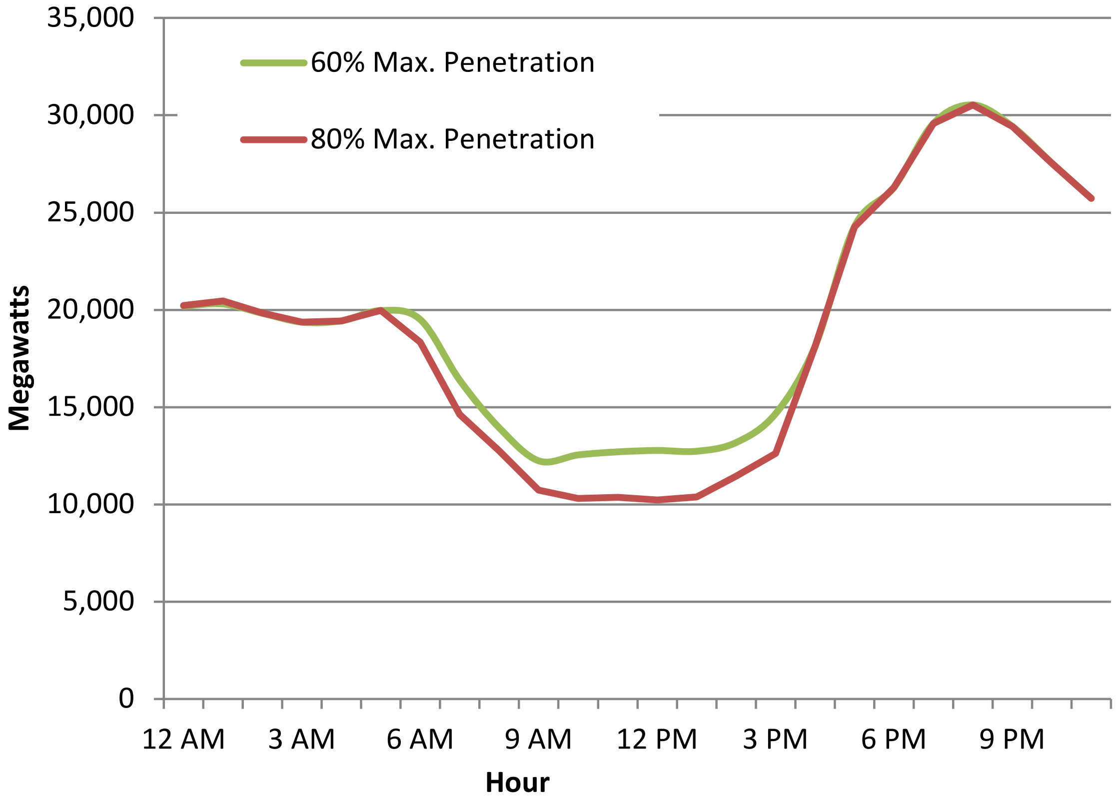
Impact of flattening the duck on March 29 with 1,285 MW of added storage in a scenario with 15% annual solar

But storage can also help fatten the duck

- New storage can provide a highly flexible source of operating reserves, and allow for greater penetration of VG. Storage can reduce the need to keep partially loaded generators operating.
- We examine this scenario by increasing the maximum VG penetration level to 80% and eliminating the local generation requirement.
- This assumes that distributed storage, including behind-the-meter storage, is controllable and able to respond to grid system requirements – storage acts as part of a "smart grid."

