SunShot
U.S. Department of Energy

CSP Program Summit 2016

Beyond LCOE: The Value of CSP with Thermal Energy Storage

Mark S. Mehos, Program Manager, CSP NREL

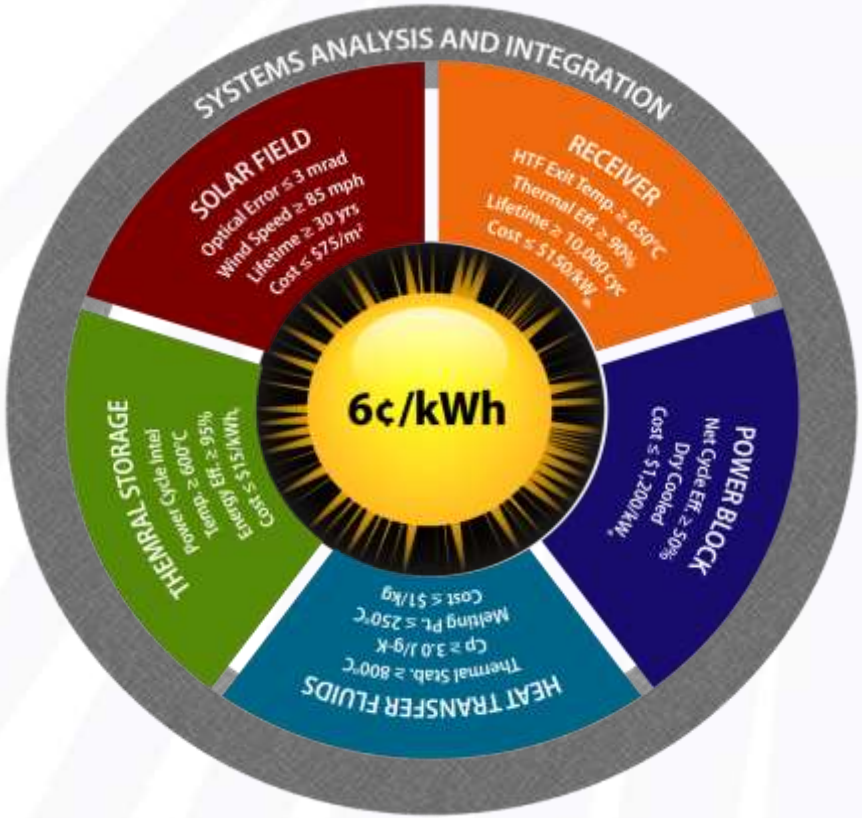
Discussion

- SunShot and LCOE
- Understanding the Value of CSP with Thermal Energy Storage
- Net System Cost – A Better Metric

DOE SunShot Initiative – Concentrating Solar Power

6¢/kWh by 2020

- Technology and cost objectives for solar field, receiver, thermal storage/HTF, & power block necessary to achieve SunShot 6¢ target.



DOE SunShot Initiative – Concentrating Solar Power

6¢/kWh by 2020

- Technology and cost objectives for solar field, receiver, thermal storage/HTF, & power block

- 14 hours of thermal energy storage
- Solar Multiple of 2.7

Case	2010 Trough	2015 Trough Roadmap	2015 Tower Roadmap	2020 Trough Roadmap	2020 Tower Roadmap	2020 SunShot Target
Design Assumptions						
Technology	Oil-HTF Trough	Oil-HTF Trough	Salt Tower	Salt-HTF Trough	Salt Tower	s-CO_2 Combined-Cycle Tower
Solar Multiple	1.3	2.0	1.8	2.8	2.8	2.7
TES (hours)	–	6	6	12	14	14
Plant Capacity (MW, net)	100	250	100	250	150	200
Power-Cycle Gross Efficiency	0.377	0.356	0.416	0.397	0.470	0.550
Cooling Method	wet	dry	dry	dry	dry	dry
Cost Assumptions						
Site Preparation ($/m^2)	20	20	20	20	20	10
Solar Field ($/m^2)	295	245	165	190	120	75
Power Plant ($/kW)	940	875	1,140	875	1,050	880
HTF System or Tower/Receiver ($/m^2 or $/kW$_{th}$)	90	90	180	50	170	110
Thermal Storage ($/kWh$_{th}$)	–	80	30	25	20	15
Contingency (%)	10	10	10	10	10	10
Indirect (% of Direct Costs + Contingency)	24.7	24.7	24.7	24.7	24.7	19.7
O&M ($/kW-yr)	70	60	65	50	50	40
Performance and Cost						
Capacity Factor (%)	25.3	42.2	43.1	59.1	66.4	66.6
Total Installed Cost ($/kW)	4,500	7,870	5,940	6,530	6,430	3,770
LCOE (¢/kWh, real) [SunShot financial assumptions]	20.4	19.4	14.4	11.6	9.8	6.0

DOE SunShot Initiative – Concentrating Solar Power

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→67% Capacity Factor "Baseload" Product

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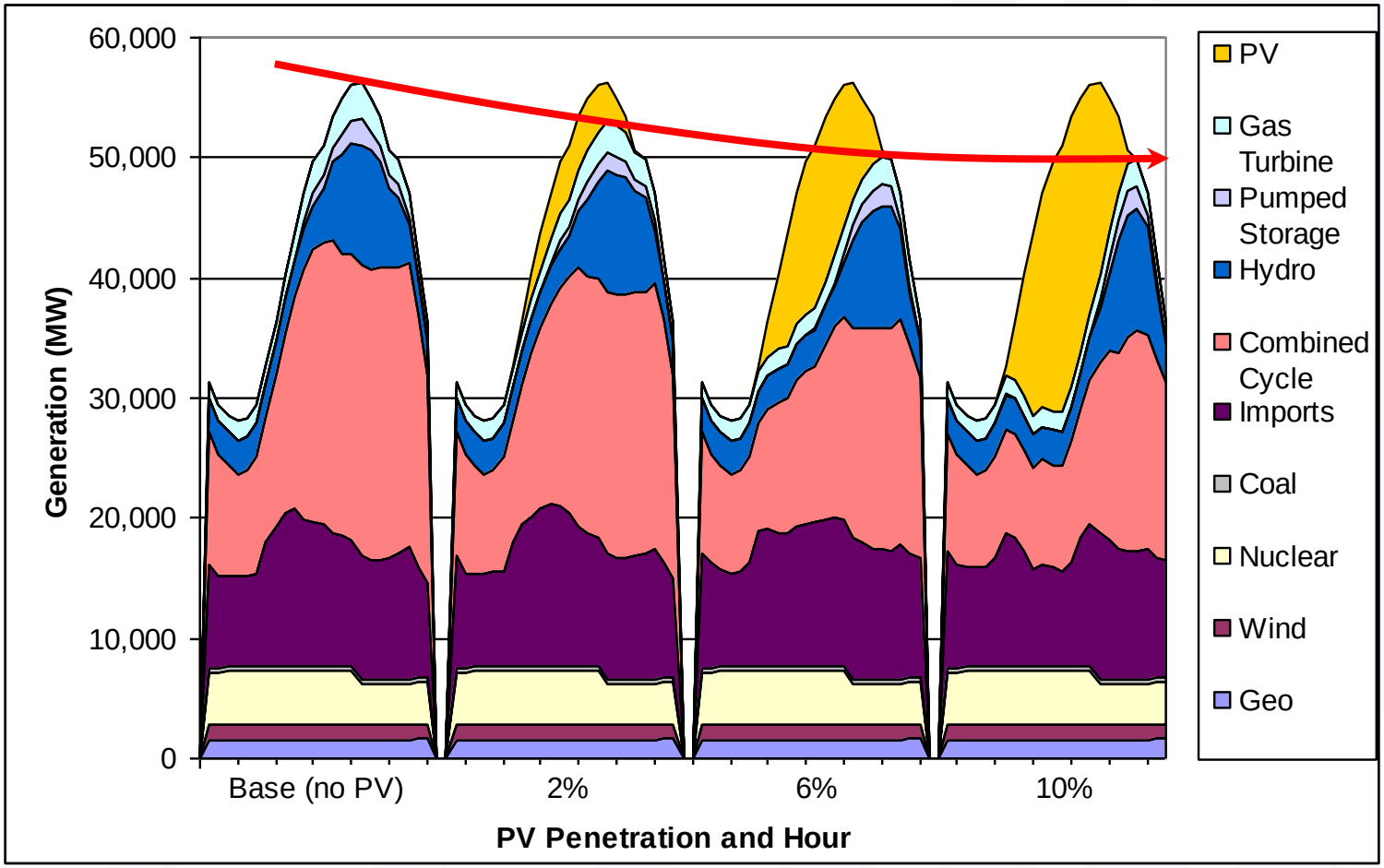
- Net System Cost – A Better Metric

