# Quantifying the Value of CSP with Thermal Energy Storage

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Presentation to the SunShot CSP Program Review

April 23, 2013

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

# Overall Motivation

- What is the addition of TES to a CSP plant actually worth?
- Dispatchable energy
- Ancillary services
- Firm capacity
- System Flexibility

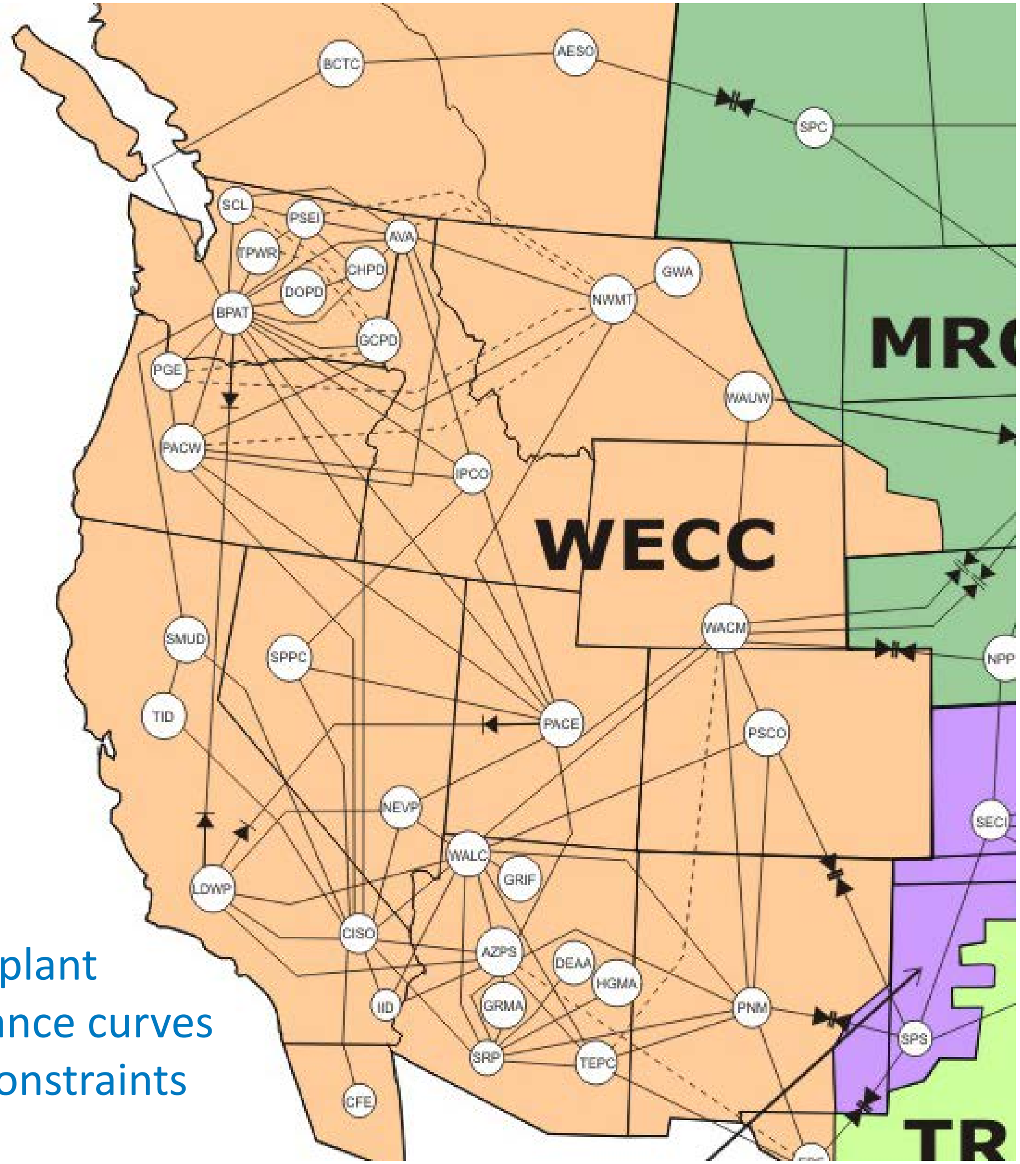
# DOE supported analysis to date

- Implement concentrating solar power (CSP) with thermal energy storage (TES) in a commercial production cost model
  - Develop approaches that can be used by utilities and system planners to incorporate CSP in standard planning tools
- Evaluate the optimal dispatch of CSP with TES
  - How would a plant actually be used to minimize system production cost?
- Quantify the value of adding storage to CSP in a high renewable energy (RE) scenario in California
  - How does TES change the value of CSP?

# Analytic Approaches

- Price-Taker
  - Simulates a relatively small CSP plant that does not affect prices
  - Dispatches CSP against historical prices
  - Cannot perform forward-looking analysis in a future system
  - Limited in scope, but relatively low-cost effort
- Full-grid simulation
  - Use production cost (unit commitment and economic dispatch) model
  - Can simulate future grid mixes
  - Can evaluate interaction of CSP with the grid
  - Can be costly and time consuming to develop and implement

# Example analysis – CSP in California




**Rest of Western Electricity Coordinating Council (WECC):**

- Simple plant performance curves
- Linear operation

**California:**

- Detailed plant performance curves
- Integer constraints

# California Independent System Operator (CAISO) Scenarios

| Scenario | Region | Incremental Capacity (MW) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Biomass/ Biogas | Geo-thermal | Small Hydro | Solar Photovoltaics (PV) | Distributed Solar | CSP | Wind | TOTAL |
| Trajectory | CREZ-North CA | 3 | 0 | 0 | 900 | 0 | 0 | 1,205 | 2,108 |
| | CREZ-South CA | 30 | 667 | 0 | 2,344 | 0 | 3,069 | 3,830 | 9,940 |
| | Out-of-State | 34 | 154 | 16 | 340 | 0 | 400 | 4,149 | 5,093 |
| | Non-CREZ | 271 | 0 | 0 | 283 | 1,052 | 520 | 0 | 2,126 |
| | *Scenario Total* | *338* | *821* | *16* | *3,867* | *1,052* | *3,989* | *9,184* | *19,266* |
| Environmentally Constrained | CREZ-North CA | 25 | 0 | 0 | 1,700 | 0 | 0 | 375 | 2,100 |
| | CREZ-South CA | 158 | 240 | 0 | 565 | 0 | 922 | 4,051 | 5,935 |
| | Out-of-State | 222 | 270 | 132 | 340 | 0 | 400 | 1,454 | 2,818 |
| | Non-CREZ | 399 | 0 | 0 | 50 | 9077 | 150 | 0 | 9,676 |
| | *Scenario Total* | *804* | *510* | *132* | *2,655* | *9,077* | *1,472* | *5,880* | *20,530* |
| Cost-Constrained | CREZ-North CA | 0 | 22 | 0 | 900 | 0 | 0 | 378 | 1,300 |
| | CREZ-South CA | 60 | 776 | 0 | 599 | 0 | 1,129 | 4,569 | 7,133 |
| | Out-of-State | 202 | 202 | 14 | 340 | 0 | 400 | 5,639 | 6,798 |
| | Non-CREZ | 399 | 0 | 0 | 50 | 1,052 | 150 | 611 | 2,263 |
| | *Scenario Total* | *661* | *1,000* | *14* | *1,889* | *1,052* | *1,679* | *11,198* | *17,493* |
| Time-Constrained | CREZ-North CA | 22 | 0 | 0 | 900 | 0 | 0 | 78 | 1,000 |
| | CREZ-South CA | 94 | 0 | 0 | 1,593 | 0 | 934 | 4,206 | 6,826 |
| | Out-of-State | 177 | 158 | 223 | 340 | 0 | 400 | 7,276 | 8,574 |
| | Non-CREZ | 268 | 0 | 0 | 50 | 2,322 | 150 | 611 | 3,402 |
| | *Scenario Total* | *560* | *158* | *223* | *2,883* | *2,322* | *1,484* | *12,171* | *19,802* |

Note: CREZ = Competitive Renewable Energy Zone

# Approach

1. Start with base case – Get total production cost
    - Base case is a 32% scenario, produced by reducing PV generation in Southern CA
    - Also adjusted reserve requirements
2. Add a generator – Get total production cost
3. Subtract – Difference is operational benefit of added generator
4. Calculate capacity benefits separately

# CSP Scenarios

Four scenarios, each with an added plant producing approximately equivalent annual energy:

1. CSP plant with 6 hours of storage
   - 762 MW, SM = 2.0
   - Generates about 3,050 GWh, or enough to provide about 1.0% of California demand
   - No change in reserve requirements
2. CSP with reserves
   - Same as before, but can provide regulation, load-following, and spin
3. Solar PV
   - 1548 MW
   - This plant also required additional reserves due to uncertainty and variability
4. Flat block (baseload) resource
   - 359 MW of constant output with zero fuel costs

# Reserves

- Three classes of ancillary service requirements were included (Contingency, Regulation, Flexibility)
  - Contingency reserves not modified
  - Regulation and flexibility requirements based on variation of net load using WWSIS II methods

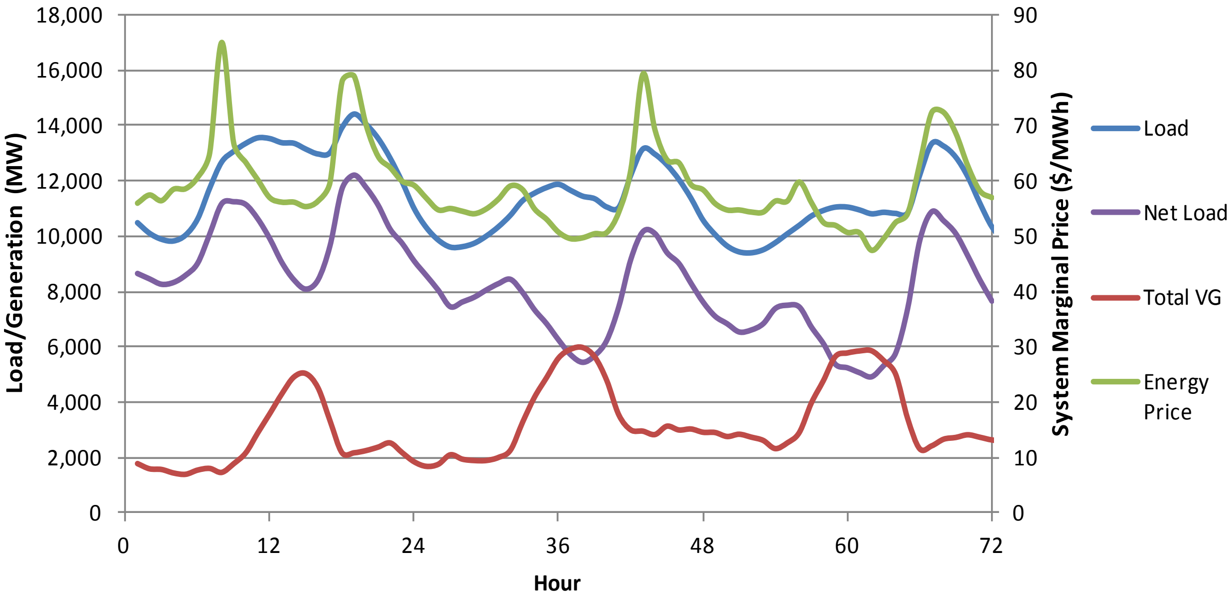
# Operational Value Results

PLEXOS generates hour sources of costs for system operation:

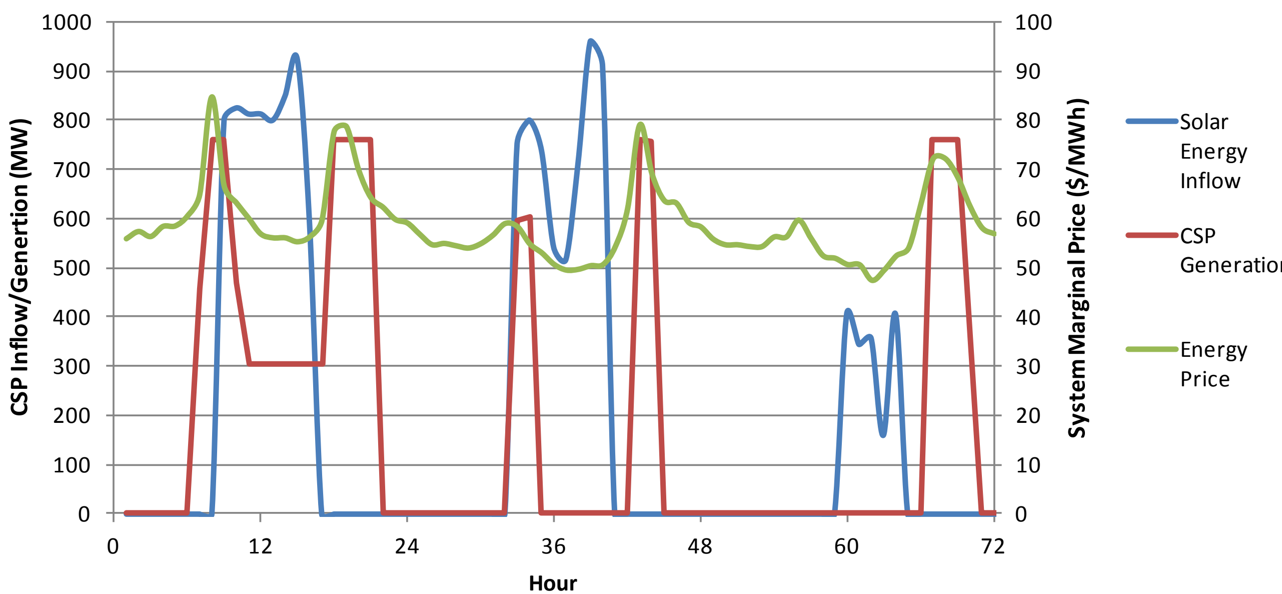
1. Operational fuel
2. Variable operations and maintenance (O&M)
3. Startup (fuel + start O&M)
4. Emissions

Examining dispatch can explain the origin and differences of these costs.

# January Price and Dispatch

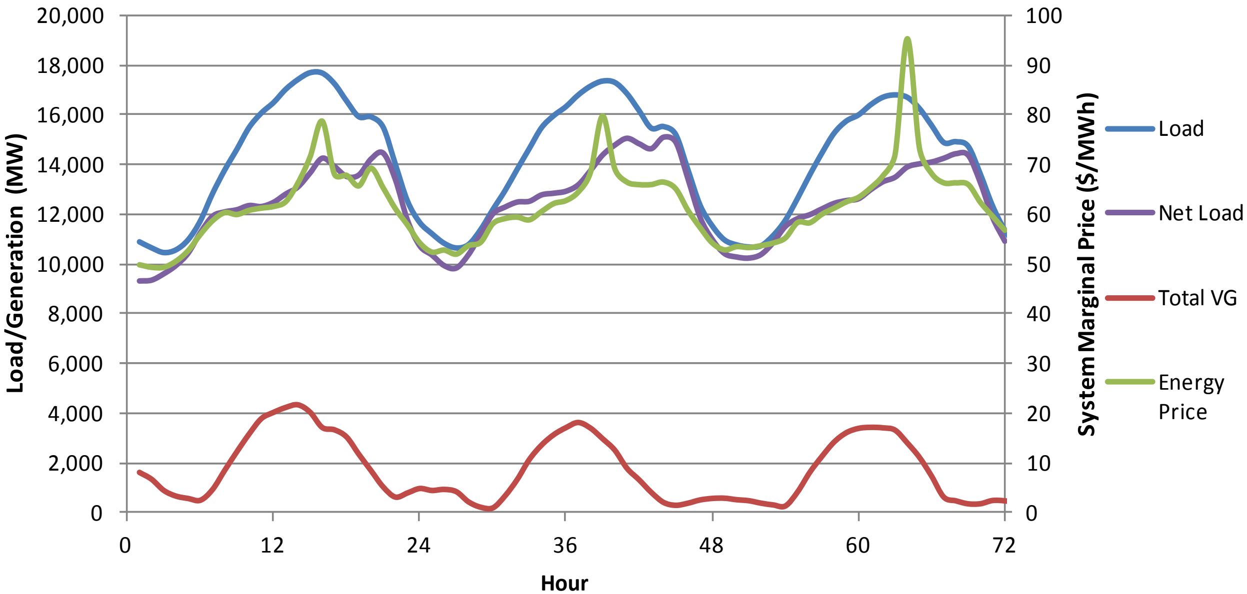



System net load and marginal price for January 31–February 2



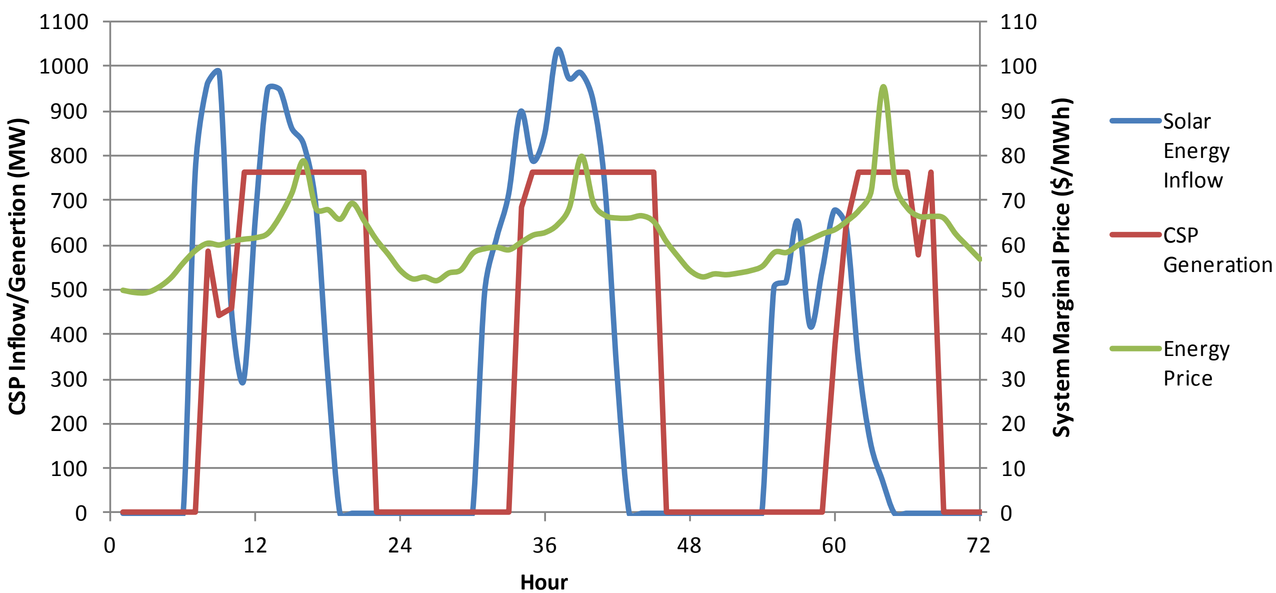

System marginal price and corresponding CSP generation on January 31–February 2

# June Price and Dispatch




System net load and marginal price for June 24–26

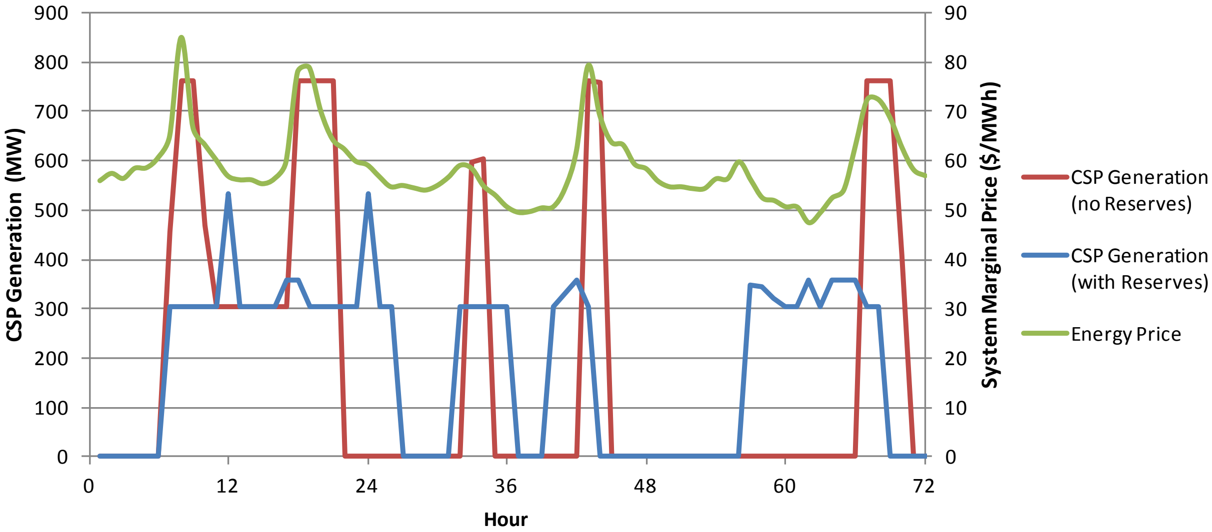
System marginal price and corresponding CSP generation on June 24–26