Impact of fattening the duck

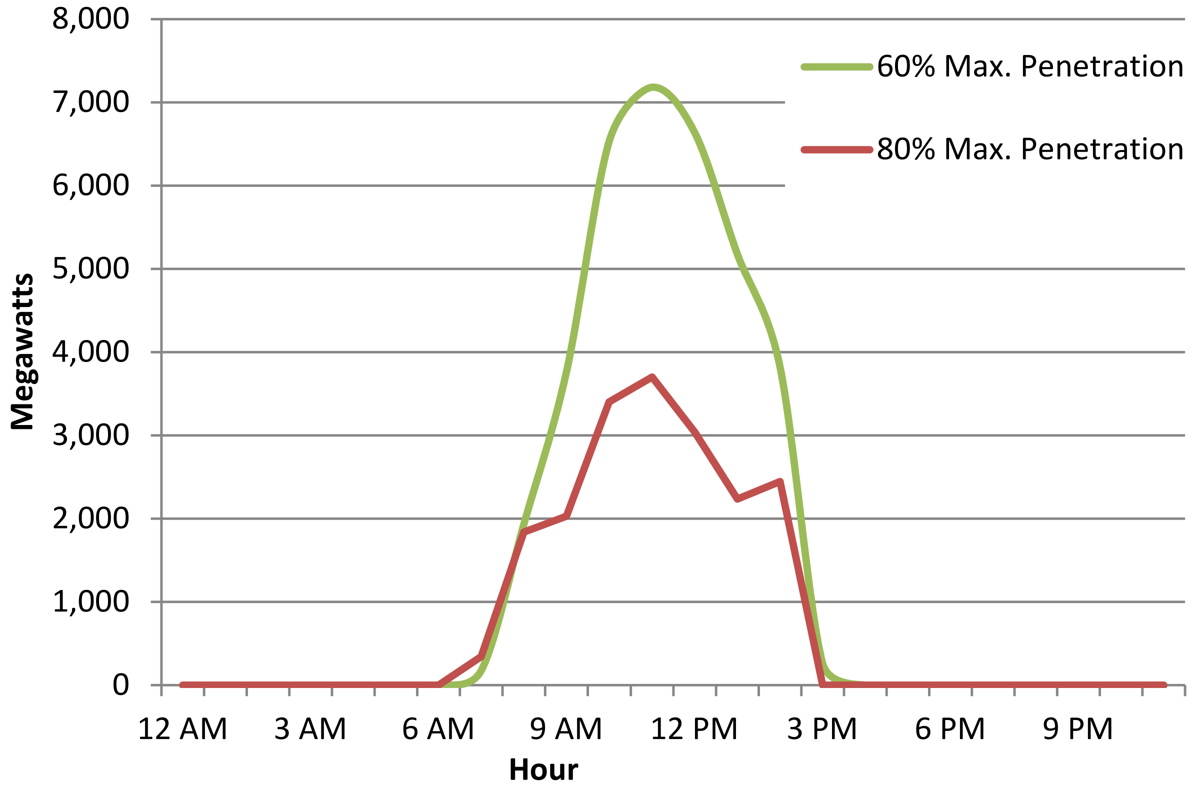
The minimum generation level has dropped to about 10,000 MW, increasing the amount of load served by PV



Net load on March 29 in a scenario with 15% annual solar increasing the maximum penetration of VG to 60% to 80% and eliminating the local generation constraint

