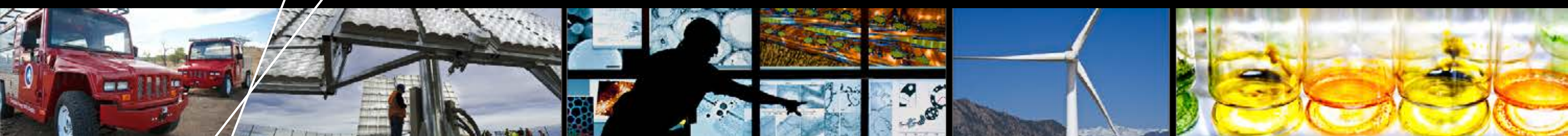
Estimating the Value of Utility-Scale Solar Technologies in California Under a 40% Renewable Portfolio Standard
(Report Summary)



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California’s Renewable Portfolio Standard

- CA currently has a 33% Renewable Portfolio Standard (RPS) for 2020, which means 33% of retail electricity sales must come from eligible renewable energy resources
- Governor Brown sees California’s RPS goal of 33% by 2020 as a floor, not a ceiling.
- Within reasonable costs, the Governor has stated that 40% renewables is achievable in the near future*
- In this analysis, we compare the relative value of two utility-scale solar technologies (PV and Concentrating Solar Power with Thermal Energy Storage [CSP-TES]) under a 40% RPS scenario

*Source: Press release, April 12, 2011. Office of Governor Jerry Brown website, Source: Press release, April 12, 2011. Office of Governor Jerry Brown website, http://gov.ca.gov/news.php?id=16974.

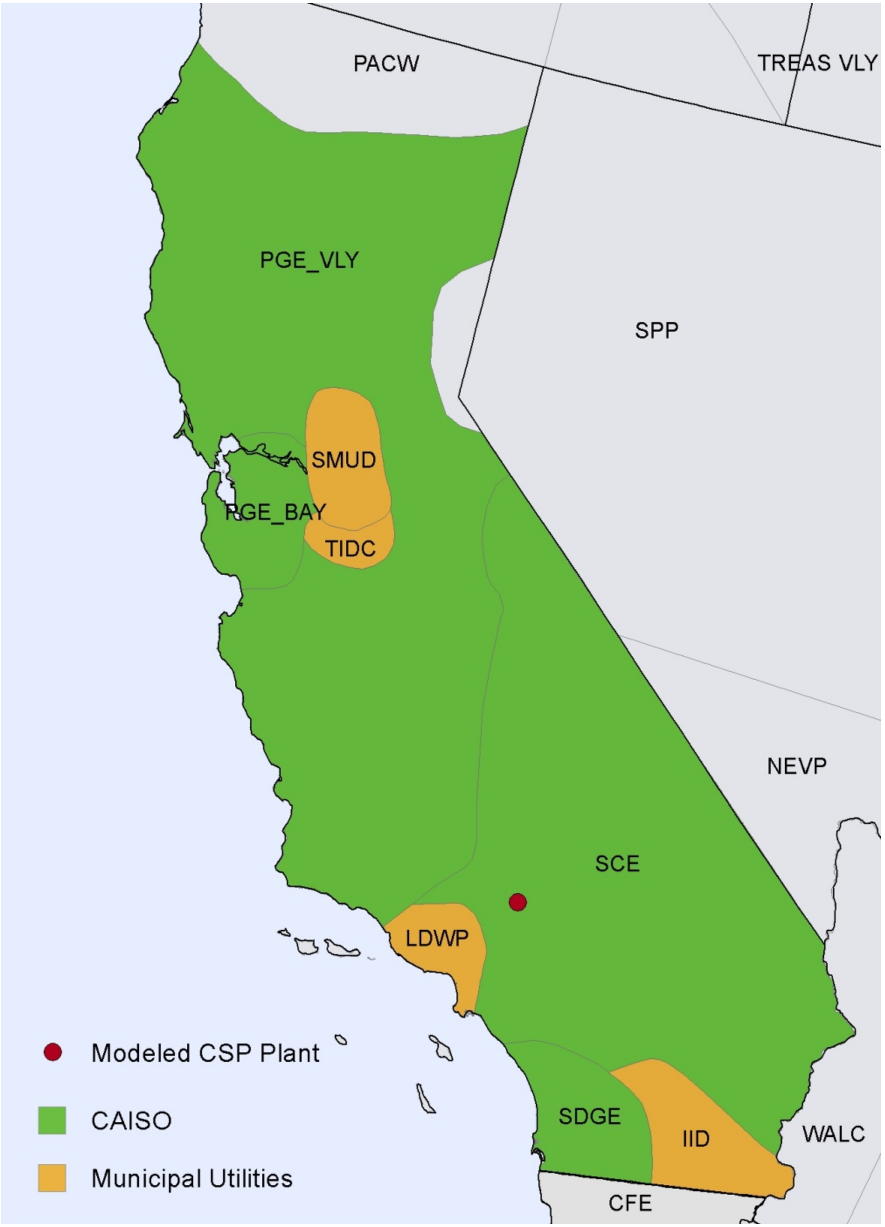
Analysis of California's Electricity Sector

- The California Independent System Operator (CAISO) oversees CA's bulk power system and energy market
- To analyze the originally proposed 33% RPS, they developed a database with generator-level detail for all of the Western US (CA historically imports a lot of power from neighboring regions)
- To reduce run-time, generators outside of CA are simplified, and don't enforce integer "unit commitment" status and constraints
- The model enforces transmission limits between ~25 regions (zones) in the Western U.S.