# Operation with Reserves

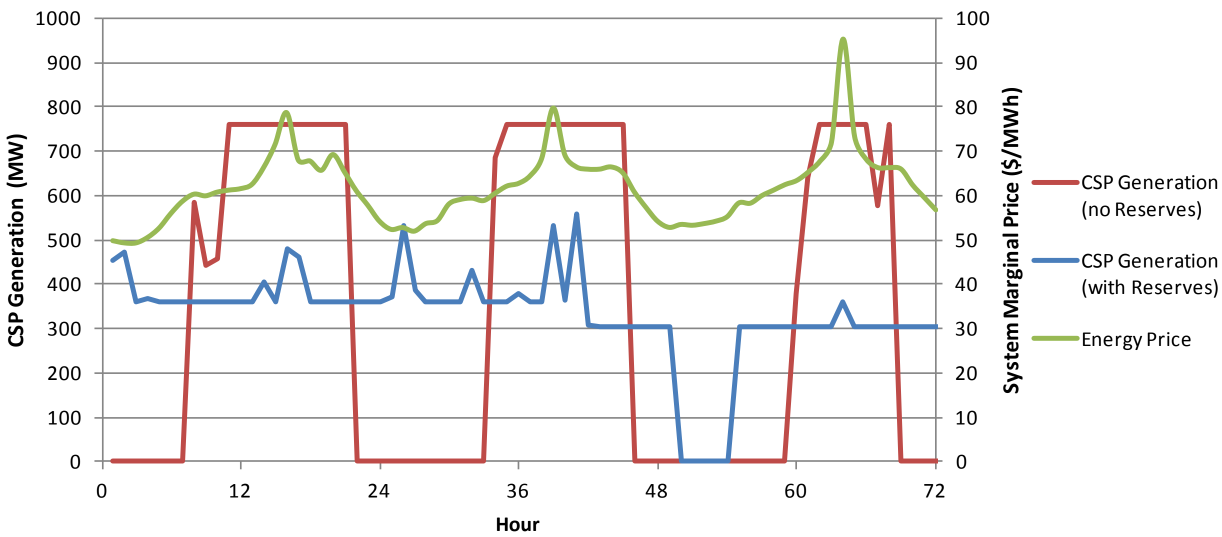
- Much more part-load operation
  - Plant without reserves operates at full output during about 66% of on-line hours
  - Plant providing reserves operates at full output during about 11% of on-line hours
- Stays on line longer
  - 25% fewer starts
- Operates at lower output even when price is high

# Operation with Reserves




System marginal price and corresponding CSP generation on January 31–February 2

System marginal price and corresponding CSP generation on June 24–26



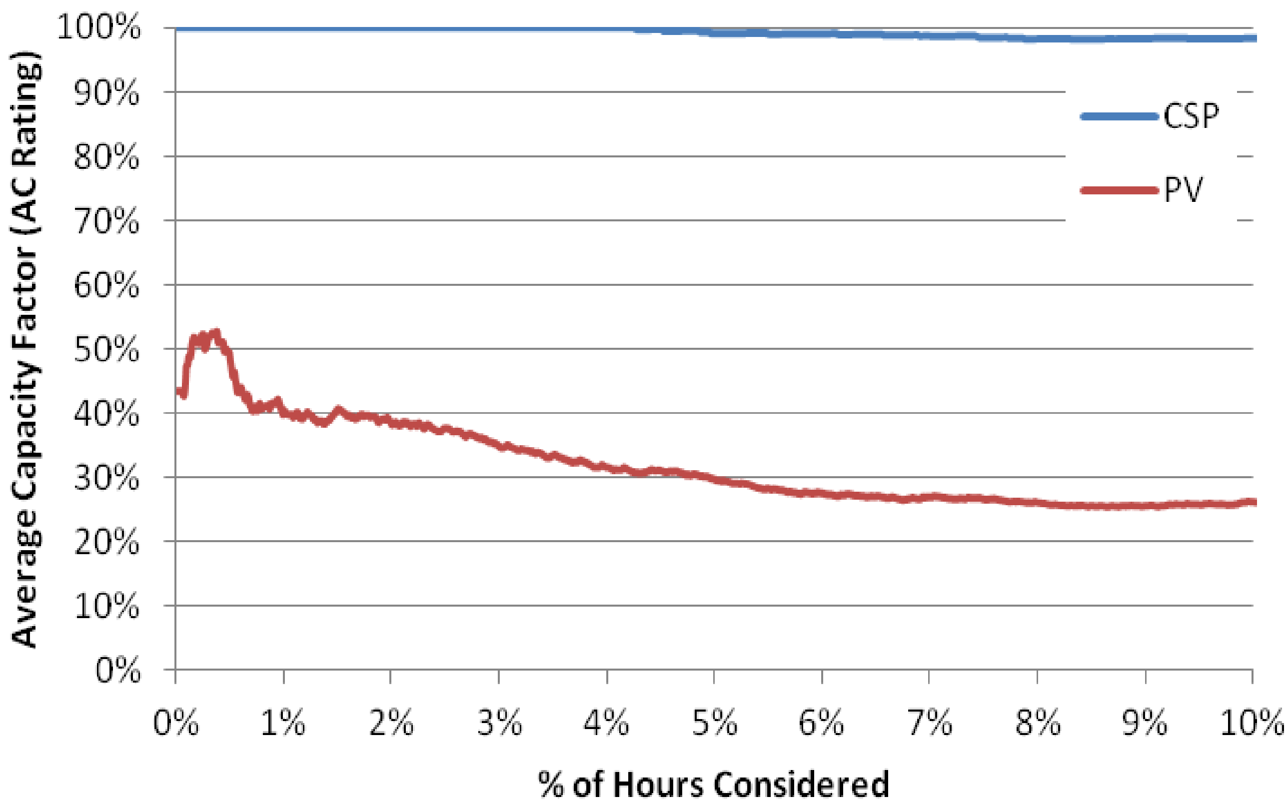
# Total Operational Value

| | Operational Value per Unit of Delivered Energy ($/MWh) | | | |
|---|---|---|---|---|
| | Baseload | PV | CSP (no Reserves) | CSP (with Reserves) |
| Fuel | 33.9 | 29.1 | 38.9 | 54.0 |
| Variable O&M | 4.7 | 4.4 | 5.2 | 6.0 |
| Start | 0.1 | -2.3 | 2.1 | 4.7 |
| Emissions | 21.9 | 22.7 | 20.1 | 18.3 |
| **Total** | 60.6 | 53.9 | 66.2 | 83.0 |

# Capacity Value

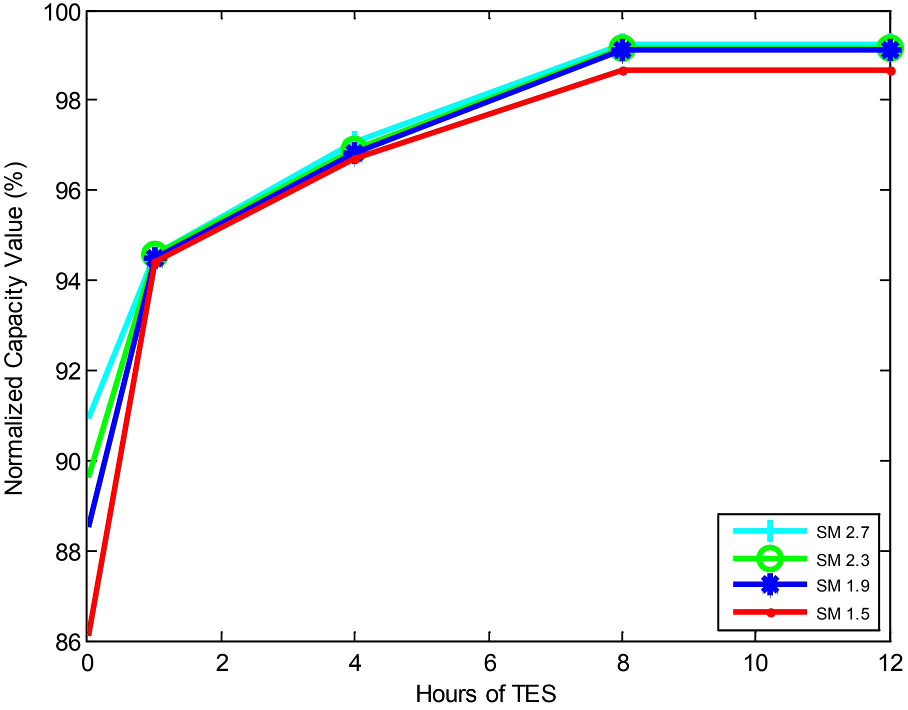
- Operation value considers only the variable costs of system operation
- Capacity value represents the ability of CSP to displace fossil or other conventional generation resources
- Determined by the ability of a resource to provide generation during periods of highest net load periods

# Capacity Value



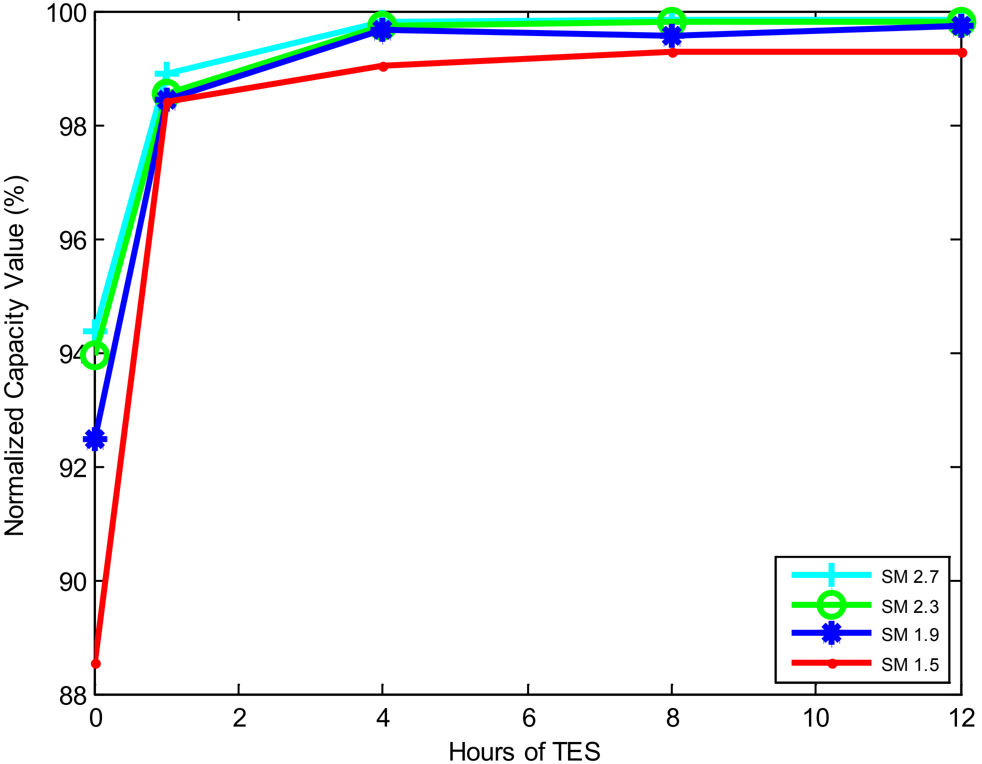

Output during the highest-price hours

# Capacity Value (Previous Study)




Arizona

Death Valley, Ca



# Capacity Value

| | Flat Block | PV | CSP with TES |
|---|---|---|---|
| Capacity Credit (%) | 100 | 47 | 100 |
| Capacity Value (Low / High) ($/kW) | 55 / 212 | 26 /100 | 55 / 212 |
| Capacity Value of Energy (Low / High) ($/MWh) | 6.3 / 24.7 | 10.7 / 41.3 | 13.6 / 52.3 |

"Low" case assumes the cost of new capacity is $55/kW-yr,
"High" case assumes the cost of new capacity is $212/kW-yr