This can substantially reduce curtailment

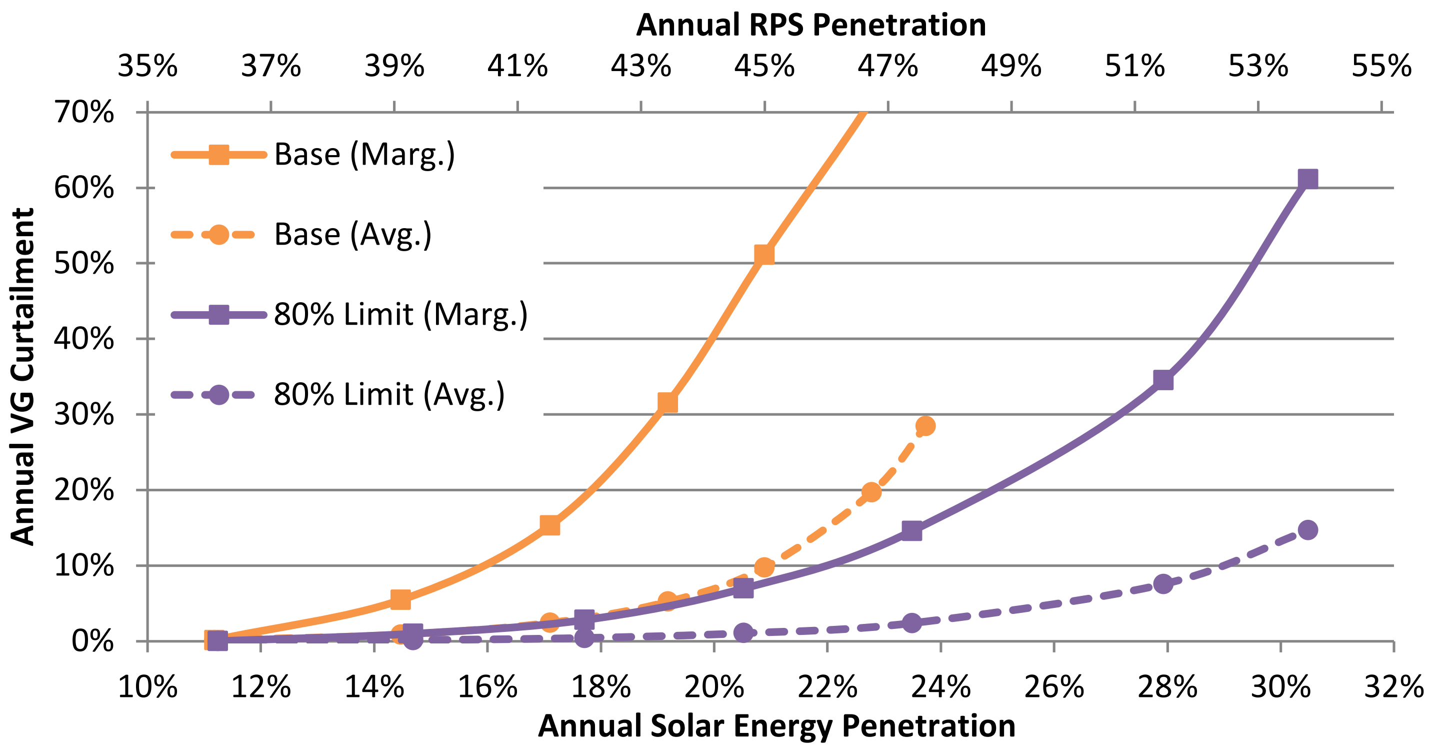
By reducing minimum generation constraints, the curtailments on this day have been reduced by about 50%



VG curtailment on March 29 in a scenario with 15% annual solar increasing the maximum penetration of VG to 60% to 80% and removing the local generation requirement

Greater penetration of VG

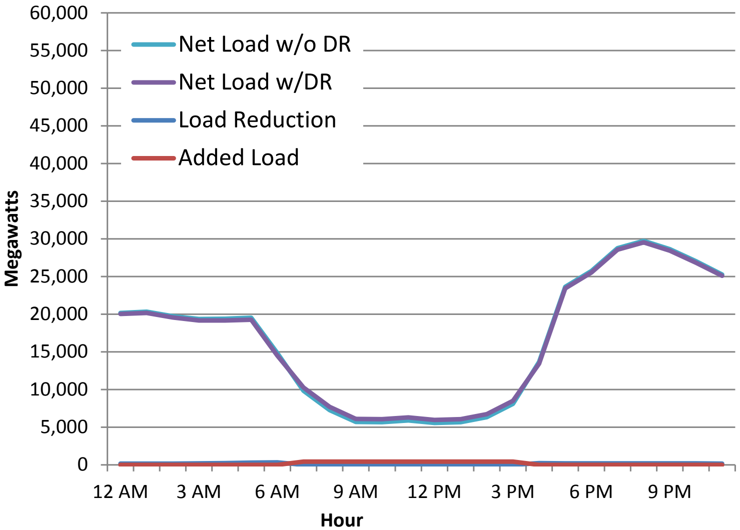
A fatter and flatter duck increases the penetration of VG at the same level of curtailment