Simulated Dispatch in California for Summer Day for 0% to 10%PV Penetration

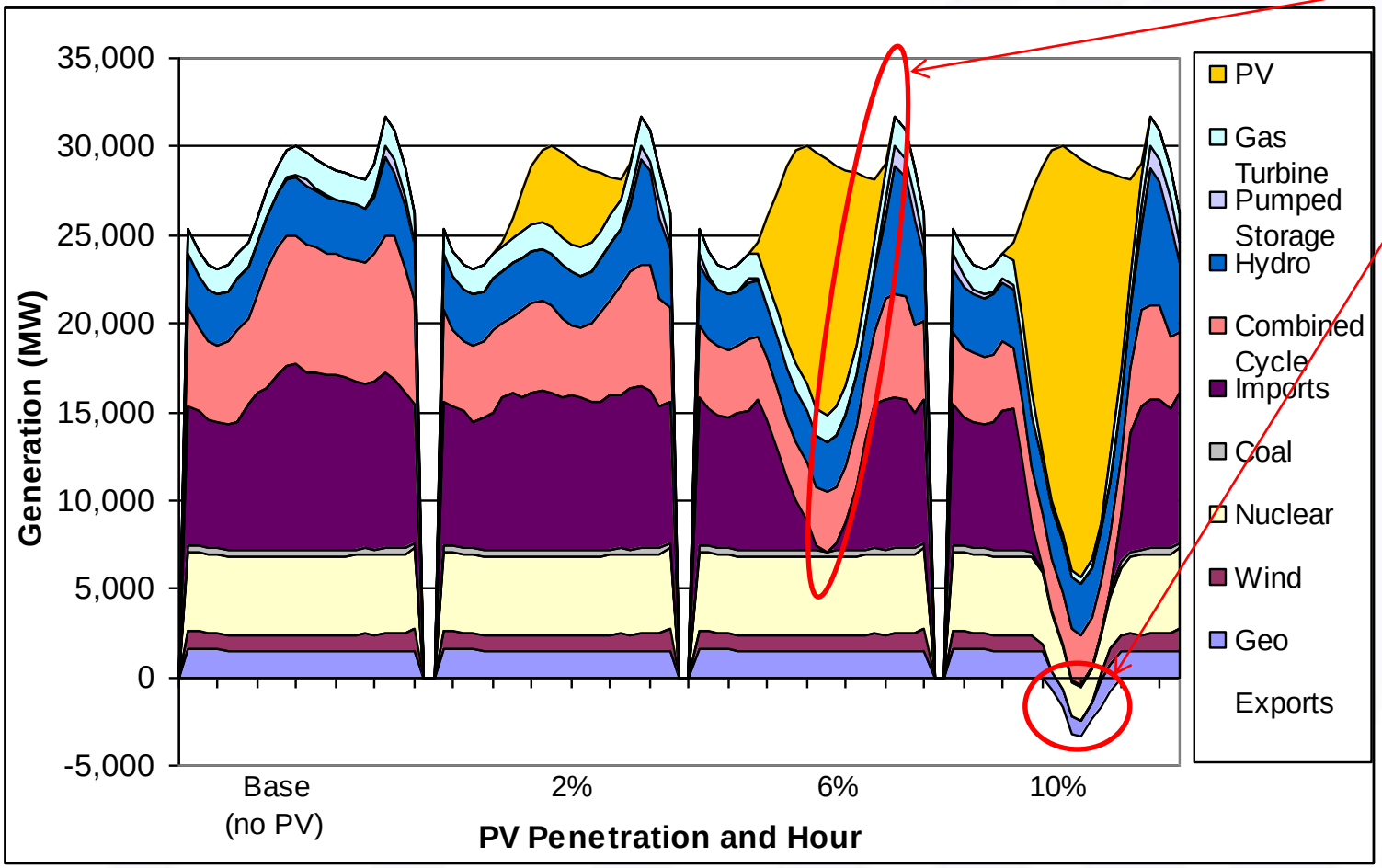


Denholm and Mehos, 2012

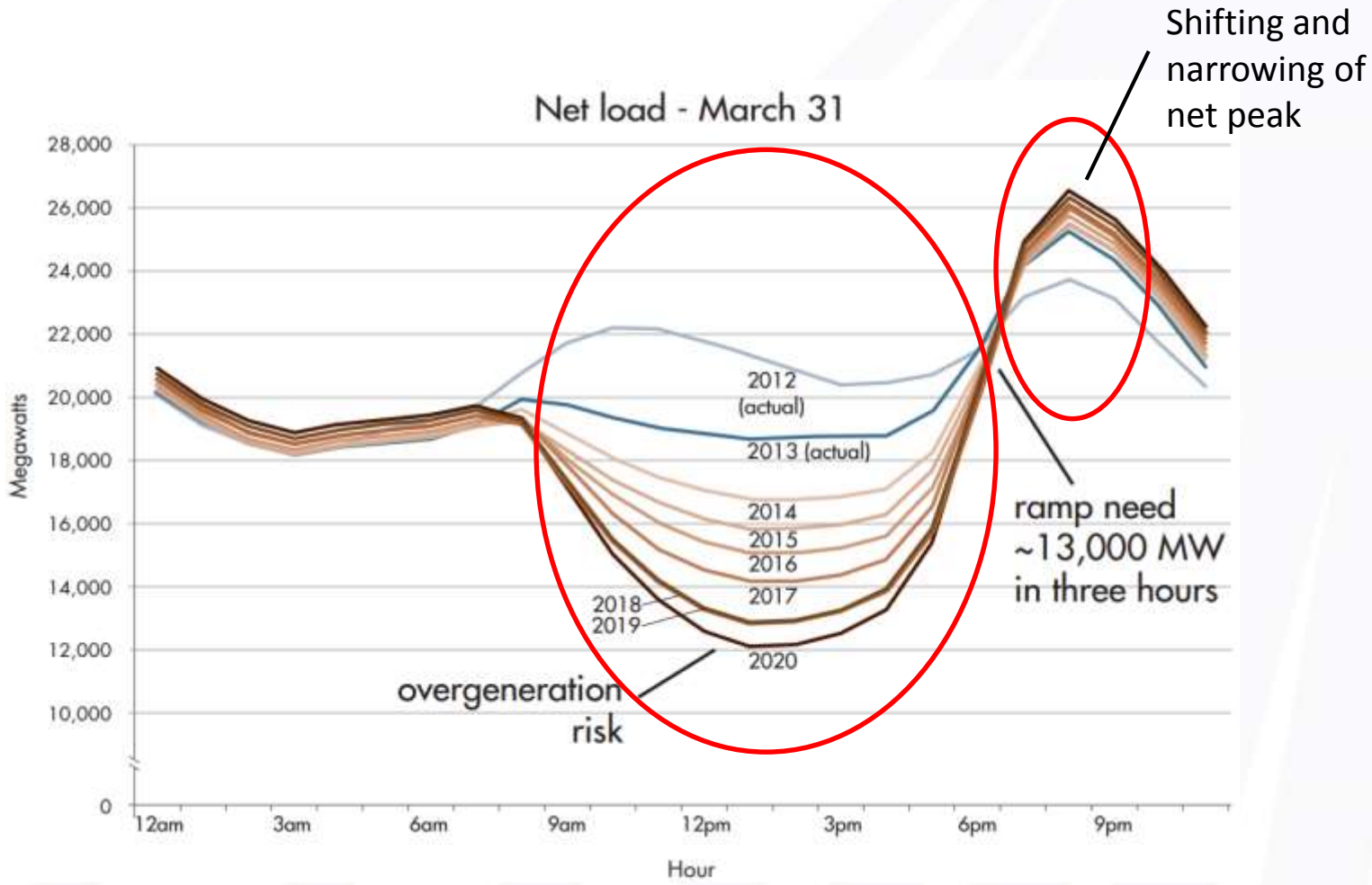
Decreased Capacity Value

Increased PV Penetration