# Total Operational and Capacity Value

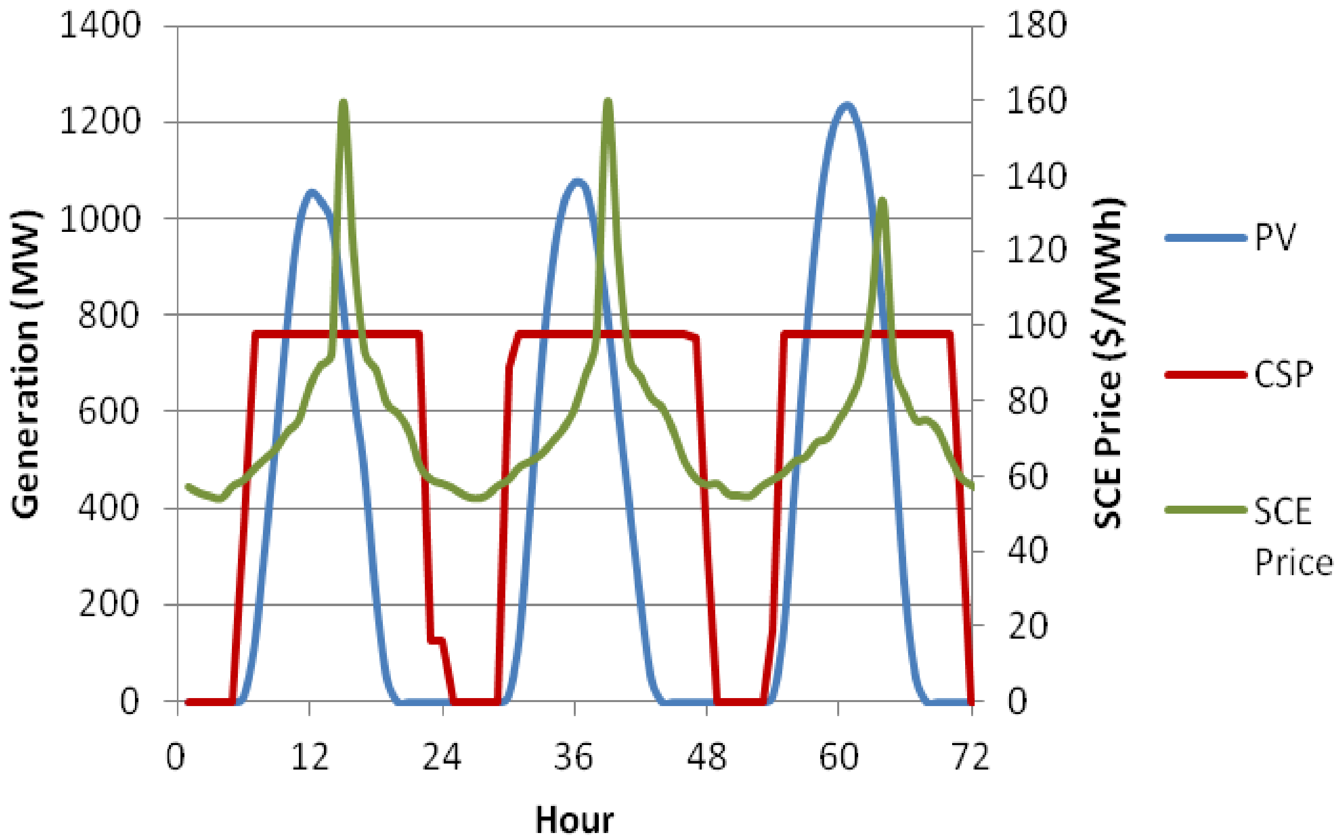
| | Value per Unit of Delivered Energy ($/MWh) | | | |
|---|---|---|---|---|
| | Baseload | PV | CSP (no Reserves) | CSP (with Reserves) |
| Fuel | 33.9 | 29.1 | 38.9 | 54.0 |
| Variable O&M | 4.7 | 4.4 | 5.2 | 6.0 |
| Start | 0.1 | -2.3 | 2.1 | 4.7 |
| Emissions | 21.9 | 22.7 | 20.1 | 18.3 |
| Capacity (Low / High) | 6.3 / 24.7 | 10.7 / 41.3 | 13.6 / 52.3 | 13.6 / 52.3 |
| **Total** | 66.8 / 84.7 | 64.6 / 95.3 | 79.8 / 118.5 | 96.6 / 135.3 |

Higher emissions benefits from PV and baseload generators are from avoided out-of-state coal generation. CSP times its output to avoid mostly higher-value, in-state gas generation.

# Value Difference

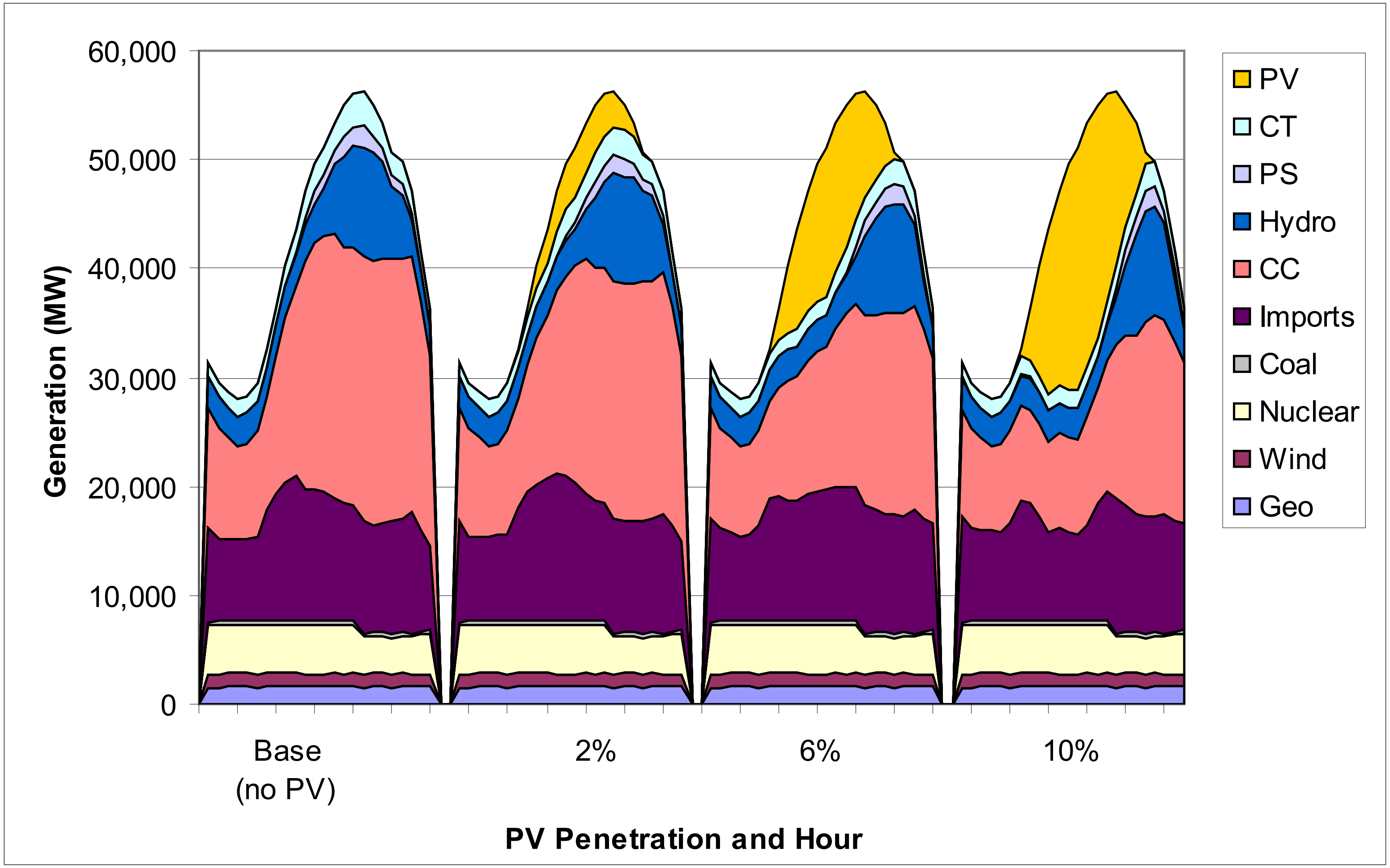
| | Difference in Value per Unit of Delivered Energy for a CSP Plant Providing Reserves ($/MWh) | | |
|---|---|---|---|
| | **Baseload** | **PV** | **CSP (no Reserves)** |
| Fuel | 20.1 | 24.9 | 15.1 |
| Variable O&M | 1.3 | 1.6 | 0.8 |
| Start | 4.6 | 7.0 | 2.7 |
| Emissions | -3.6 | -4.4 | -1.8 |
| Capacity (Low / High) | 7.3 / 20.8 | 2.8 / 8.1 | 0 / 0 |
| **Total (Low / High)** | 29.8 / 50.6 | 32.0 / 40.1 | 16.8 / 16.8 |

# Challenges of Higher Solar Penetration



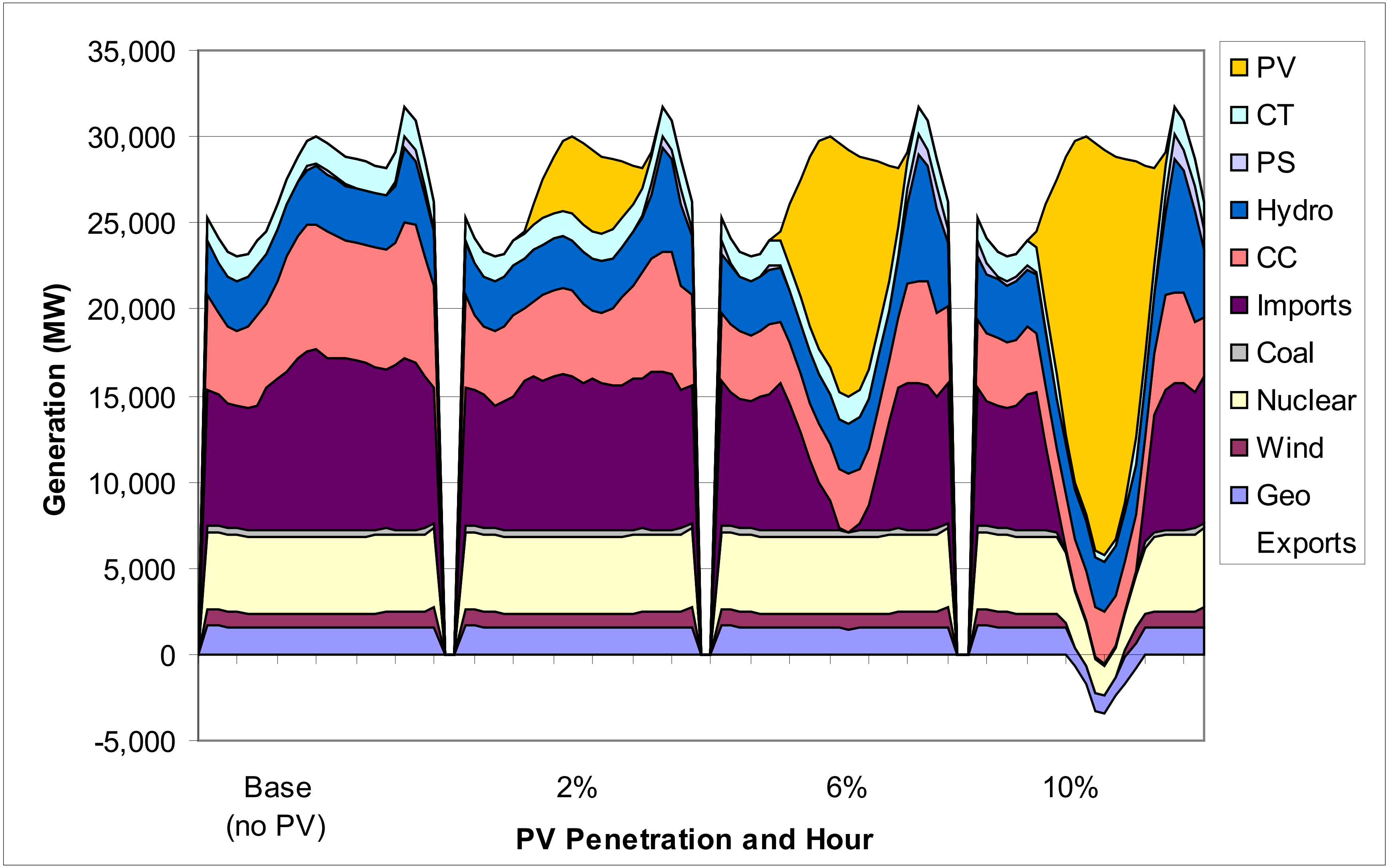

System marginal price and corresponding CSP generation on July 21–23. Short price spike partially driven by decrease in PV output.