Analysis Goals

- To use the CAISO database as a foundation for understanding the operational value of utility-scale solar technologies in a scenario with relatively high existing solar penetration in the base 33% RPS scenario, and a higher 40% RPS environment
- Determine the sensitivity of operational value to system assumptions:
  - Configuration of CSP-TES plant
  - Presence of existing energy storage
  - Ability of CAISO to export energy
- Develop more robust capacity valuations for either solar technology

Analysis of California's Electricity Sector at a 33% RPS



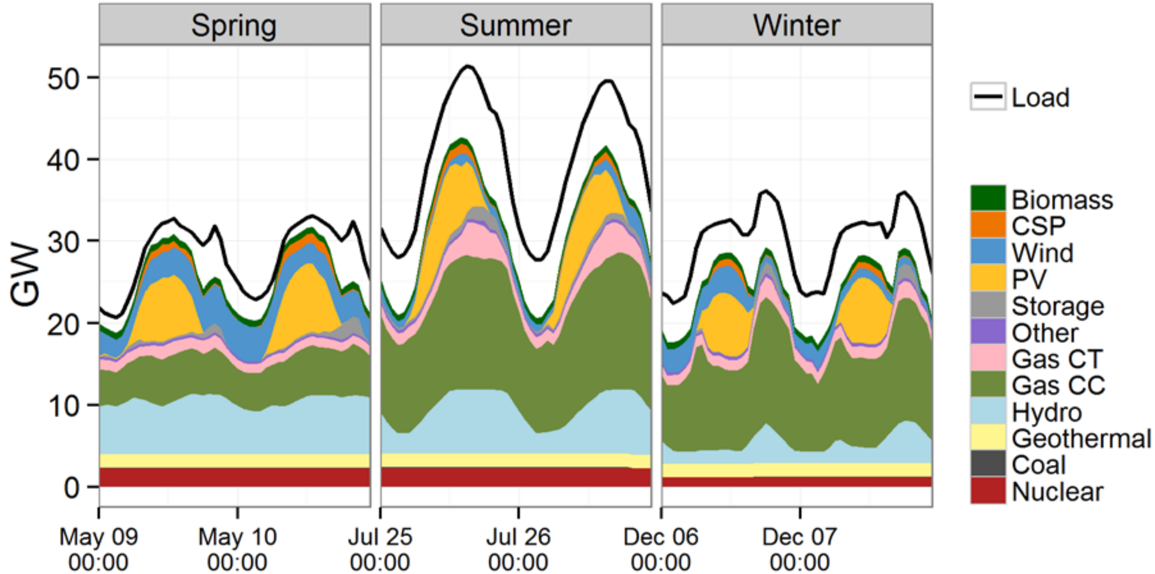
Summary of modeled regions in the original 33% RPS database:

	CAISO	Munis	Rest of the West
Peak Load (GW)	54.3	12.0	122.9
Annual Demand (TWh)	254	58.0	753
CA RPS Energy (TWh)	60.4	9.2	18.2
Other Wind and Solar Energy (TWh)	6.4	0	69.4
Annual Net Imports (TWh)	46.2	29.6	-75.8
Areas Served/ Balanced By	SCE, SDG&E PG&E	LDWP, IID, TIDC, SMUD	Rest of the West (includes areas in CO, AZ, WY, NM, AZ, WA, OR, NV, ID, UT, MT, Alberta, and British Colombia)

Analysis of California's Electricity Sector at a 33% RPS

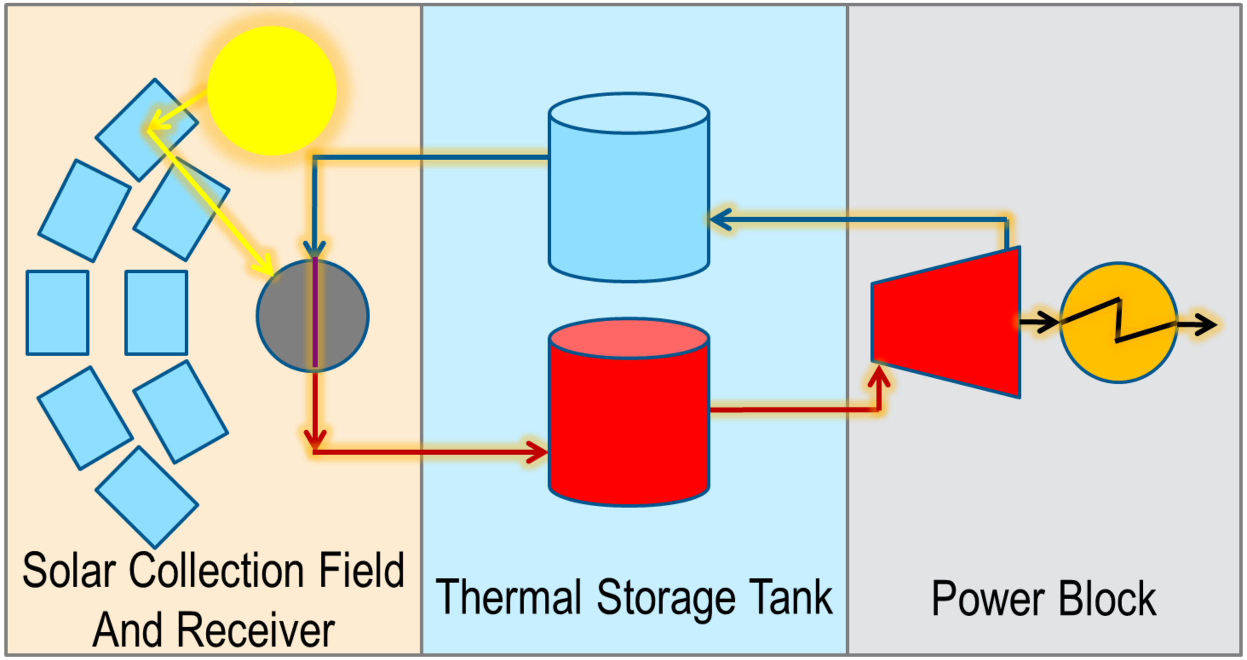
Summary of installed capacity in the CAISO region for the original 33% RPS database

	Capacity Installed (MW)	
	Non RPS	RPS
Biomass	-	1,080
Coal	138	-
CSP	-	1,400
Demand Response	2,730	-
Gas Combined-Cycle	17,900	-
Gas Combustion Turbine	7,430	-
Geothermal	-	2,460
Hydropower	7,350	1,380
Nuclear	2,240	-
PV	2,080	9,950
Steam/Other	615	-
Storage	3,025	-
Wind	-	10,400
Total	**42,300**	**26,600**



Dispatch (generator output) stack for the 33% RPS case in CAISO in different seasons – CAISO is almost always a net importer of energy

Adding Utility-Scale PV or CSP-TES to the original California 33% RPS



CSP is modeled as a modified storage plant, which gets energy inflow from the sun, and can: 1) send solar energy to thermal storage, 2) send solar energy to the power block to generate electricity, 3) a combination of both, or 4) draw energy from storage to generate electricity