Simulated Dispatch in California for Spring Day for 0% to 10%PV Penetration



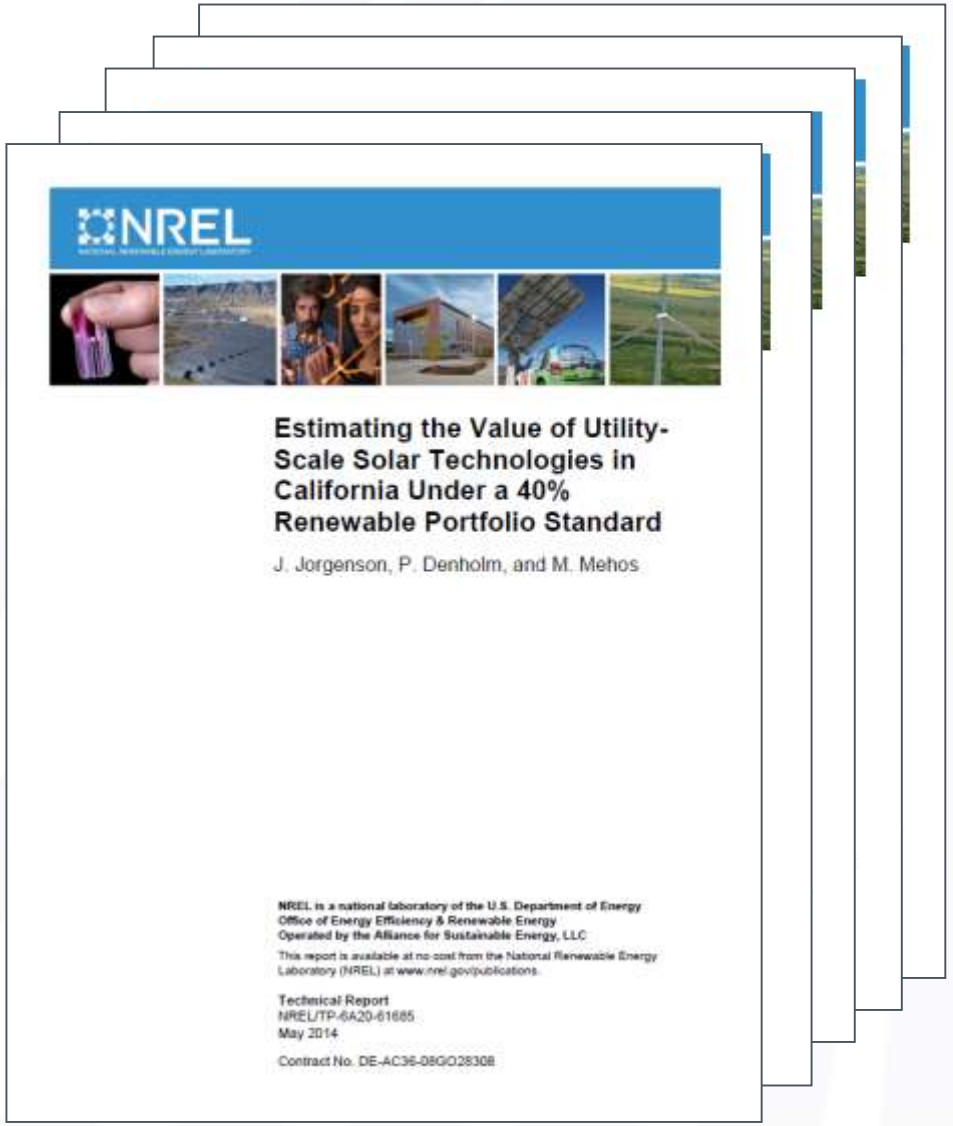
CAISO Duck Curve – Circa 2013



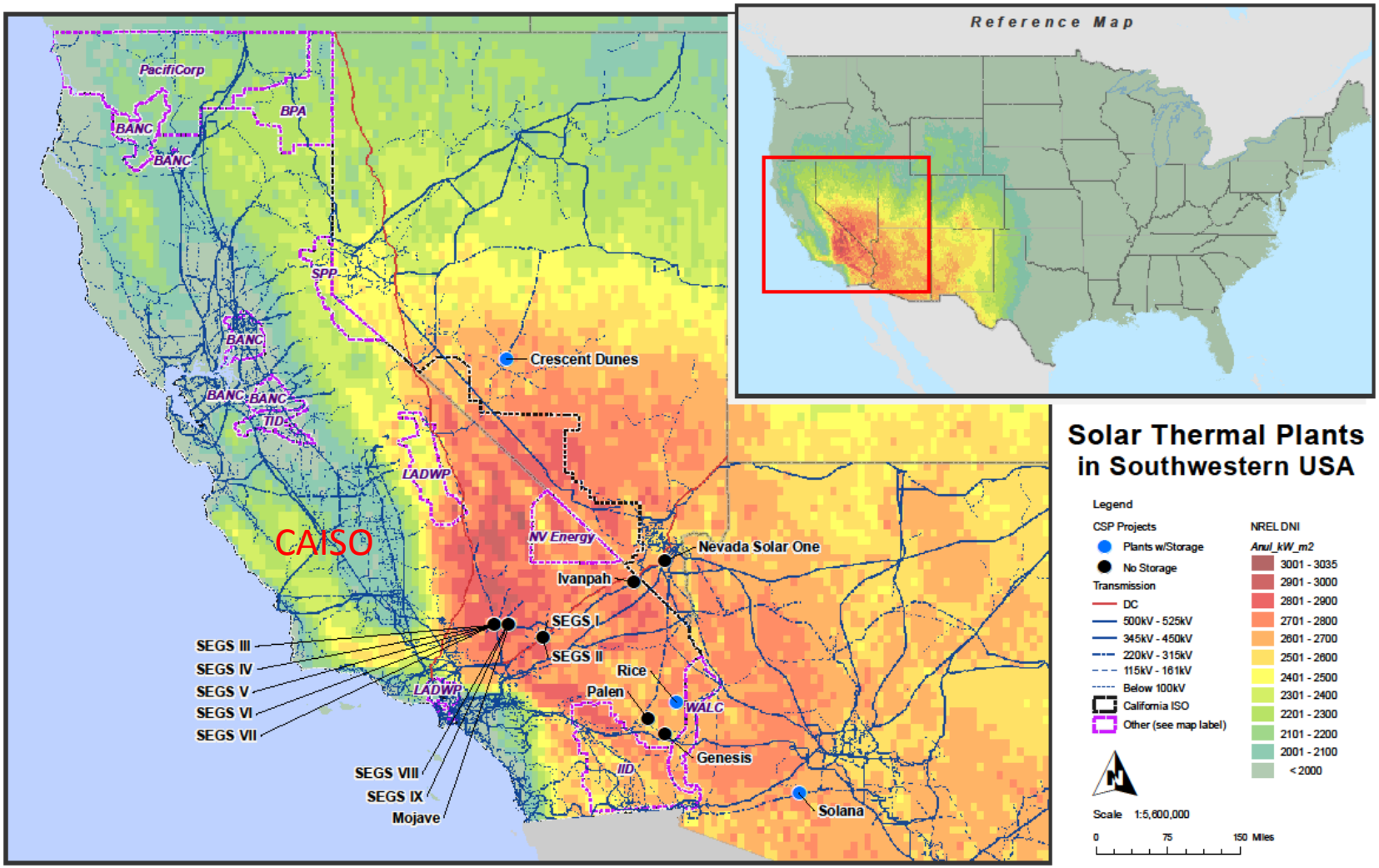
Quantifying the Benefits of CSP with Thermal Energy Storage