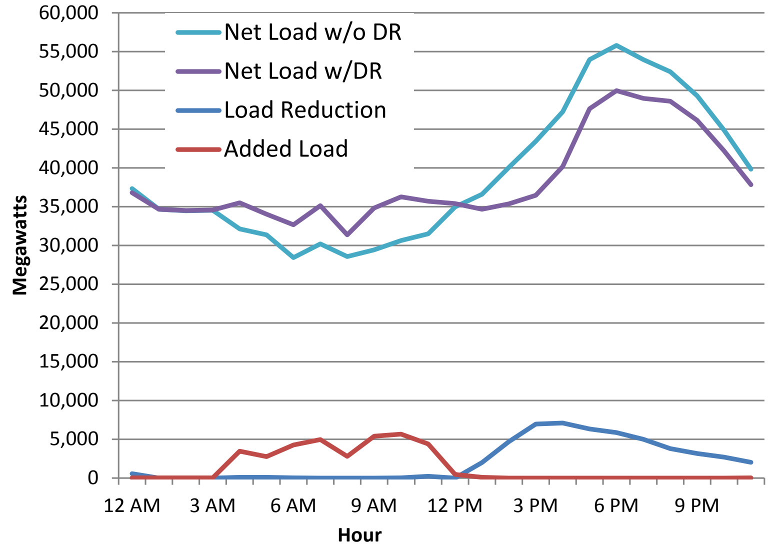
Marginal and average annual curtailment due to overgeneration under increasing penetration of PV in California after adding mandated storage, removing local generation constraint, and increasing maximum instantaneous VG penetration to 80%

Engaging responsive demand?

What if demand response provides BOTH shiftable load and more flexible operation?



Limited load shifting on the duck curve day, but flexible operation may allow greater penetration