Base case configuration has a solar multiple (SM) of 1.3, meaning that the solar field and receiver is over-sized to collect 1.3 times as much energy from the sun than it can generate in the power block, and 6 hours of thermal storage

Adding Utility-Scale PV or CSP-TES to the original California 33% RPS

Marginal operational value of either solar technology is calculated by attributing the savings in generation costs (from conventional thermal generators) to the new solar plant. This value comes from 4 categories:

	Marginal Operational Value in 33% RPS Case ($/MWh)	
	CSP-TES (SM = 1.3, 6 hrs TES)	PV
Variable Operation and Maintenance Costs (VO&M)	1.6	1.2
Start-up and Shut-down	2.5	-0.9
Fuel	34.4	27.9
Emissions	8.1	3.7
Total	**46.6**	**31.9**

Note: CO_2 Emissions cost about $22/ton in database for CA generators

Avoided fossil fuels and biomass consumption by technology:

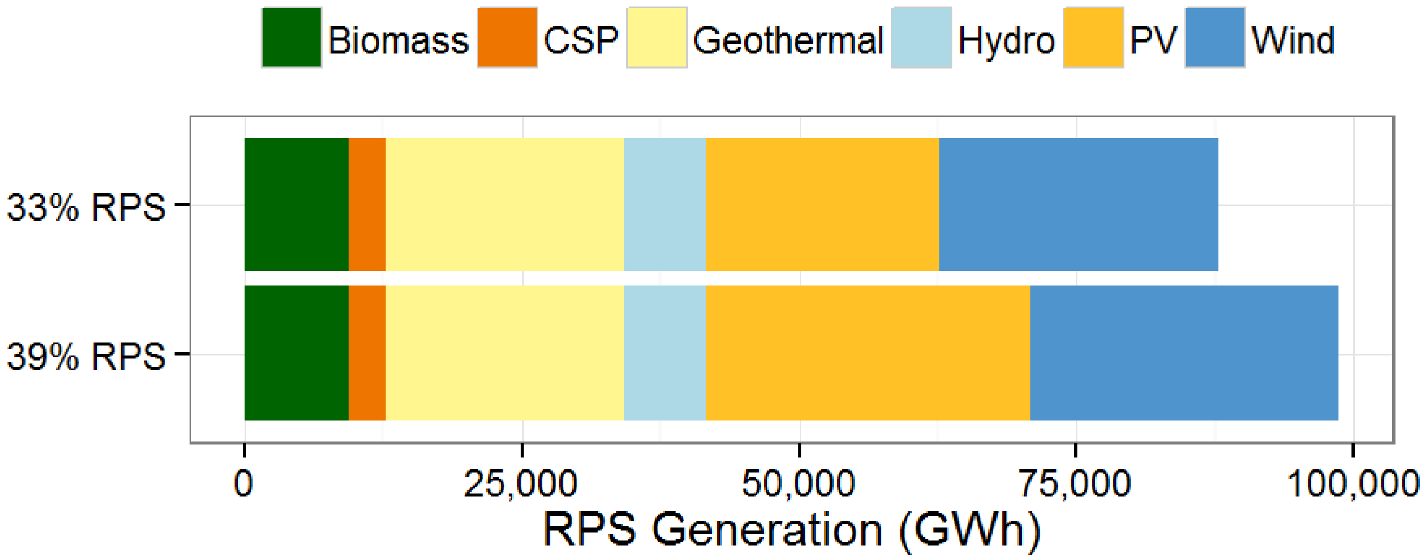
	Avoided Fuel per Unit Energy (MMBTu/MWh)	
	CSP-TES (SM = 1.3, 6 hrs TES)	PV
Biomass	0.2	0.5
Coal	0.3	0.9
Gas Combined Cycle	6.8	6.0
Gas Combustion Turbine	0.7	0.1
Total	**7.9**	**7.5**

Next: Creating a 40% RPS scenario in California

1) Start with CA's 33% RPS database
2) Scale RPS up to 39%
    - Due to many incentives within CA to promote distributed PV, we added 75% PV and 25% wind to existing locations to achieve this level first level of 39% RPS
3) Analyze a situation where CSP-TES provides the final 1% of RPS energy to reach a 40% RPS
4) or analyze a situation where utility-scale PV provides the final 1% of RPS energy
5) Compare the value of the two
6) Test sensitivities to the relative value:
    - Compare various configurations (SM and TES capacity) of CSP
    - Sensitivity to existing energy storage capacity
    - Sensitivity to constricting exports from CA

2) Scaling CA RPS from 33% to 39%

Annual Generation from RPS sources in Two RPS scenarios	33% RPS	39% RPS (before remaining 1% PV or CSP is added)
Biomass	9,400	9,400
Geothermal	21,500	21,500
Small Hydropower	7,200	7,200
Wind	25,100	27,800
PV	21,200	29,300
CSP	3,400	3,400
Total RPS	**87,500**	**98,600**
Non-RPS PV	6,400	6,400
Total RE	**94,200**	**105,000**