- Colorado “Test” System
- California/WECC

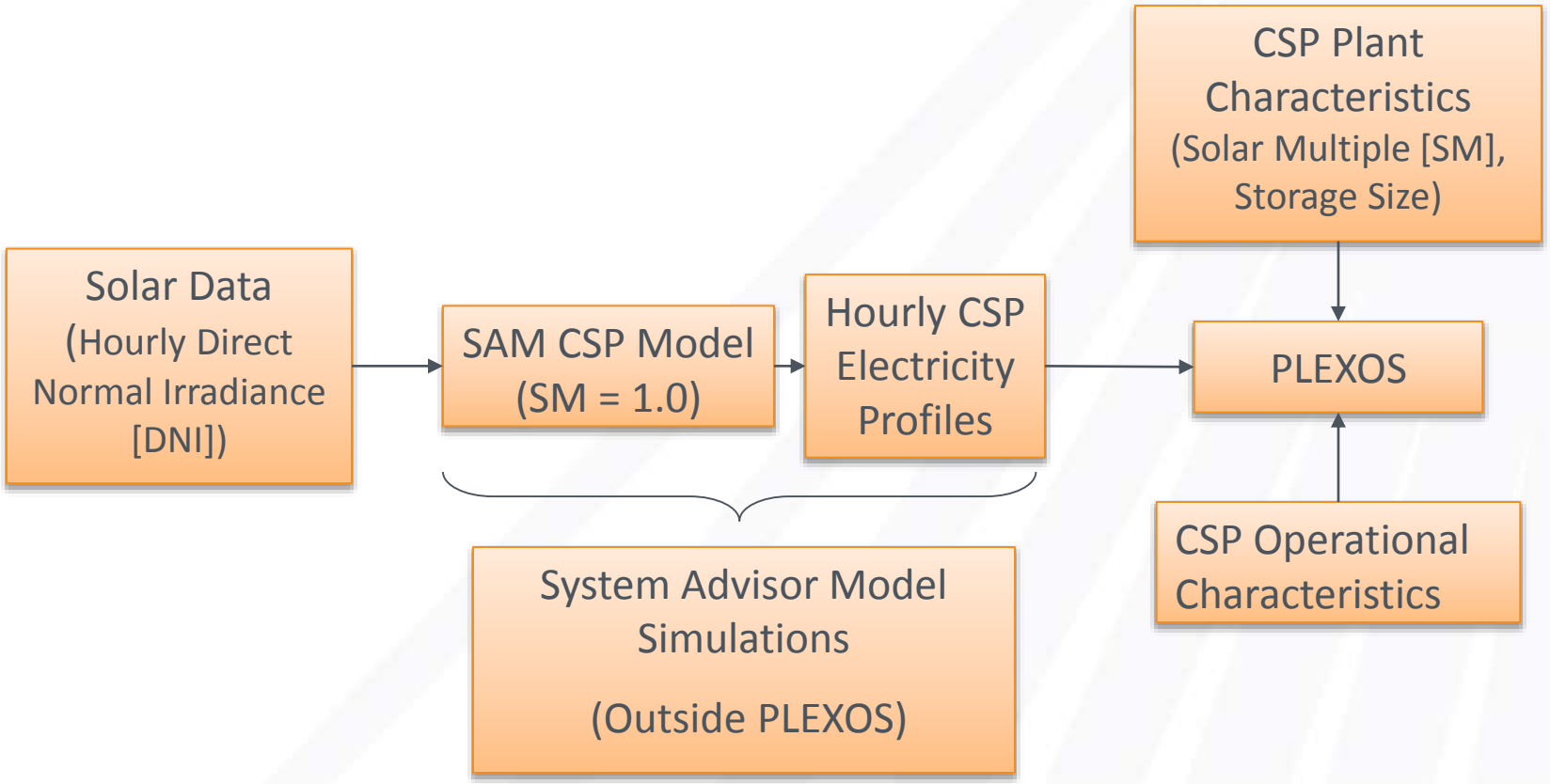
http://www.nrel.gov/publications



Analysis of Operational and Capacity Benefits of CSP in Southwest Balancing Area



Implementation of CSP with TES in a Commercial Unit Commitment and Economic Dispatch Model (PLEXOS)