# Example Dispatch in CAISO



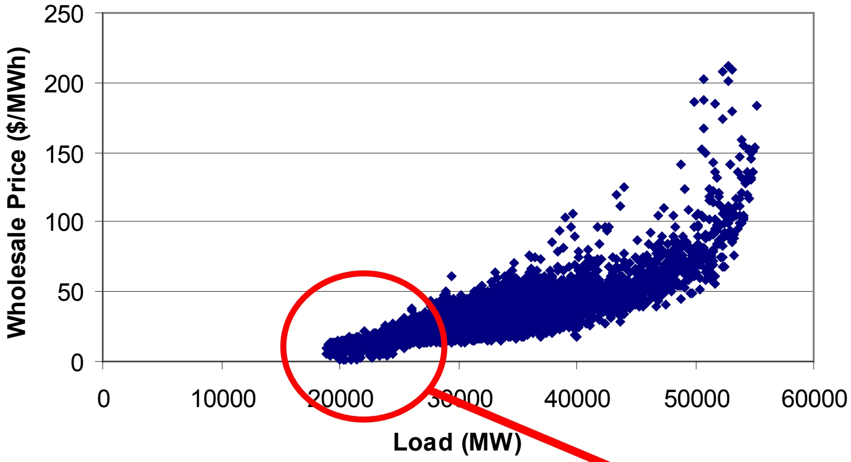

PV looks good – high energy and capacity value

# Too much of a good thing?



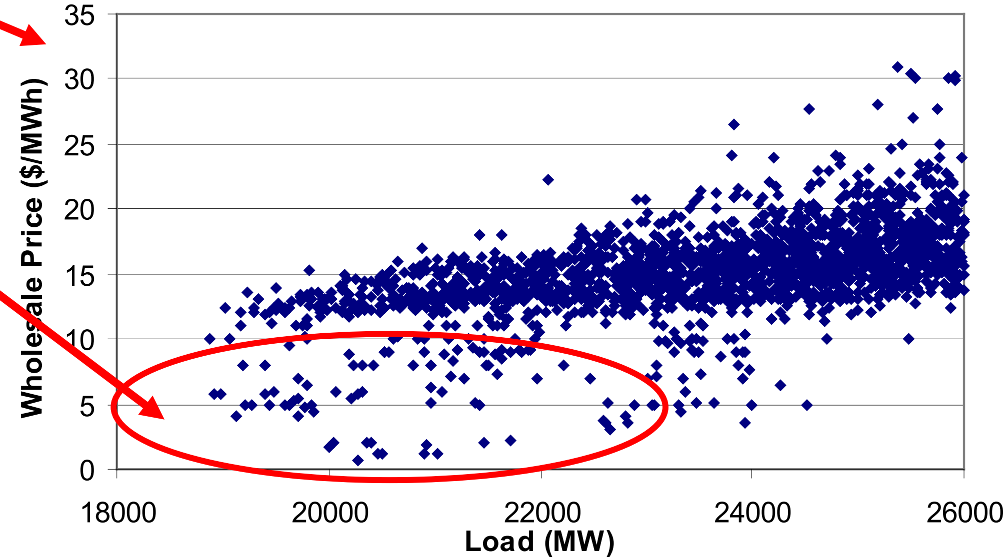
# Current System Flexibility

## Limited by Baseload Capacity



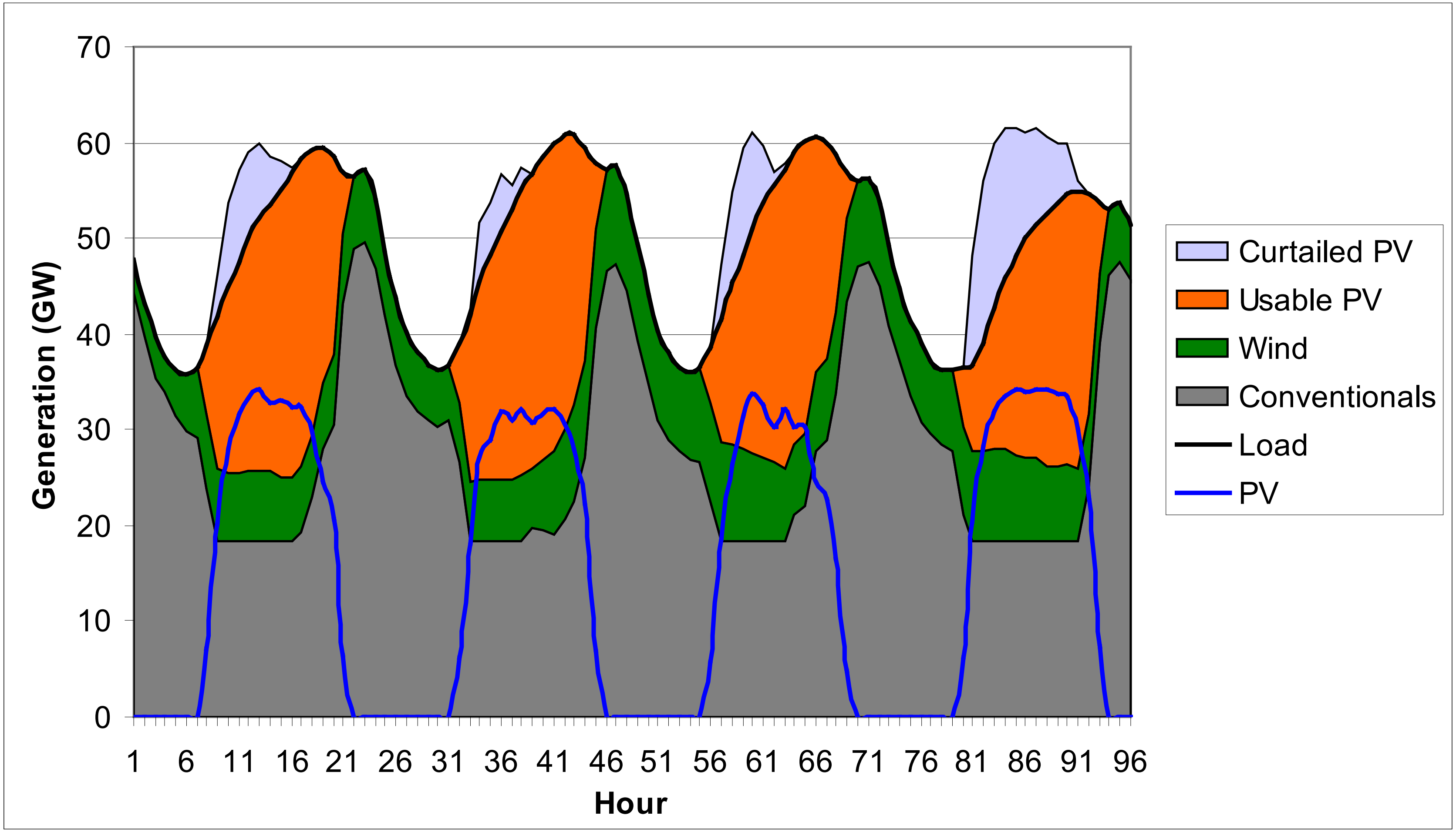

Price/Load Relationship in PJM

Below Cost Bids



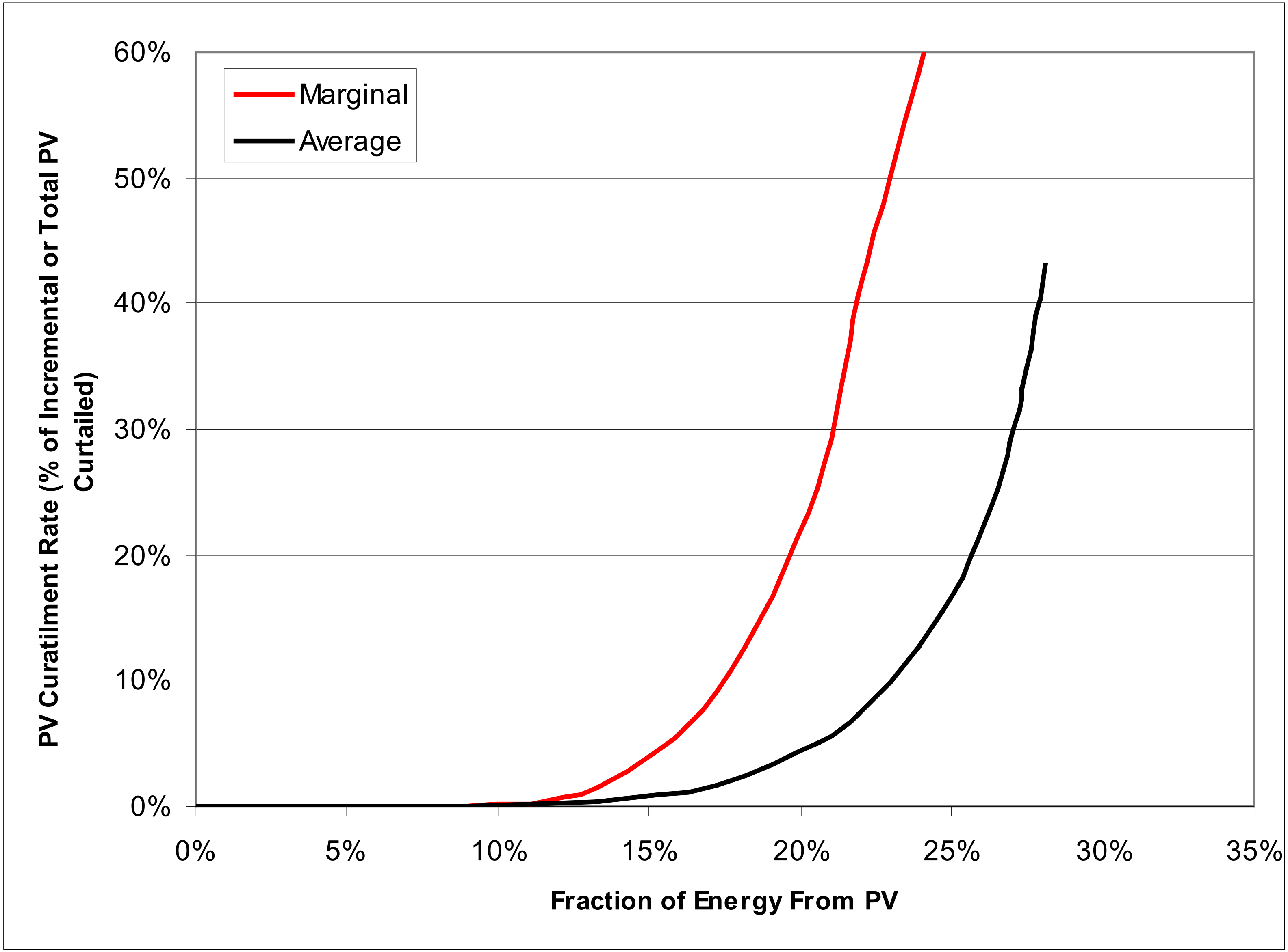

Plant operators would rather sell energy at a loss than incur a costly shutdown. Solar/wind may be curtailed under these conditions