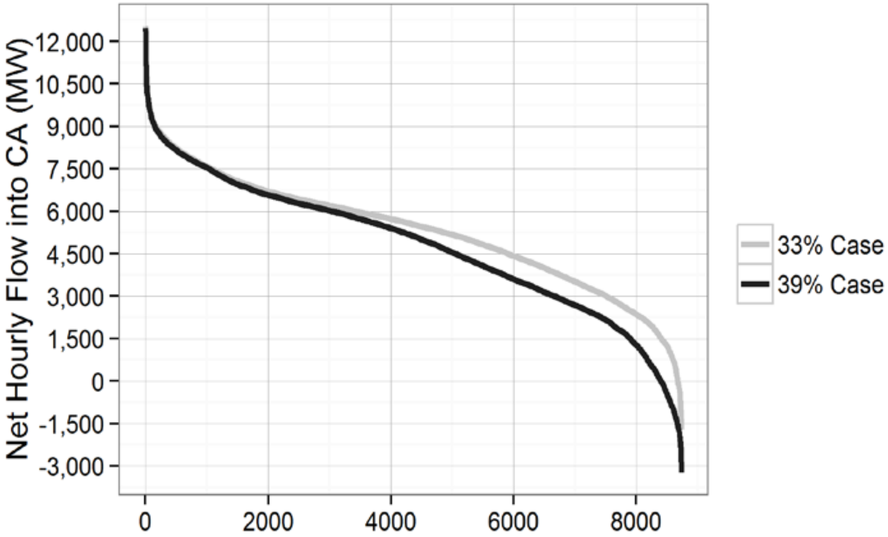


2) Scaling CA RPS from 33% to 39%

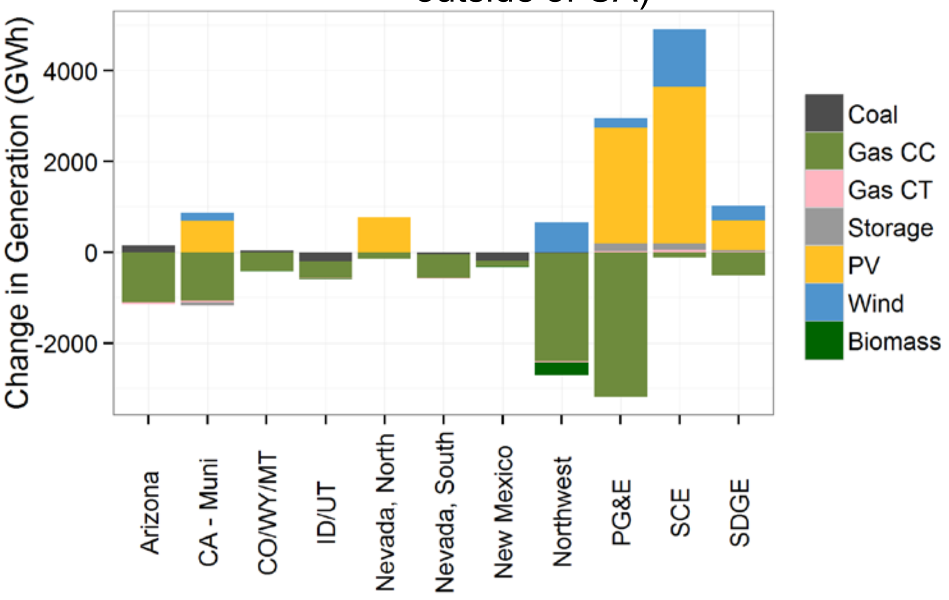
Observed operational changes between the 33% and 39% cases

	CAISO	Munis	WECC
Peak Load (GW)	54.3	12.0	122.9
Annual Demand (TWh) (% of total Western Interconnection)	254 (23.8%)	57.9 (5.4%)	754 (70.7%)
CA RPS Energy (TWh) (% of total CA RPS)	68.9 (69.8%)	10.1 (10.2%)	19.7 (20.0%)
Other Wind and Solar Energy (TWh)	6.4	0	69.4
Net Annual Imports (TWh)	41.2	29.8	-71.0
Incremental CA RPS Energy (TWh)	8.5	0.9	1.5
% of CA RPS Generation Displaced in Region (%)	32.7	11.5	55.8

Change in Imports (reduced imports, and increased exports)

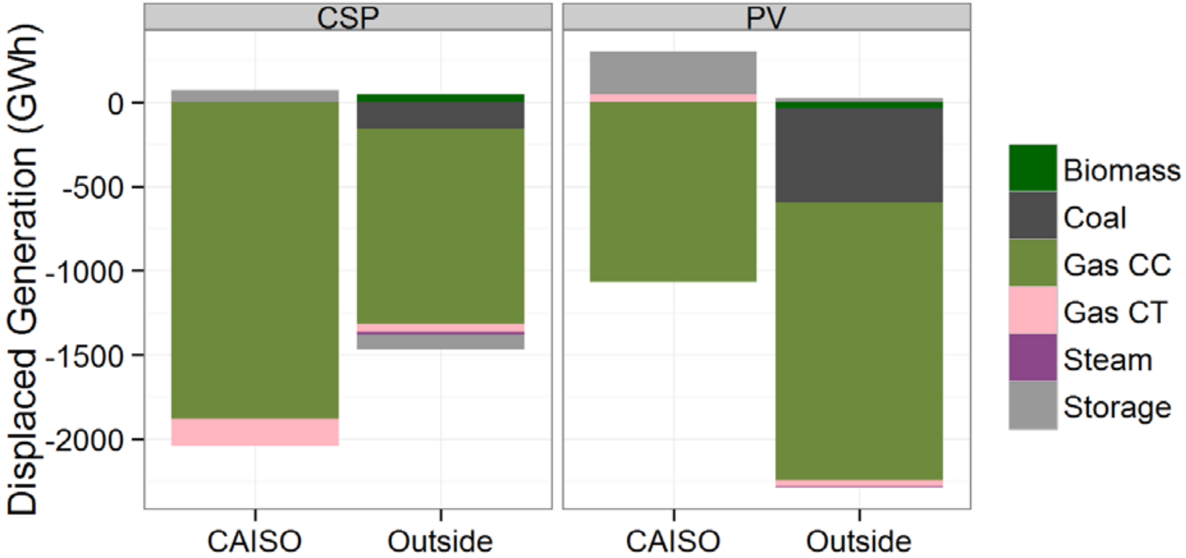


Change in generation (much of displaced energy is outside of CA)