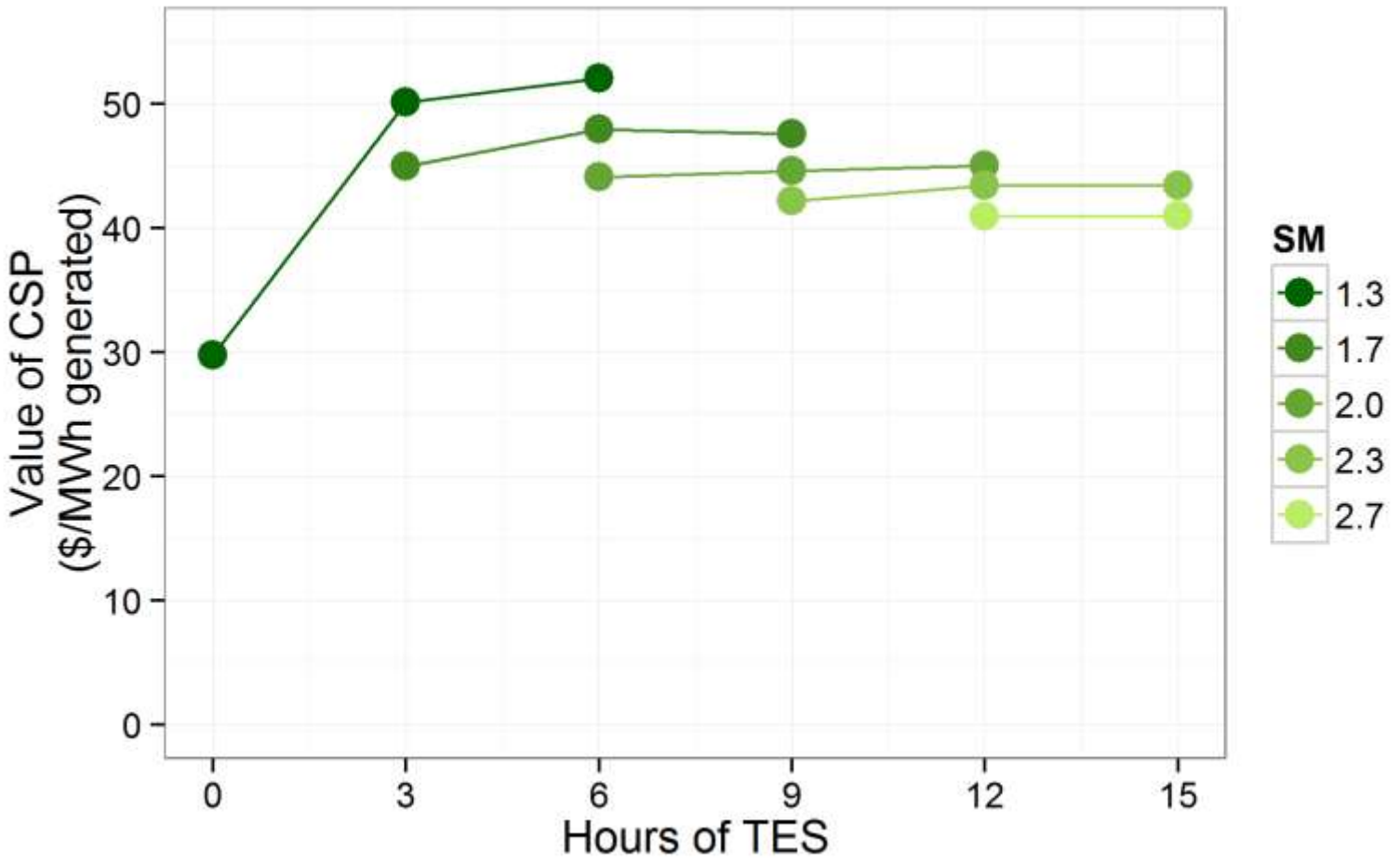
CSP has historically not been included in commercial production cost models. Analysts must consider the flexibility of CSP configurations

California ISO Analysis – 33% Renewable Portfolio Standard

Relative to PV, CSP provides additional operational Value to California grid

	Marginal Operational Value ($/MWh)	
	CSP-TES (SM = 1.3, 6 hrs TES)	**PV**
Displaced Fuel	40.2	27.8
Displaced Emissions	10.3	3.1
Reduced Startup & Shutdown	1.6	-0.6
Reduced Variable O&M	0.4	1.2
Total	**52.7**	**31.6**

CAISO Analysis – Operational Value



Lowest solar multiples (lower annual capacity factors) yield the highest operational system value

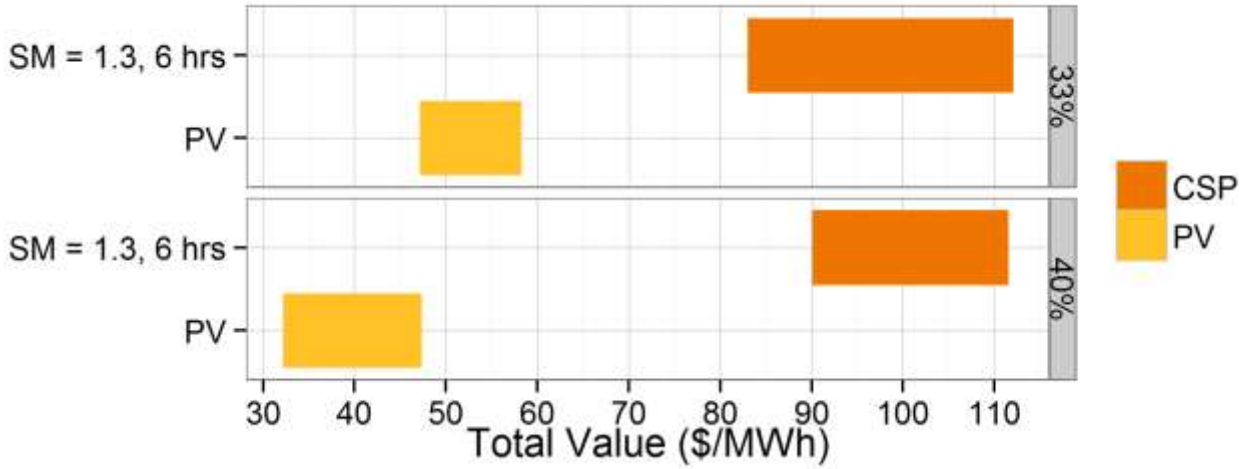
CAISO Analysis – Capacity Value

CSP integrated with thermal energy storage maintains high capacity value

	Capacity Credit (%)	
	CSP-TES (with > 3 Hrs Storage)	PV
33% RPS Scenario	92.2%	22%
40% RPS Scenario	96.6%	3.4%

CAISO Analysis – Total Valuation

- Relative value of CSP is $48/MWh greater than PV in the 33% scenario and about $63/MWh greater in the 40% scenario



Discussion

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Solar as a capacity product

- We investigated the following options for procuring firm capacity and renewable energy:
  - Combustion Turbine (peaker)
  - Combined Cycle (intermediate and baseload)
  - CSP-TES Plant (various configurations)
  - PV Plant + Long-duration storage device
  - PV Plant + Gas combustion turbine (CT)

Annualized Capital Cost of each option

- Avoided Operational Costs

Net Cost of each option

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Net Cost of each option

Cost Assumptions – Conventional*

Generator Type	$/kW-yr
Combustion Turbine	
- Capital and Financing – Construction	115.48
- Insurance	7.90
- Ad Valorem Costs	11.50
- Fixed O&M	33.08
- Corporate Taxes	33.35
Total Fixed Costs (Combustion Turbine)	201.31
Combined Cycle	
- Capital and Financing – Construction	117.66
- Insurance	7.91
- Ad Valorem Costs	11.52
- Fixed O&M	45.31
- Corporate Taxes	38.81
Total Fixed Costs (Combined Cycle)	221.21

*Source: California Energy Commission Cost of Generation (COG) Model – Version 3.98 (2015)

Cost Assumptions – Current and Future CSP-TES Tower Scenarios

Case	CSP-TES Tower (current)	CSP-TES Tower (SunShot)
Location	Daggett, CA	Daggett, CA
System Costs		
- Site improvements ($/m2)	10	10
- Solar field (heliostat and receiver)a ($/m2)	260	160
- Thermal energy storage ($/kWht)	27	15
- Power block ($/kWe)	1,550	880
- EPC and owners costs	10% of direct costs	10% of direct costs
- Land costs ($/acre)	10,000	10,000
- Fixed O&M ($/kW-yr)	65	40
Construction loan period and interest rate	24 months at 6%	24 months at 6%
Cycle Performance		
- Cycle gross efficiency (%)	41.2	55

Modeling Assumptions

Generator Performance	
Generator Type	Heat Rate (Btu/kWh)[a]
Combustion Turbine	9,500
Combined Cycle	7,500