# Example 20% Annual Contribution from PV

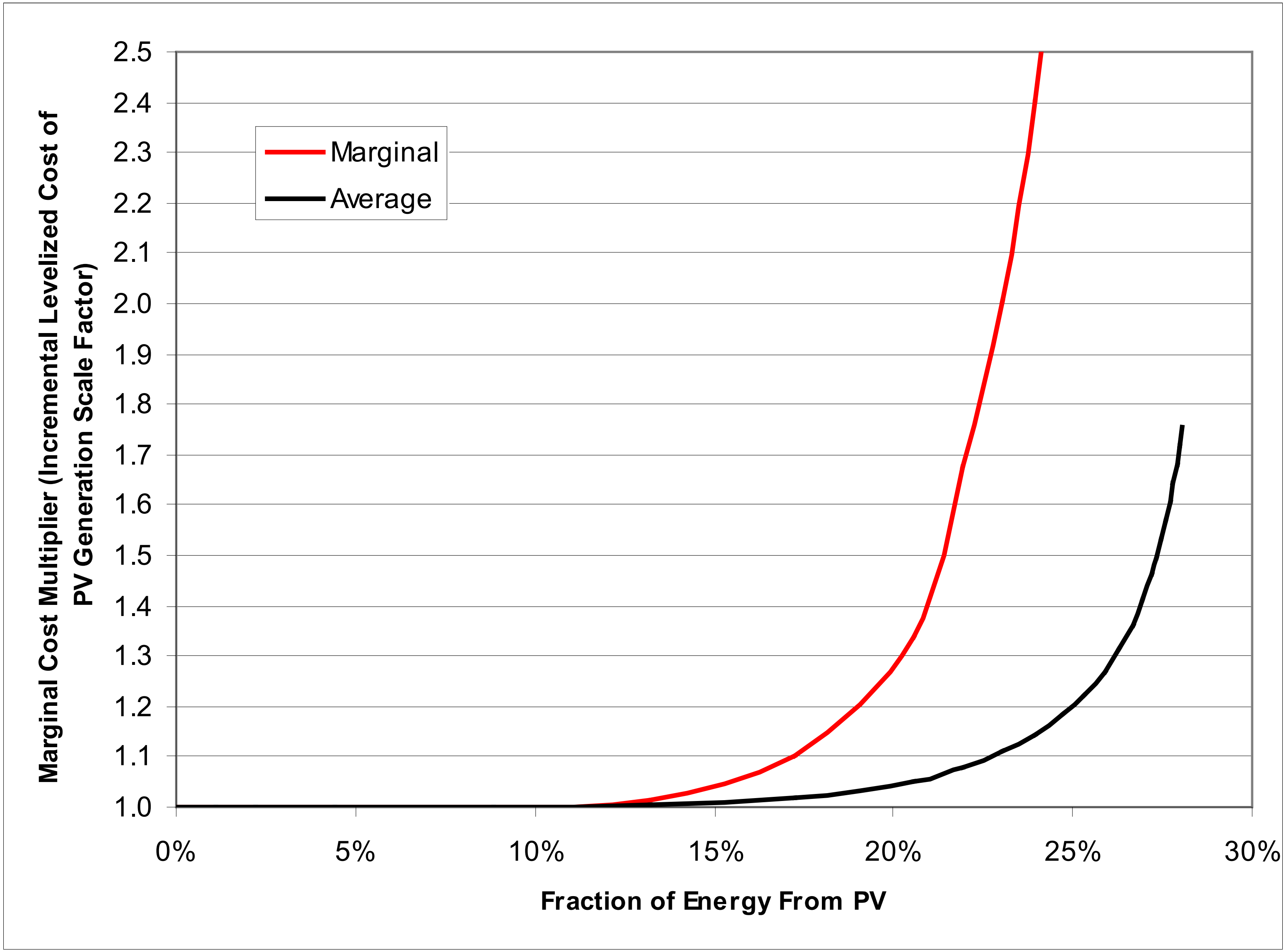



WECC-Wide Simulation May 10-13 – 16% of PV is curtailed (5% annual)

# PV Curtailment



# PV Cost Impact





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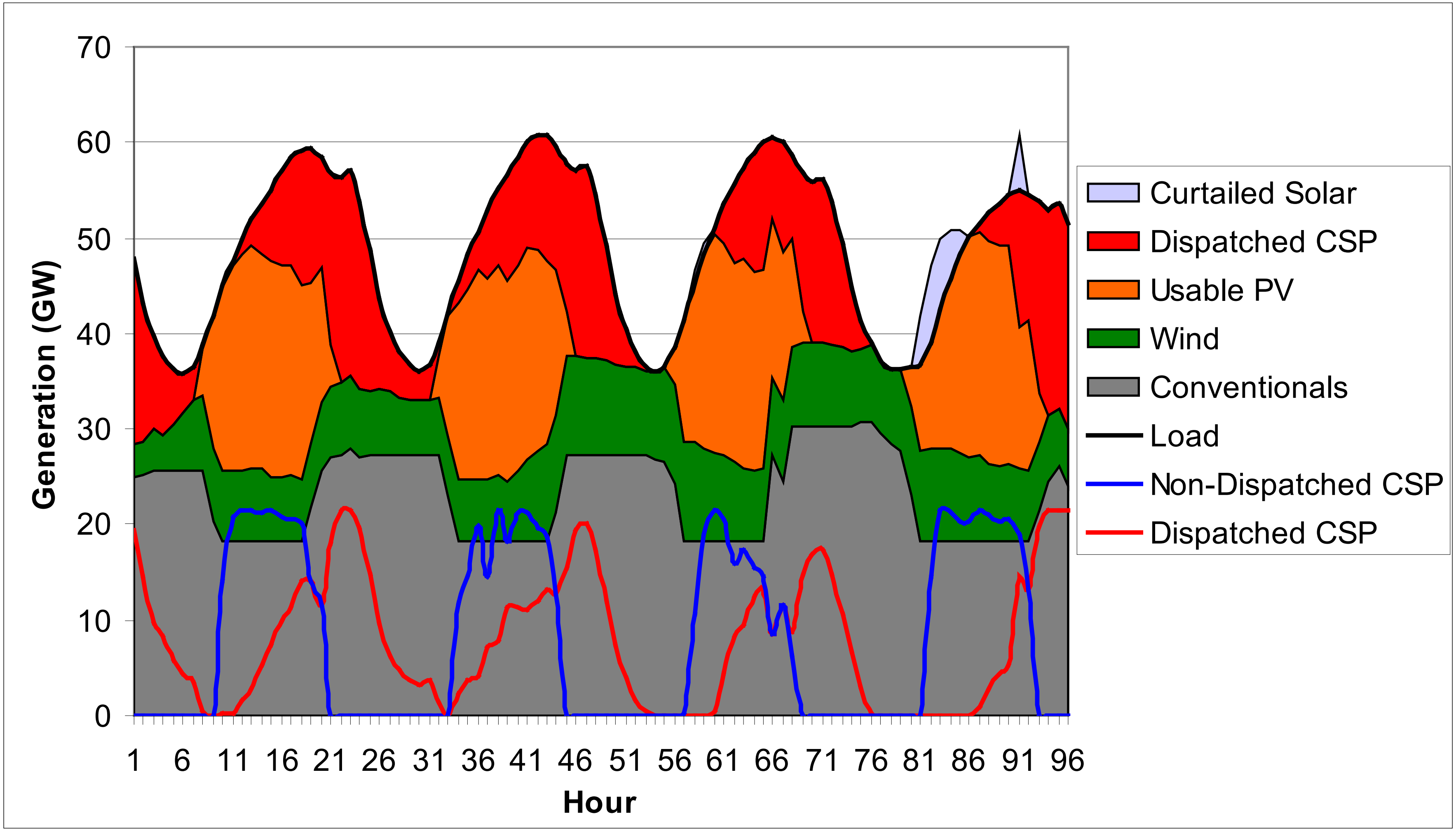
# What Can CSP/TES do?

- **Shift solar generation with very high efficiency (close to 100%)**
- **Add a flexible source of generation with low minimum generation constraints**
- **Provide firm capacity that can replace retiring generators instead of supplementing their output**

# What Can CSP/TES do?

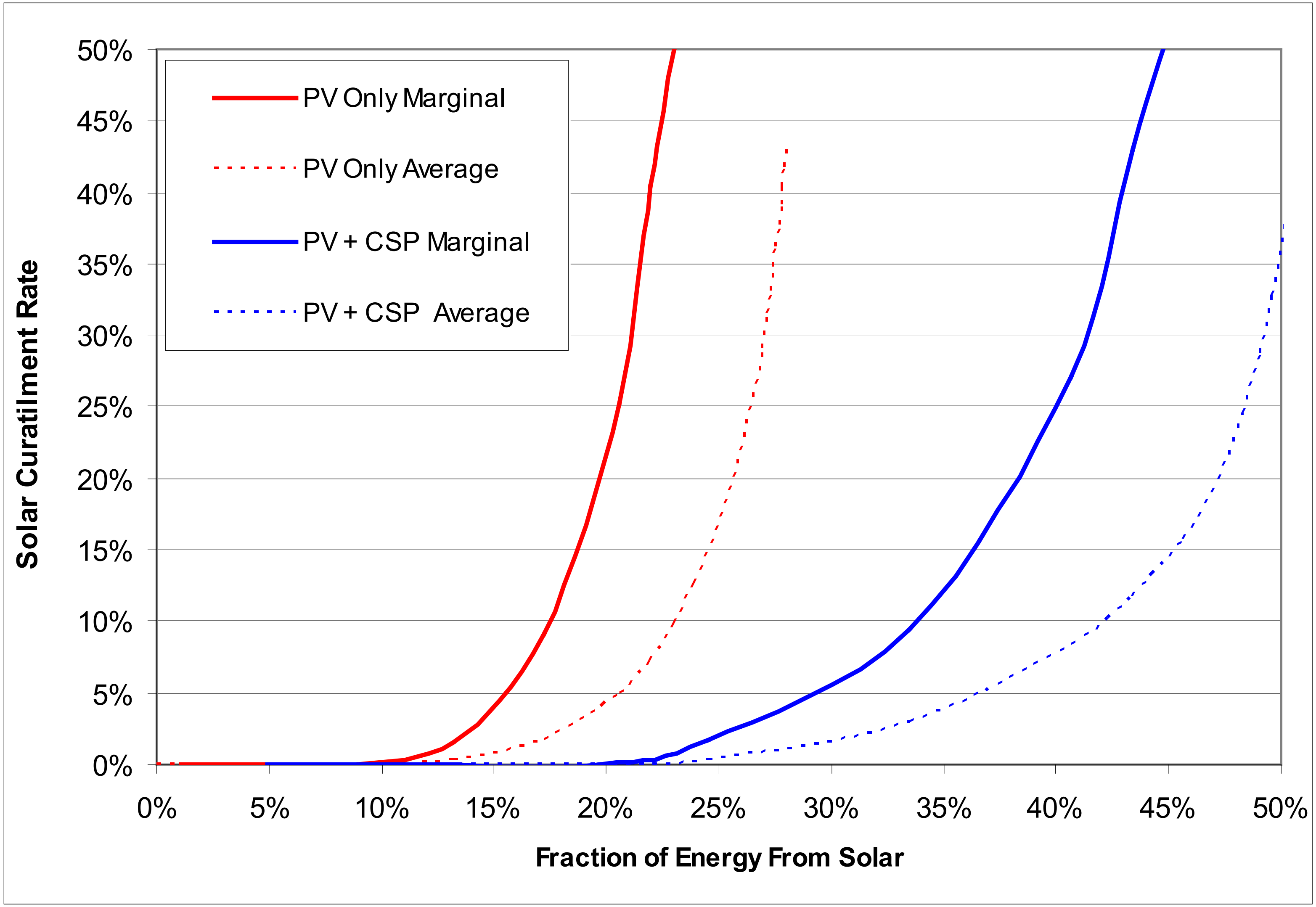
- **Lets examine just the benefits of energy shifting**