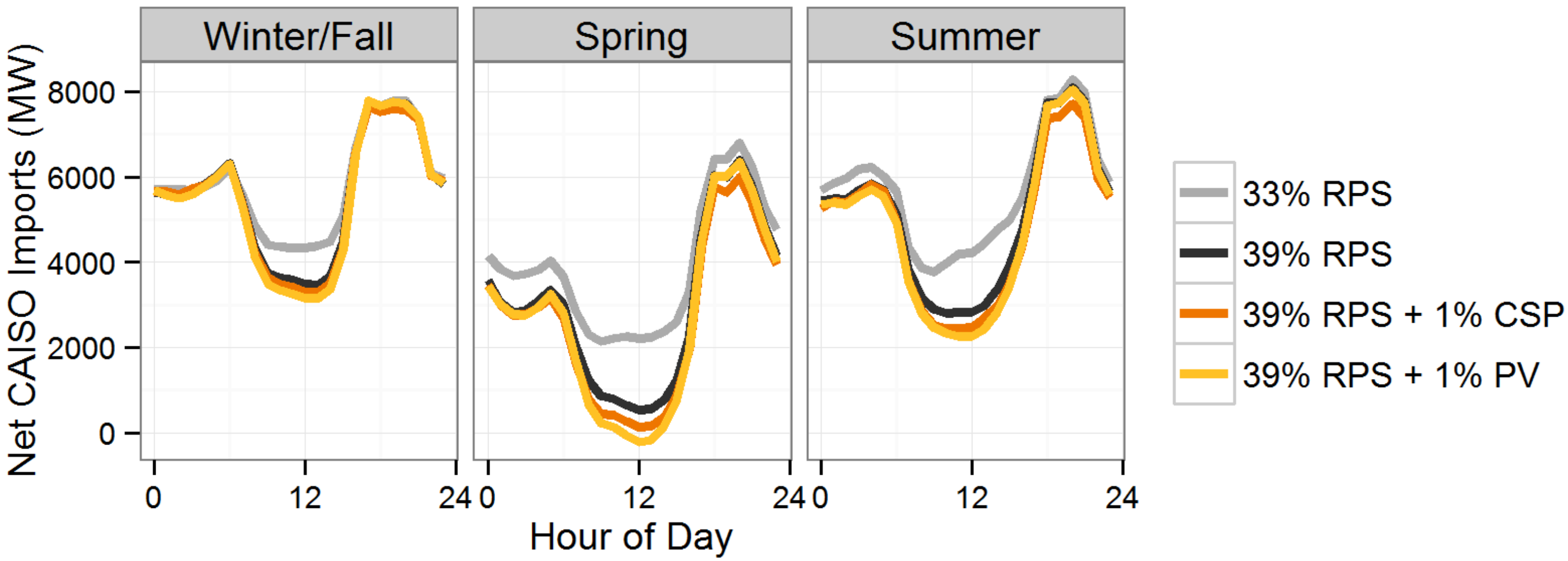
3-5) Add enough CSP-TES or PV to reach 40% RPS

	Marginal Operational Value in 33% RPS Case ($/MWh)	
	CSP-TES (SM = 1.3, 6 hrs TES)	PV
VO&M	1.5	1.2
Start-up and Shut-down	2.9	-0.4
Fuel	33.9	25.8
Emissions	7.9	3.2
Total	**46.2**	**29.8**



- CSP-TES is able to shift energy in time to displace more expensive fuels than PV
- CSP-TES and PV displace similar amounts of CO_2 (484 lbs/MWh for CSP, 507 lbs/MWh for PV)
- **But,** CSP-TES displaces twice the emissions cost compared to PV since CO_2 costs are only incurred inside CA, and CSP-TES displaces mostly generation in CA (see left graph)

3-5) Add enough CSP-TES or PV to reach 40% RPS



- Graph above shows net imports for an average day in 3 seasons into CAISO
- 39% RPS results in a severe dip in imports during the middle of the day
- Adding PV makes this dip noticeably worse compared to adding CSP-TES
- CSP-TES also decreases the evening peak – an important source of value for CSP-TES
- **Overall,** CSP shows an additional value of $16.4/MWh over PV in the 33% RPS case, and $17.4/MWh additional value in the 40% RPS case

6) Sensitivities – Reduced Export Capabilities

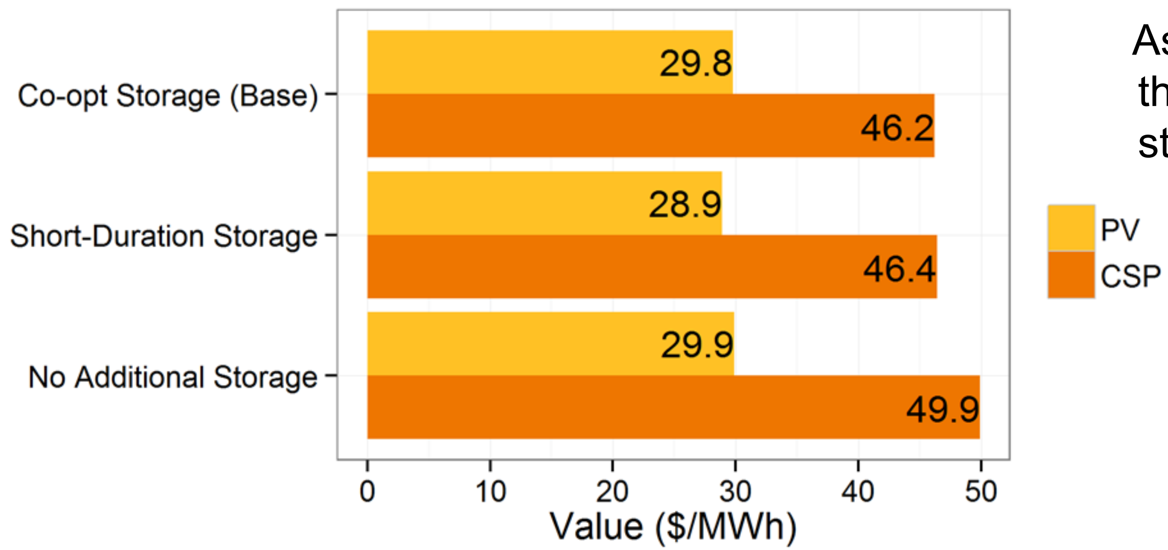
- The implications of assuming that other regions can accept exported RPS energy from CAISO represents a large shift in current operations
  - Two export restriction cases: capping net hourly exports from CAISO at 1500-MW and 0-MW
  - Comparing the marginal operational value of either technology to the value in the base case (with no restrictions on exports other than transmission capacity):

	Base Case (no export restriction)		1,500-MW Export Limit		0-MW Export Limit	
Marginal Operational Value ($/MWh)	CSP-TES	PV	CSP-TES	PV	CSP-TES	PV
VO&M	1.5	1.2	1.6	1.2	1.3	0.9
Start-up and Shut-down	2.9	-0.4	3.4	-0.5	3.5	-0.4
Fuel	33.9	25.8	34.6	26.2	35.1	21.6
Emissions	7.9	3.2	8.3	2.8	6.7	1.3
Total	**46.2**	**29.8**	**47.1**	**29.7**	**46.2**	**28.5**

- The relative value of CSP-TES over PV rises from $16.4/MWh in the base case (with unrestricted exports) to $17.4/MWh in the 1500-MW limit case, and $17.7/MWh in the 0-MW limit case
- Since the operational values in the table above are normalized by MWh of uncurtailed energy, the value of PV drops slightly as more PV must be curtailed, since its not able to be exported