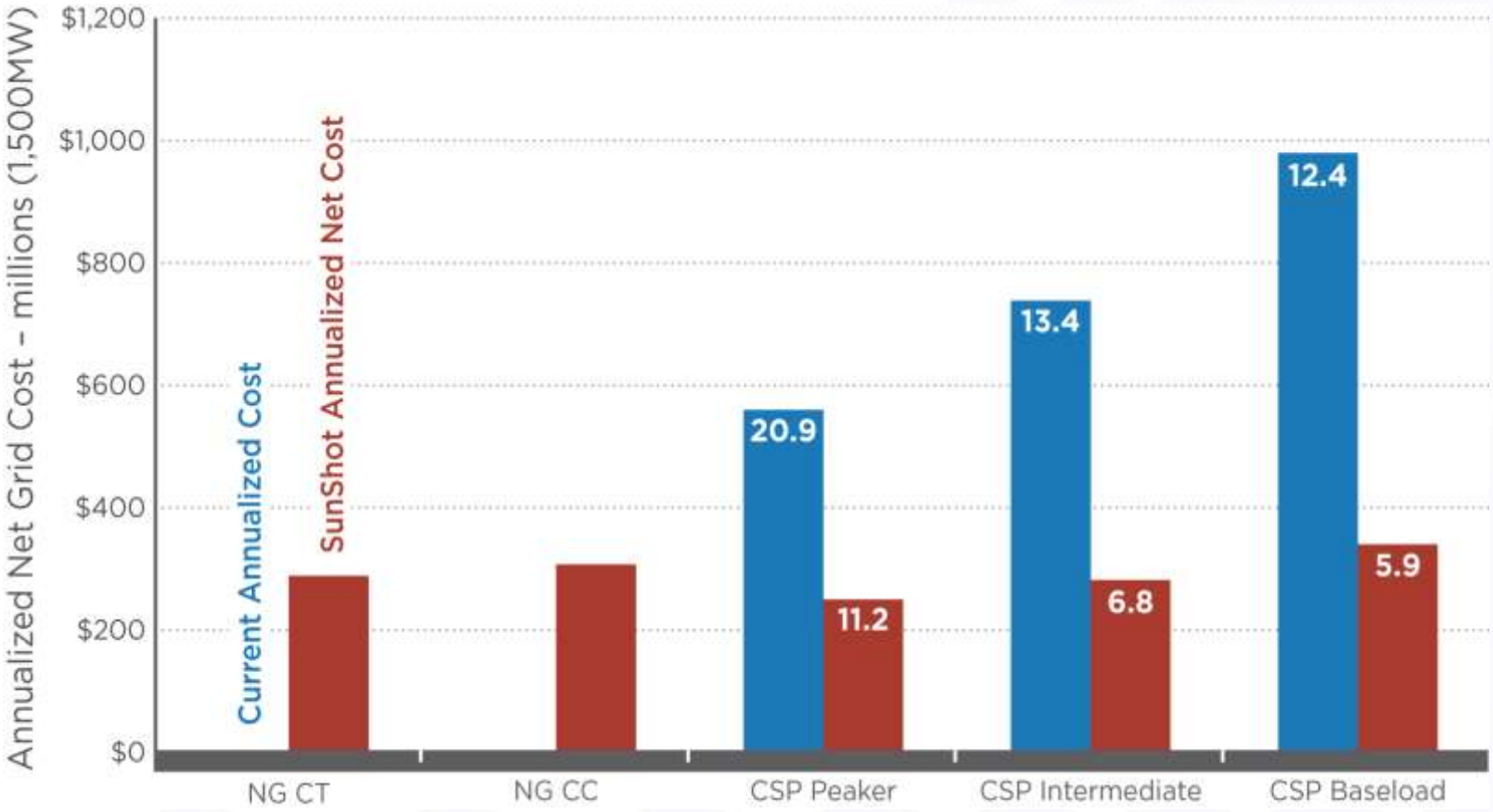
Operational Analysis	
Dollar Year	2014
Simulation Year	2025
Natural Gas Price (low/high)	$3.5–$6.1 / MMBtu
Carbon Emissions Cost (low/high)	$13–$32.4 / metric ton

Modeling Scenarios

Technology	Capacity (MW)	Energy (GWh annual)	Capacity Factor (%)
Combustion Turbine	1,500	1,580 (3,350)	12.0 (25.5)[a]
Combined Cycle	1,500	5,690 (11,270)	43.9 (85.8)
CSP-TES (peaker, SM = 1, 6 h TES)	1,500	3,220 (3,230)	24.5 (24.6)
CSP-TES (intermediate, SM = 2, 9 h TES)	1,500	6,300 (6,300)	47.9 (47.9)
CSP-TES (baseload, SM = 3, 15 h TES)	1,500	8,910 (9,240)	67.8 (70.3)

[a] Values in parentheses are results for the high natural gas and emission cost scenario.

Comparison of annualized net cost of current and SunShot CSP configurations for low natural gas and carbon cost scenarios



Values shown are LCOEs calculated by SAM for each CSP configuration.