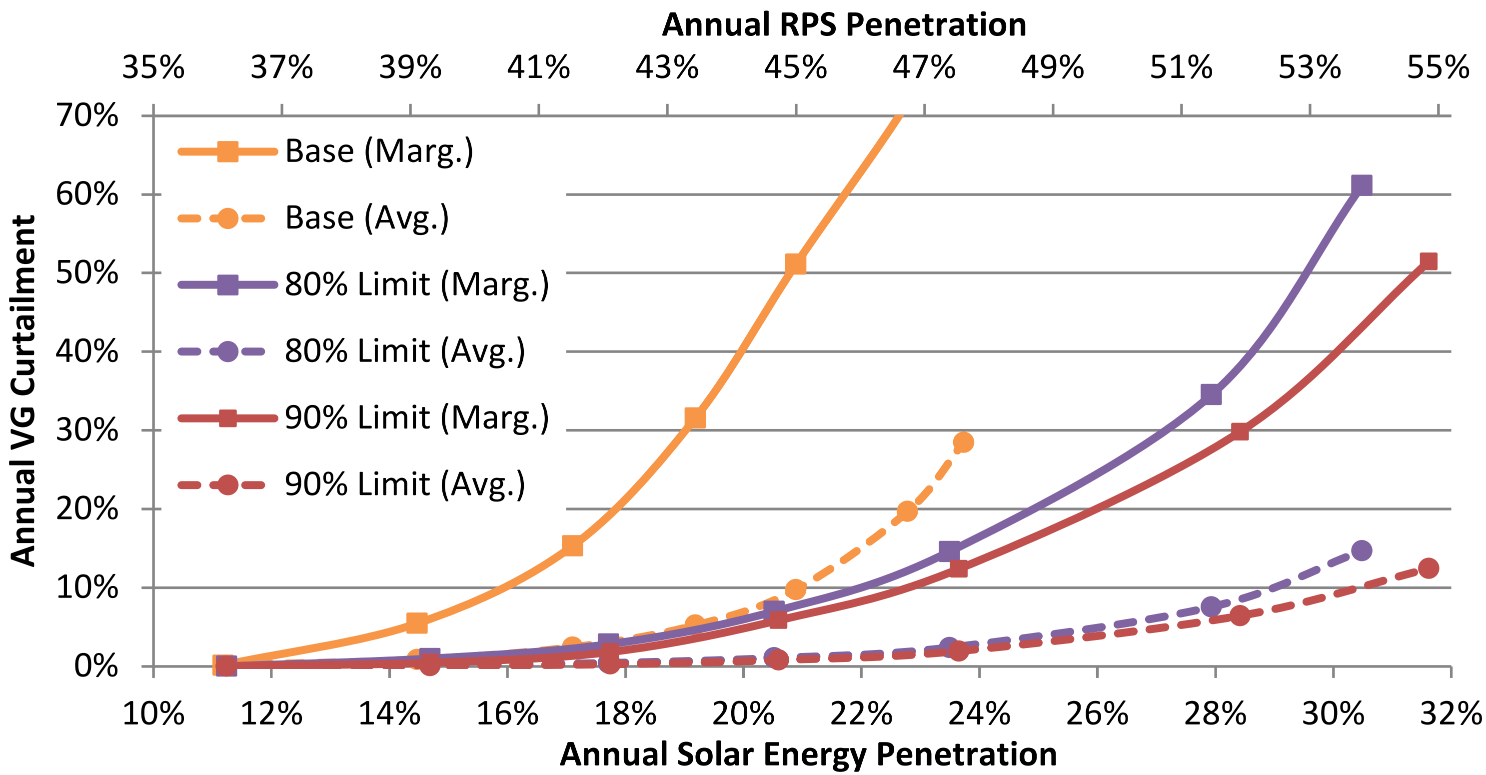


Benefits on high-demand days include capacity reduction and less use of peaking generation

Impact of additional demand response and increasing maximum penetration to 90% on system net load on March 29 and July 27

Even greater penetration of VG

PV penetration of 25% with less than 20% marginal and 5% total curtailment



Marginal and average curtailment due to overgeneration under increasing penetration of PV in California after additional demand response and increasing maximum penetration to 90%

Additional opportunities to fatten and flatten the duck

This analysis does not consider many additional options to increase VG penetration

- **Electricity storage**
- **CSP with thermal storage**
- **Regional interchange**
- **Additional generator flexibility**
- **Alternative renewable sources**

Conclusions

- This analysis indicates that near-term technology options are capable of helping mitigate challenges demonstrated by the duck chart, and increase PV penetrations exceeding 25% and total renewable penetration exceeding 50% with modest curtailment.
- Changes under way or proposed elsewhere—such as shorter scheduling intervals, increased interaction across regions, and creating new market incentives for generator dispatch—will reduce the minimum generation challenge and enable greater utilization of VG.
- In the longer term, grid operators will need non-traditional resources to supply reserves and grid stability services. In turn, this will require system operators to have visibility and control of distributed PV, storage, and load, and will likely require new market mechanisms to incentivize these resources to participate in providing grid services.

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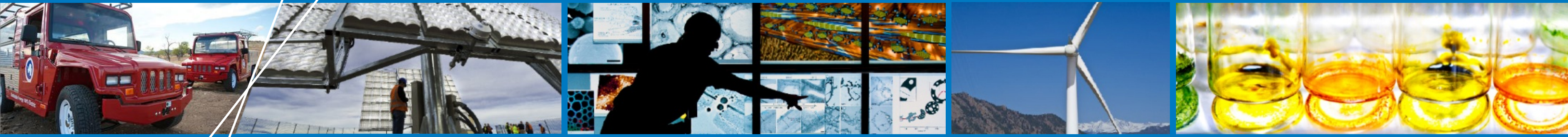

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Full report at
http://www.nrel.gov/docs/fy16osti/65023.pdf