6) Sensitivities – Existing Energy Storage Capacity

- The results presented up to this point contain an assumed an additional ~1200-MW of energy storage, in accordance with Rulemaking R.10-12-007 in CA which establishes energy storage procurement targets
- This 1200-MW of storage is assumed (up to this point) to have a large storage capacity and the ability to provide ancillary services
- Sensitivities to storage capacity:
  1) long-duration energy-shifting device with the ability to provide ancillary services (base case co-optimized device)
  2) short-duration device with only the ability to provide ancillary services (no energy shifting)
  3) remove the 1200-MW of mandated storage
- Again, compare the marginal value of CSP-TES and PV:

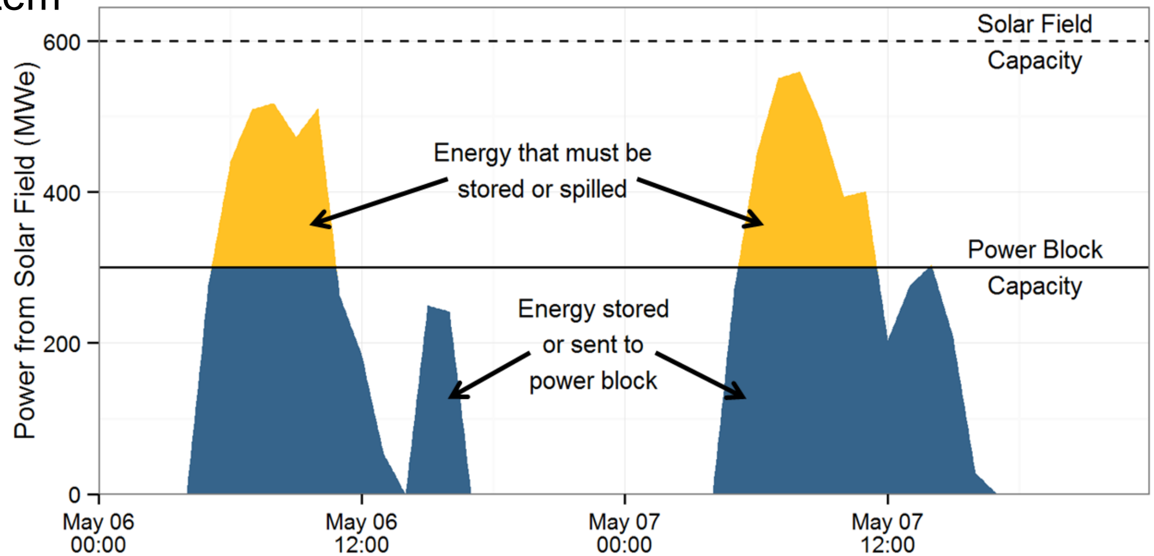


As CSP-TES can provide more services that are not being provided by the other storage devices, its value over PV rises

	Relative Value of CSP-TES Compared to PV ($/MWh)
Co-optimized Storage (Base)	16.4
Short-Duration Storage	17.5
No Additional Storage	20.0

6) Sensitivities – CSP-TES Plant Configuration

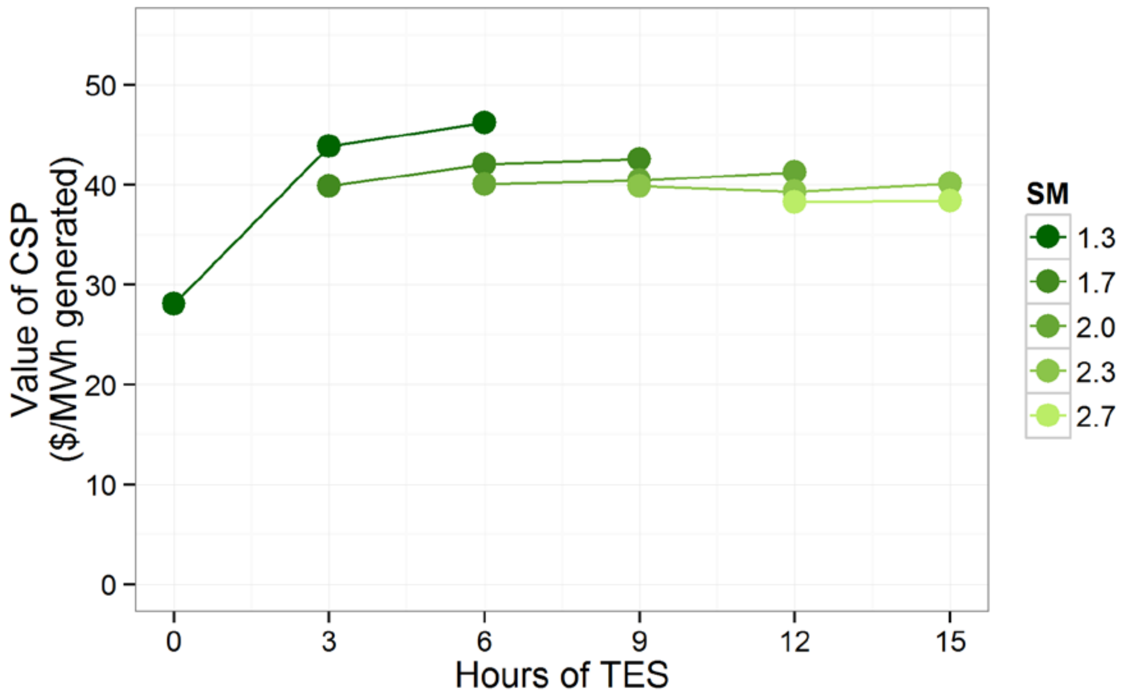
- Varying the configuration (relative ratio of the solar field capacity and power block capacity) and thermal storage capacity of a CSP-TES plant affects the value it provides to the system



- Graph above shows a plant with SM = 2 (the solar field is 2x the size of the power block capacity)
- This sensitivity evaluates SMs between 1.3 and 2.7 with the thermal energy storage capacity varying between 0 and 15 hours of plant capacity:

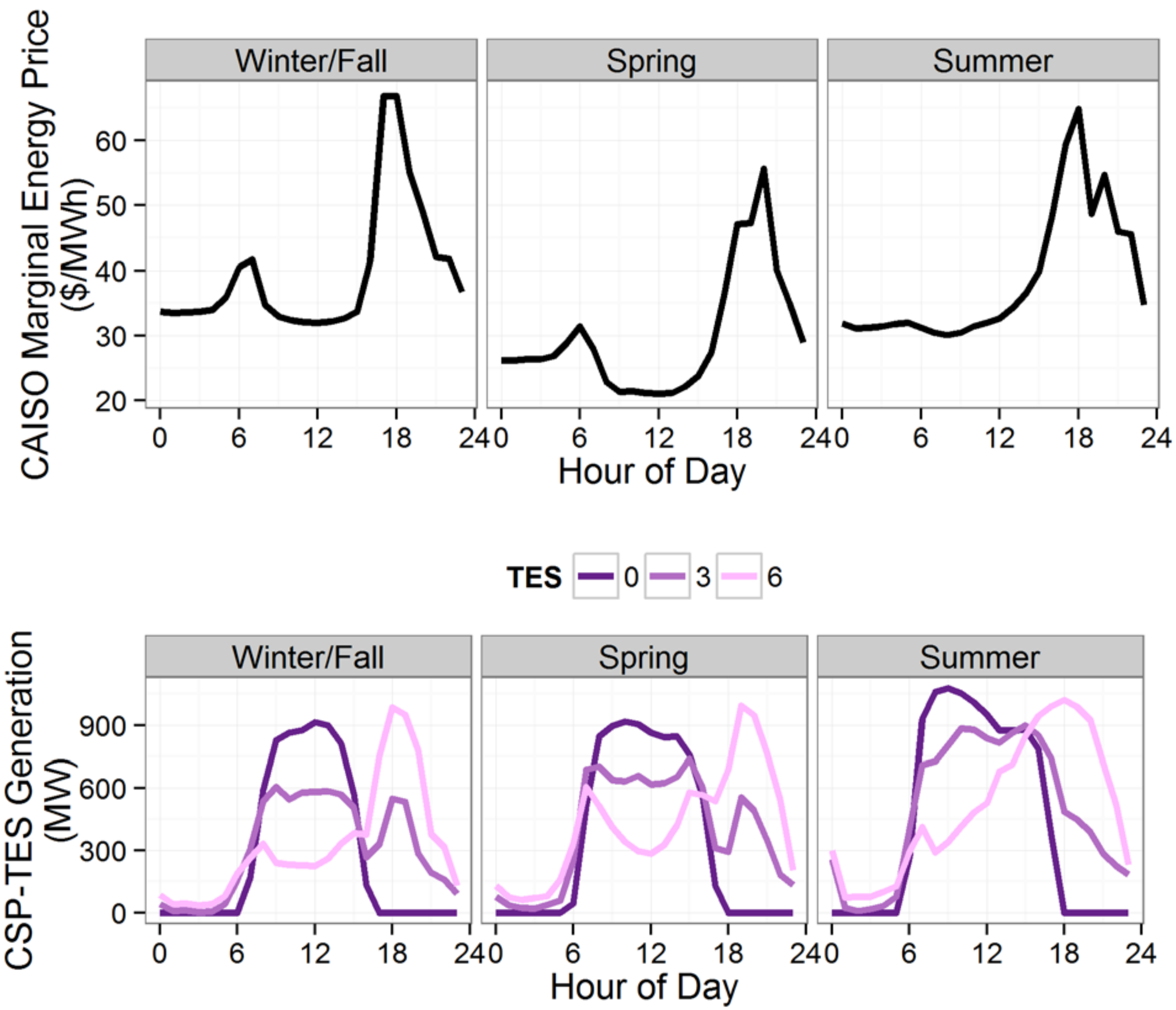
Solar Multiple	Rated Capacity of Plant (MW)	Electrical Equivalent Inflow from Field (GWh)	Hours of TES Capacity Tested
1.3	1,172	3,667	0, 3, 6
1.7	896	3,667	3, 6, 9
2	762	3,667	6, 9, 12
2.3	663	3,667	9, 12, 15
2.7	564	3,667	12, 15

6) Sensitivities – CSP-TES Plant Configuration



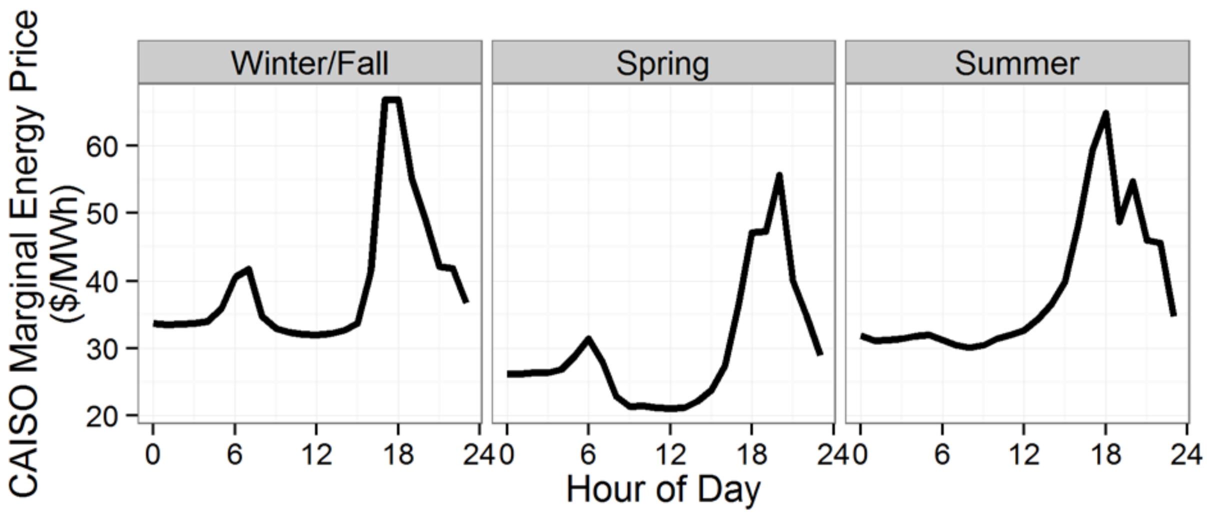
- Two trends in the above graph:
  1) increasing value with higher storage capacity at each SM. This reduces the amount of solar energy that must be spilled by allowing more to be stored, and allowing the energy to be shifted to periods of higher-cost energy
  2) value is higher for plants with lower SMs. Since power block size decreases as SM increases, plants with higher SMs are forced to store an increasing fraction of solar energy even during high-cost periods.