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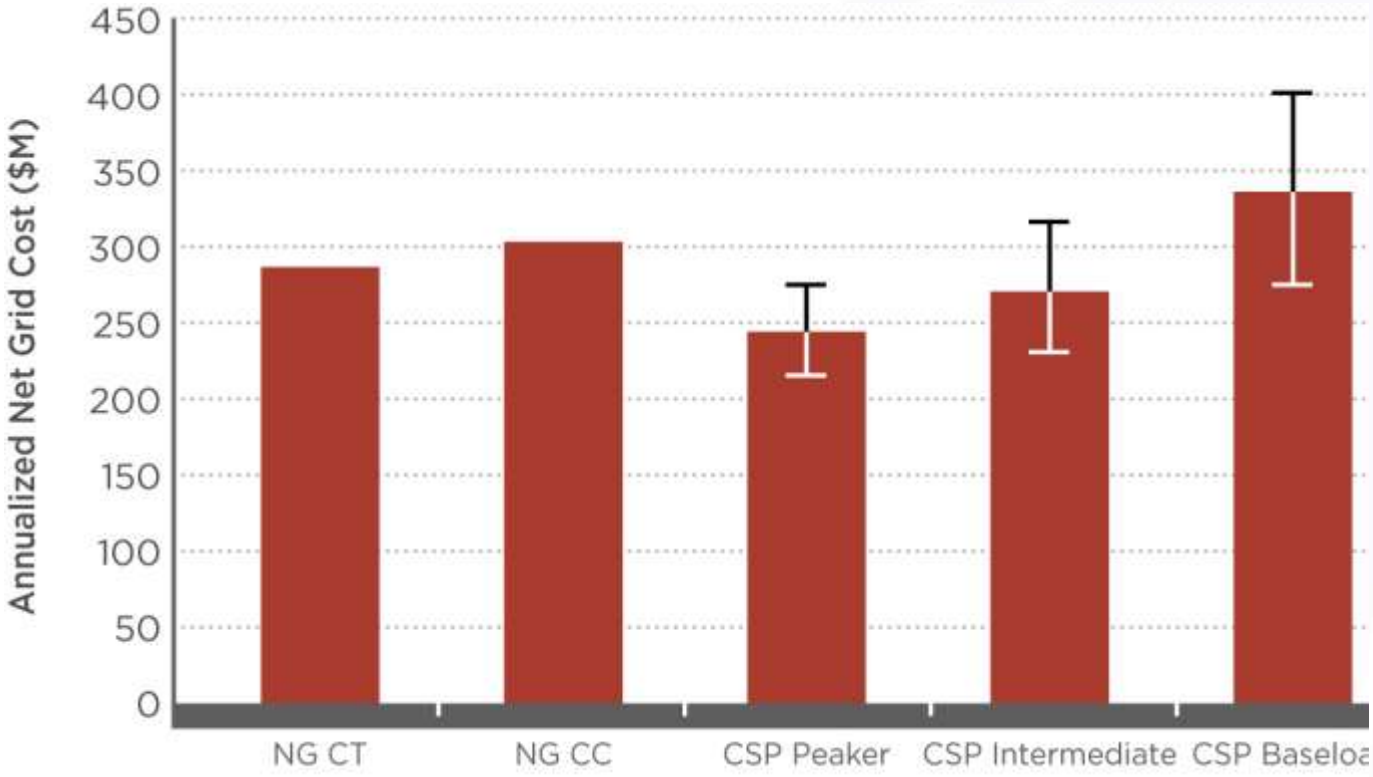
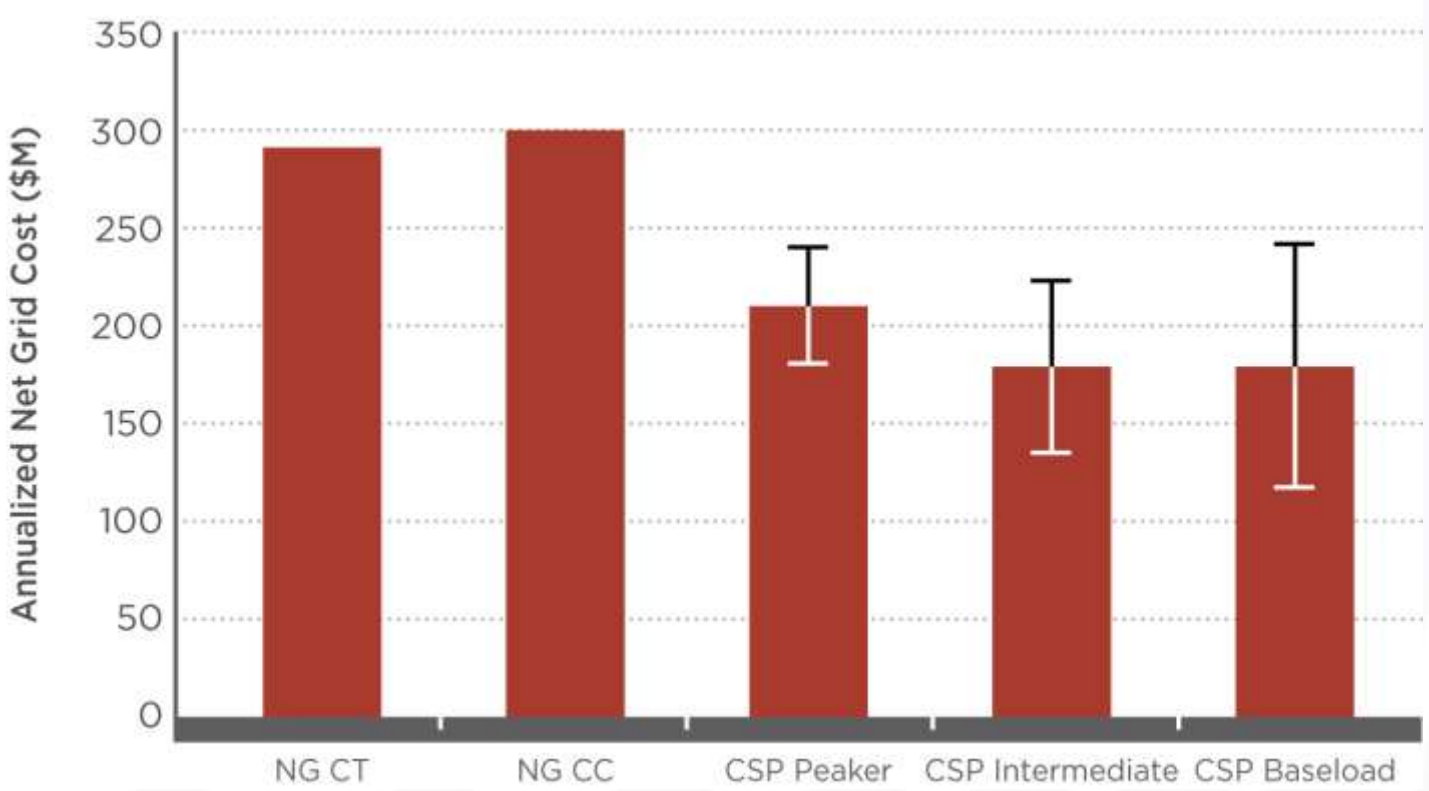


Error bars represent ± 10% variation in key SunShot cost and performance parameters

Comparison of annualized net cost of SunShot CSP configurations for high natural gas and carbon cost scenario



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$$\frac{\text{Annualized Capital Cost of each option} - \text{Avoided Operational Costs}}{\text{Net Cost of each option}}$$

Cost Assumptions

CSP-TES Cost/Performance Assumptions

System Costs	CSP-TES Tower (current)	CSP-TES Tower (SunShot)
- site improvements	$10/m^2	$10/ m^2
- solar field (heliostat and receiver)	$260/m^2	$150/ m^2
- thermal energy storage	$27/kWh$_t$	$15/ kWh$_t$
- power block	$1550/kW$_e$	$880/kW$_e$
- EPC and owners costs	10% of direct costs	10% of direct costs
- land costs	$10,000/acre	$10,000/acre
- fixed O&M	$65/kW-yr	$40/kW-yr
Construction loan period and interest rate	24 months at 6%	24 months at 6%
Cycle Performance - cycle gross efficiency	41.2%	55%