# Add Dispatchable CSP – 25% solar




May 10-13 with 15% Contribution from PV and 10% from Dispatchable CSP - Solar contribution goes up, curtailment goes down (2% annual)

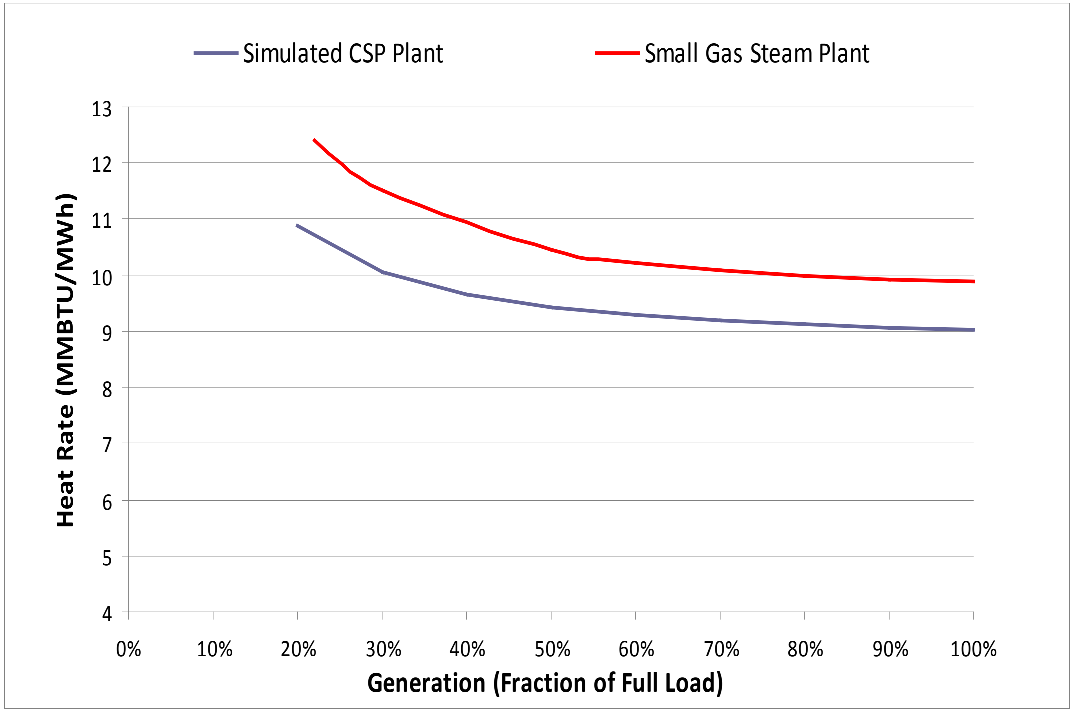
# Curtailment CSP+PV




Curtailment of solar assuming a equal mix (on an energy basis) of PV and CSP

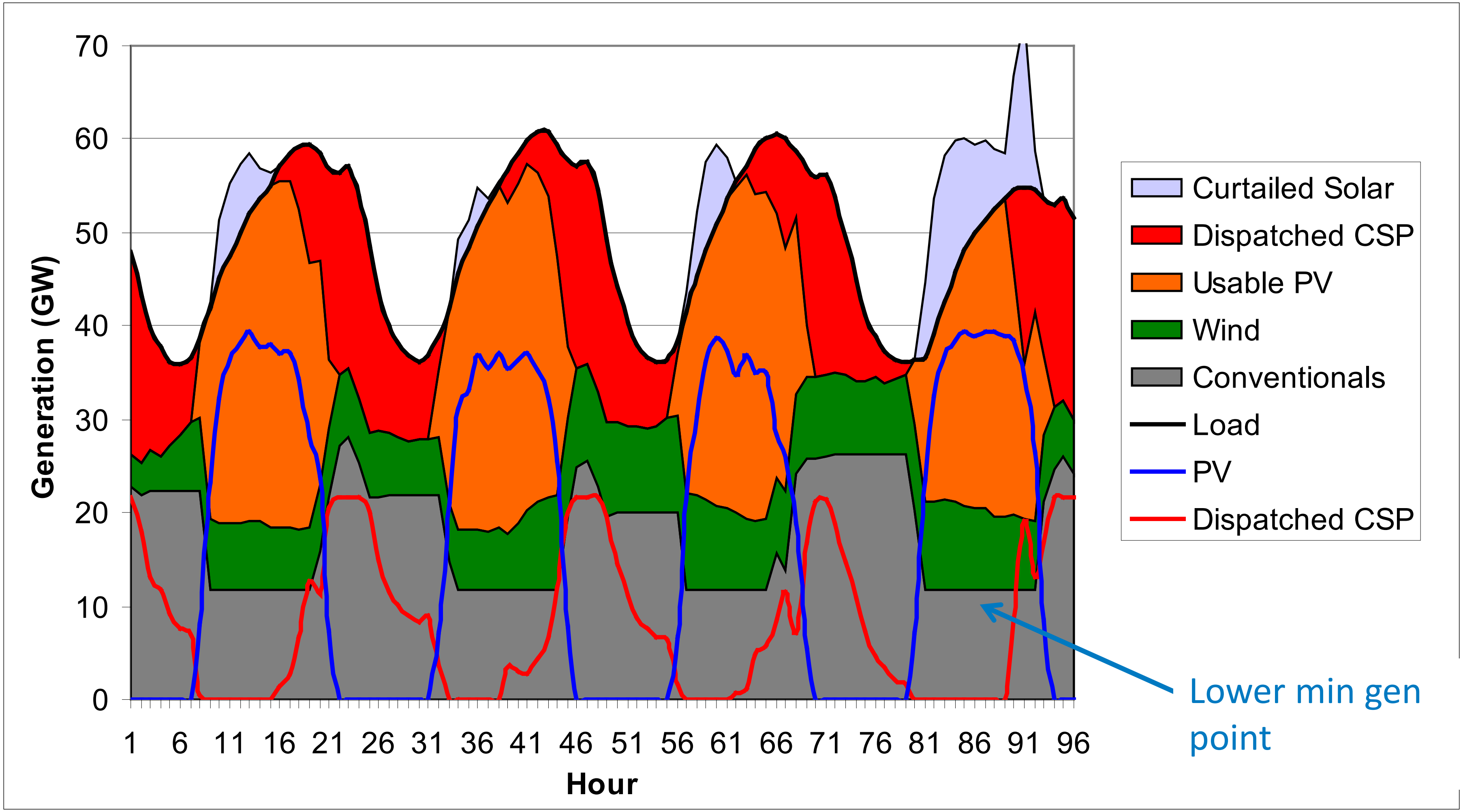
# Add the Flexibility of CSP…

- **CSP has large operating range and high ramp rates**
- **Firm capacity can replace retiring generators with limited flexibility**



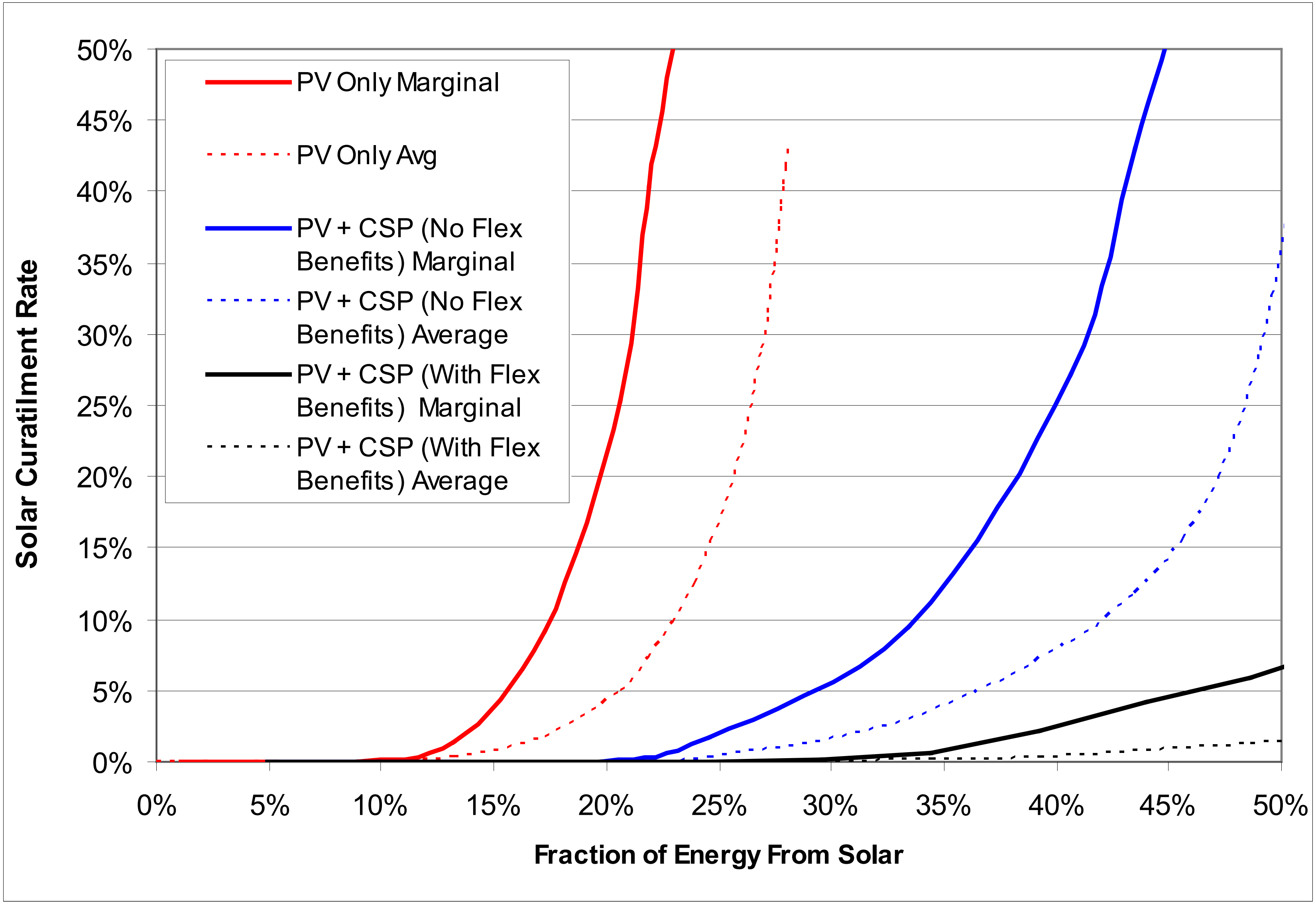

This is real performance data from the ERCOT gas steam fleet, including some old clunkers