PV Cost/Performance Assumptions

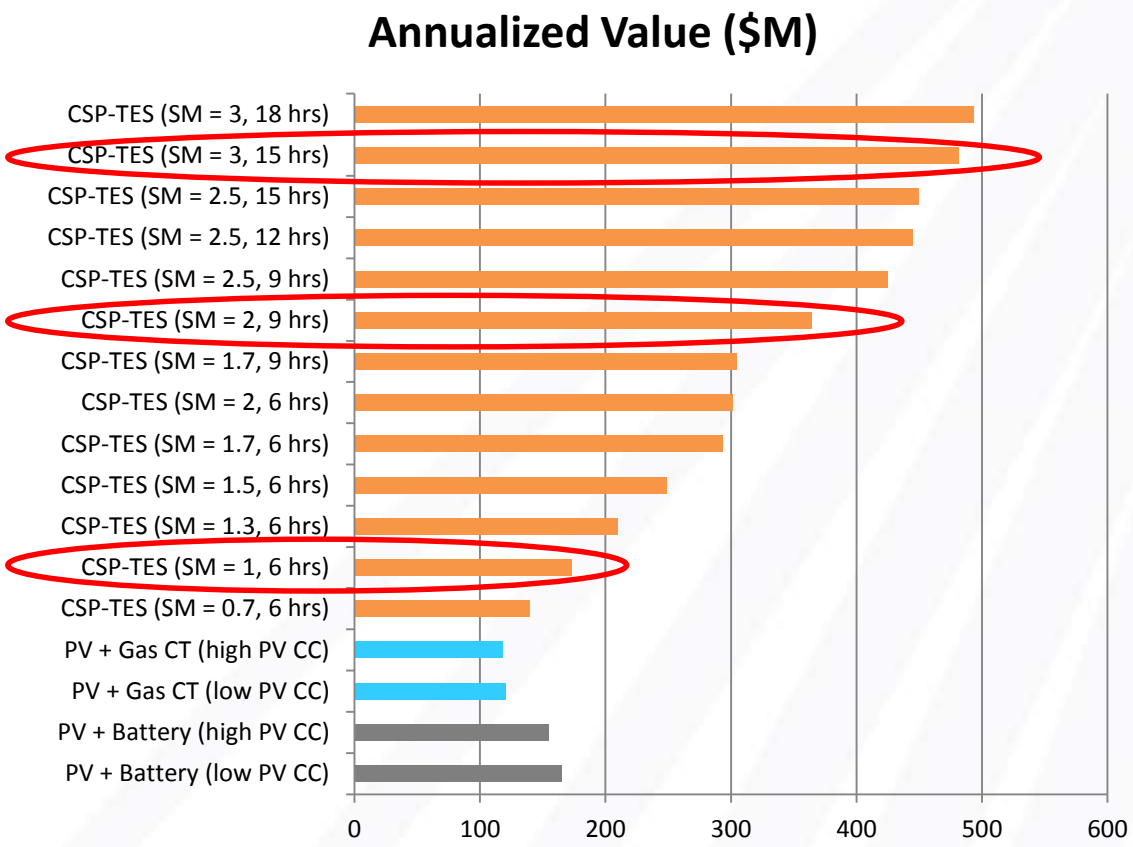
System Costs (total installed)	PV (current)	PV (SunShot)
- fixed-tilt module	$1.82/W$_{ac}$	$1/W$_{ac}$
- one-axis tracking module	$2.01/W$_{ac}$	$1.1/W$_{ac}$
- non-tracking fixed O&M	$15/kW-yr	$7/kW-yr
- one-axis tracking fixed O&M	$18/kW-yr	$15/kW-yr
Construction loan period and interest rate	6 months at 4%	6 months at 4%

Battery Cost/Performance Assumptions

System Costs (total installed)	Battery (current, low)	Battery (current, high)	Battery (future, low)	Battery (future, high)
- power-related costs	$300/kW	$600/kW	$200/kW	$400/kW
- energy-related costs	$450/kWh	$900/kWh	$150/kWh	$300/kWh
- total (for 6 hour capacity)	$500/kWh	$1000/kWh	$183/kWh	$367/kWh
Battery Lifetime	10 years	5 years	15 years	10 years

Used an annualized capacity cost of $190/kW-yr for a gas CT (CAISO 2012), representing a high-efficiency turbine (heat rate of 8700 Btu/kWh). This cost remains constant due to the mature nature of turbine technology.

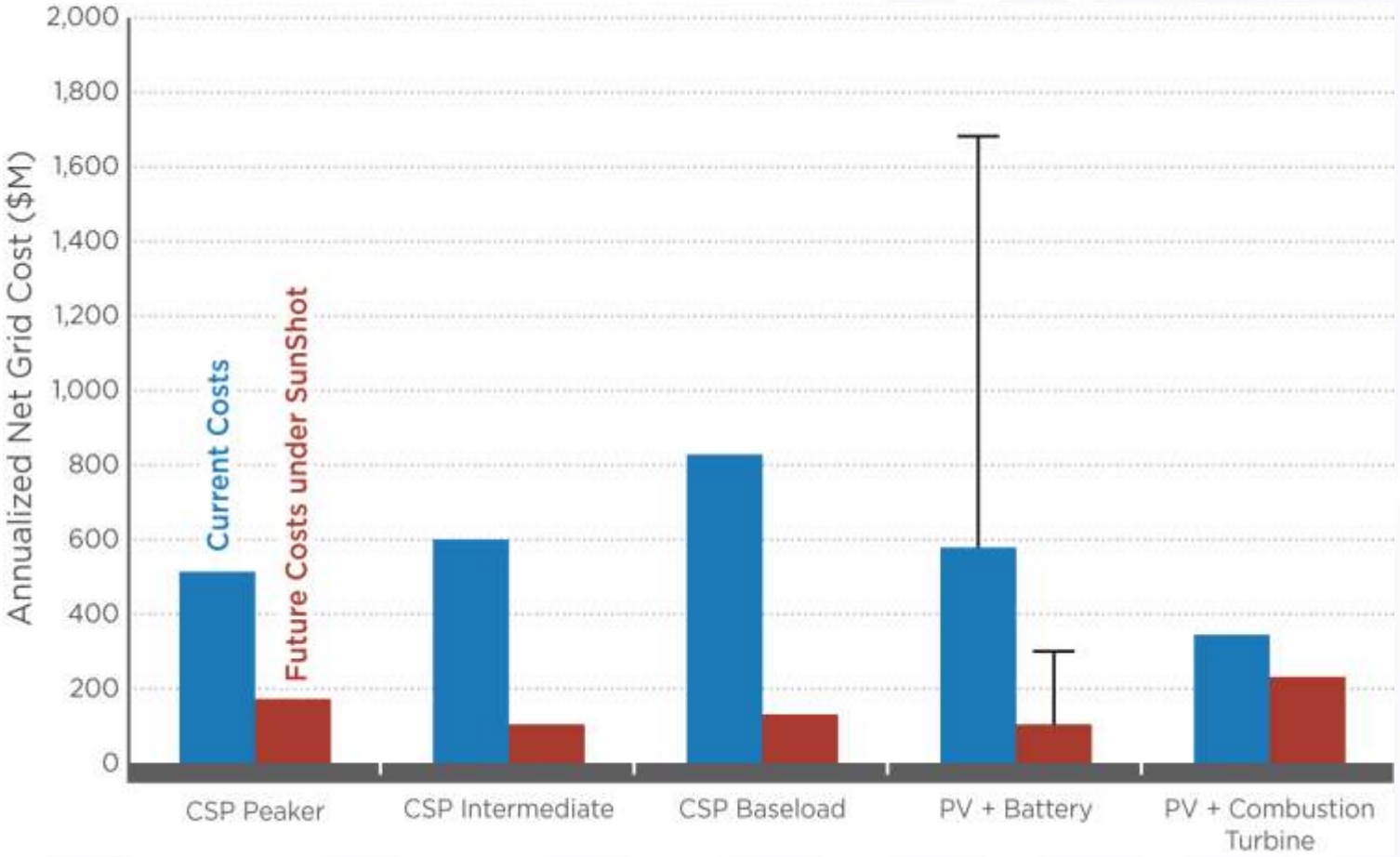
Avoided Operational Costs



Jorgensen et.al. 2015

Most configurations of CSP-TES are more ‘valuable’ than other generation options

Annualized net cost results for analysis of current and future cost scenarios for CSP, PV with batteries, and PV with combustion turbines



Conclusions

- LCOE is an incomplete metric when considering the value of dispatchable CSP
- The net system cost, defined as the operational costs minus operational savings, is more appropriate for technology comparisons
- For low natural gas and emissions costs, CSP SunShot peakers and intermediate load plants are competitive with conventional NG-fired plants, while baseload CSP is more expensive
- Current CSP-TES is more competitive than PV-batteries for providing firm capacity although PV-CTs provide the lowest cost option
- Using SunShot projections, CSP-TES is slightly better than PV-batteries but significantly better if batteries don't meet projections

Thank you!