# CSP Flexibility Impact

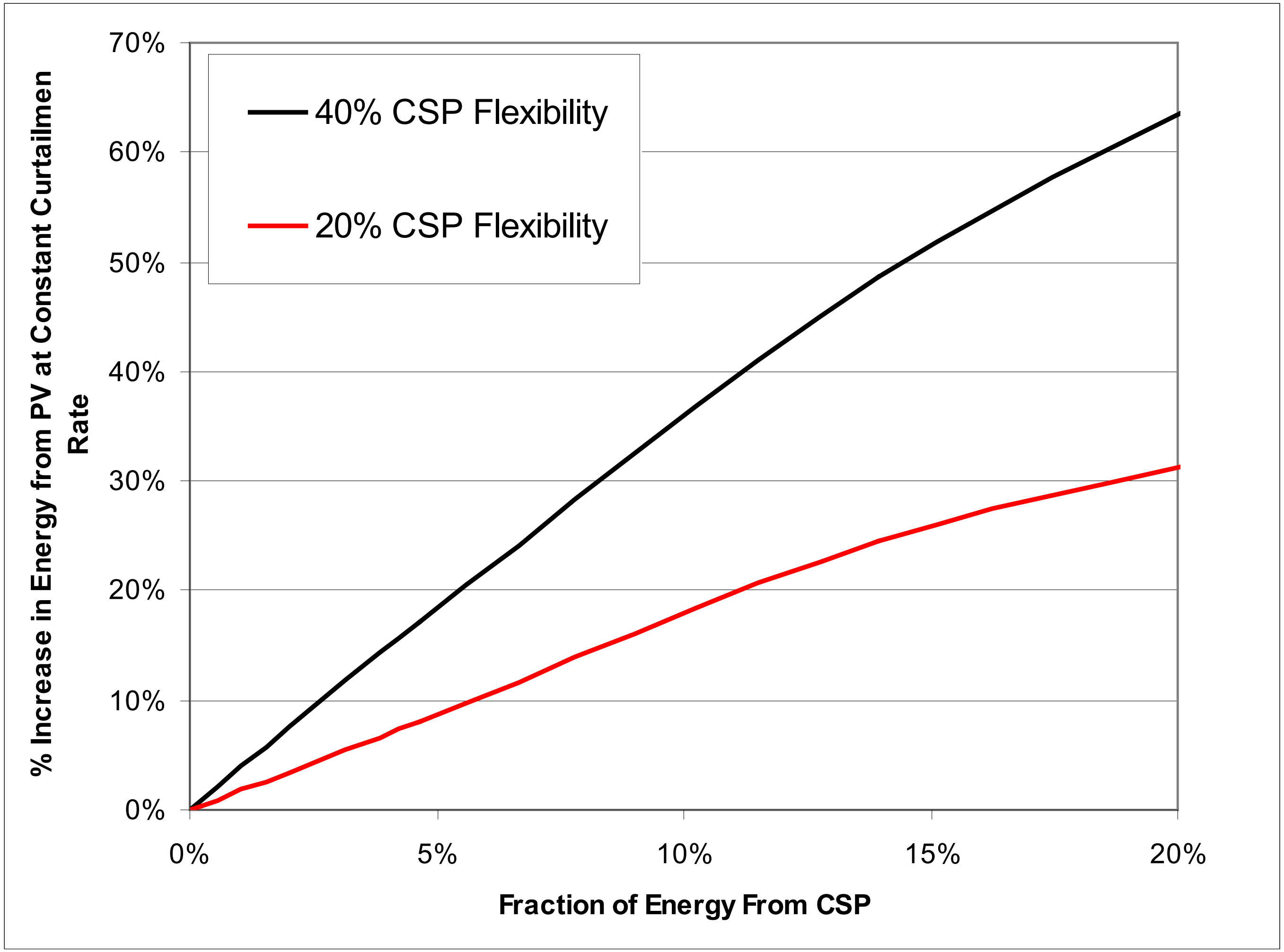



25% Contribution from PV and 10% from Dispatchable CSP where CSP Reduces the Minimum Generation Constraint

# Impact of Reduce Min Gen Constraint

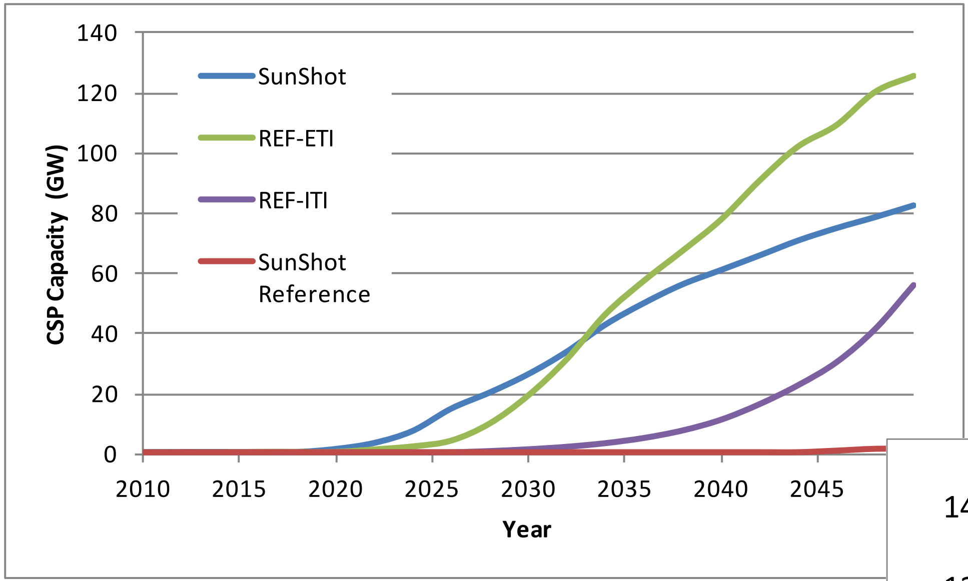


# Increased Use of PV



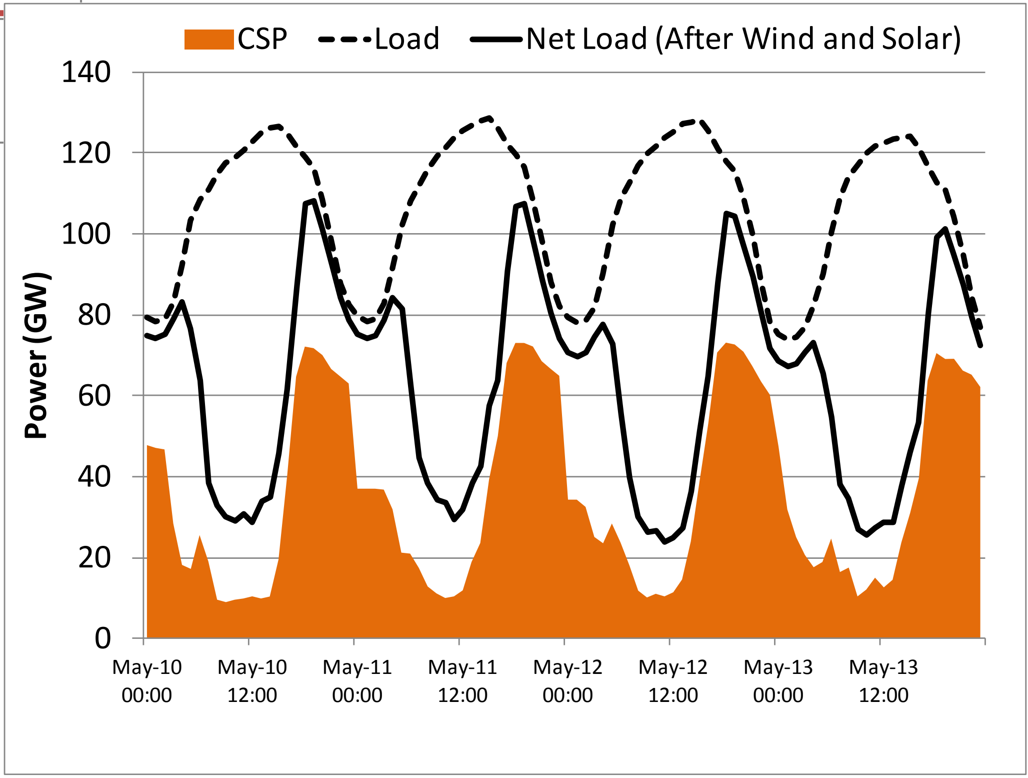

Increase in PV penetration as a function of CSP penetration assuming a maximum PV marginal curtailment rate of 20%.

# High Penetration Scenarios




CSP Penetration in de-carbonized energy scenarios

CSP as a critical component to system operation



# Project Next Steps

- Different CSP technologies and configurations
- More scenarios (RE mix, higher penetration)
- Sub-hourly dispatch
- More detailed understanding of CSP plants providing reserves
- Optimization of WECC units
- Natural gas prices
- CSP scheduling

# Conclusions

- CSP with thermal energy storage has been simulated in several grid simulation tools
- TES can add several quantifiable benefits including dispatchable energy, ancillary services, and firm capacity
- CSP with TES can actually complement other variable generation sources including solar PV and act as an enabling technology to achieve higher overall penetration of renewable energy

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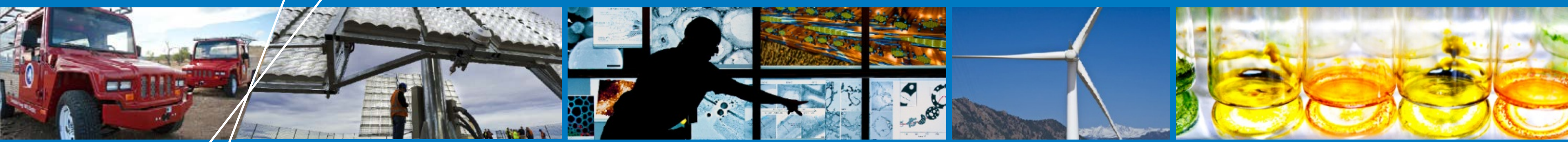

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