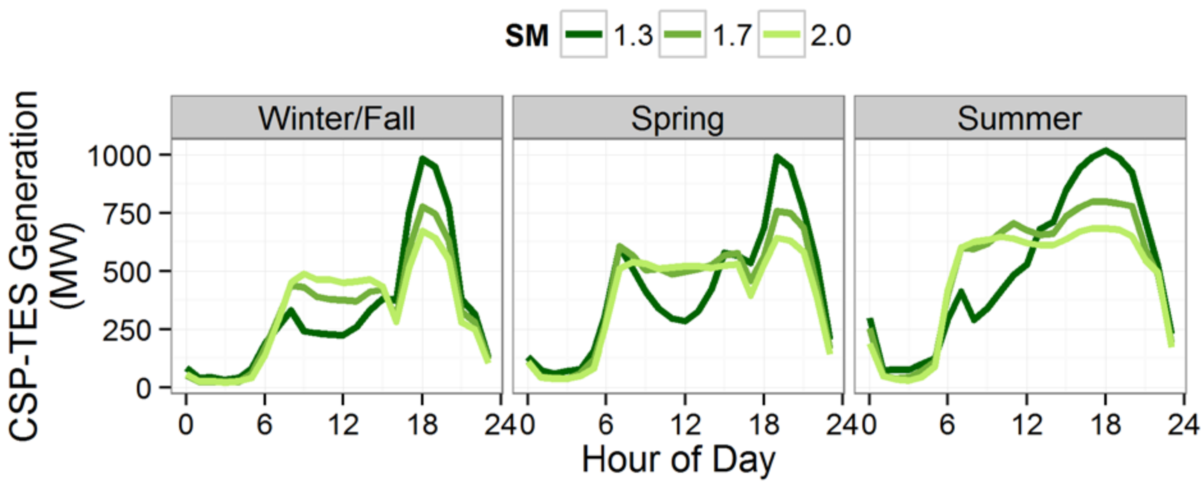
6) Sensitivities – CSP-TES Plant Configuration



More storage capacity gives the plant flexibility in when it generates energy – allowing the plant to generate during the highest-priced hours

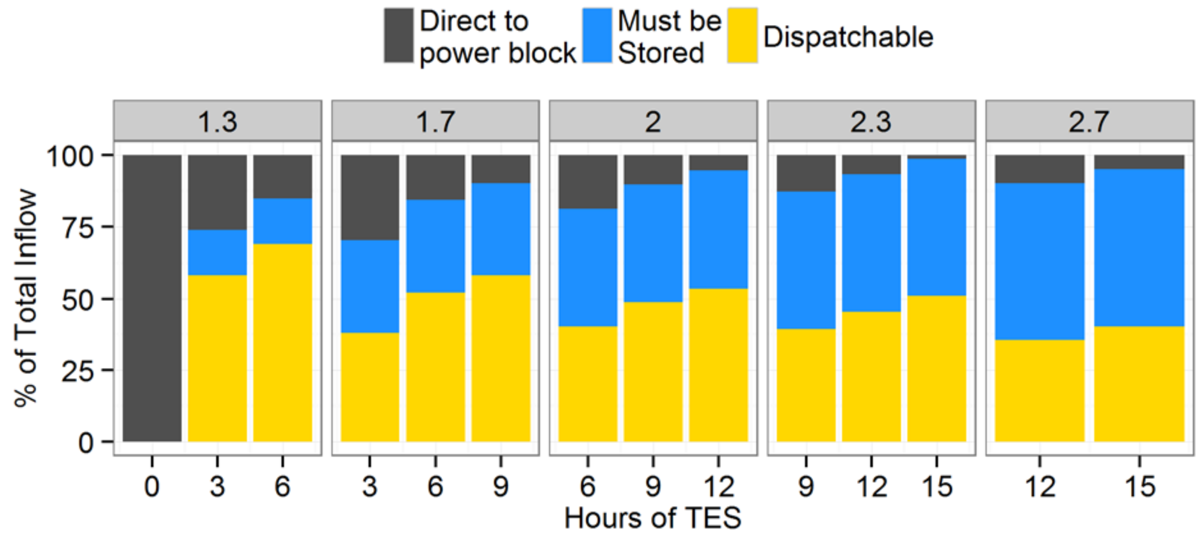
6) Sensitivities – CSP-TES Plant Configuration





- Plants with smaller SMs may output more energy when prices are high
- Plants with higher SMs exhibit a “flatter” generation profile

6) Sensitivities – CSP-TES Plant Configuration



A combination of high thermal energy storage capacity and a smaller SM gives the CSP-TES plant more flexibility in scheduling its output (energy is labeled as dispatchable since there are less constraints on when it may be used)

Other sources of value for solar?

- So far, results indicate that CSP-TES has a higher marginal operational value than PV, and that the relative value may increase slightly with increased PV penetration
- Another source of potential value besides avoided operational costs: firm capacity
- “Capacity value” reflects the ability of PV or CSP to avoid the costs of building new conventional thermal generators to meet demand (only valid in systems which need capacity in response to growing energy demand or plant retirements)
- The actual capacity credit earned by either technology is not necessarily dependent on nameplate capacity, but on a metric which reflects the generator’s availability during periods of peak net demand, or its effective load-carrying capacity (ELCC)

Capacity value for solar technologies

- Using the Renewable Energy Probabilistic Resource Adequacy tool (REPRA) that conducts a full ELCC calculation for variable resources, the capacity credit for PV is calculated:
  - In the 33% RPS case, PV gets a capacity credit of 22%
  - In the 40% RPS case, PV gets a capacity credit of 3.4%
- The low capacity credit of PV in the 40% case may be the result of using only a single year of data or other uncertainties. For a high bound, we use previously reported values:
  - 30% capacity credit in the 33% RPS case
  - 20% capacity credit in the 40% RPS case
- For CSP with TES, the ELCC calculation becomes complicated due to dispatchable storage. An approximation method uses plant output during the highest net load hours and the availability of stored energy during those hours. For CSP-TES with a SM of 1.3 and 6 hours of TES, this leads to:
  - 92.8% capacity credit in the 33% RPS case
  - 96.6% capacity credit in the 40% RPS case

Capacity value for solar technologies

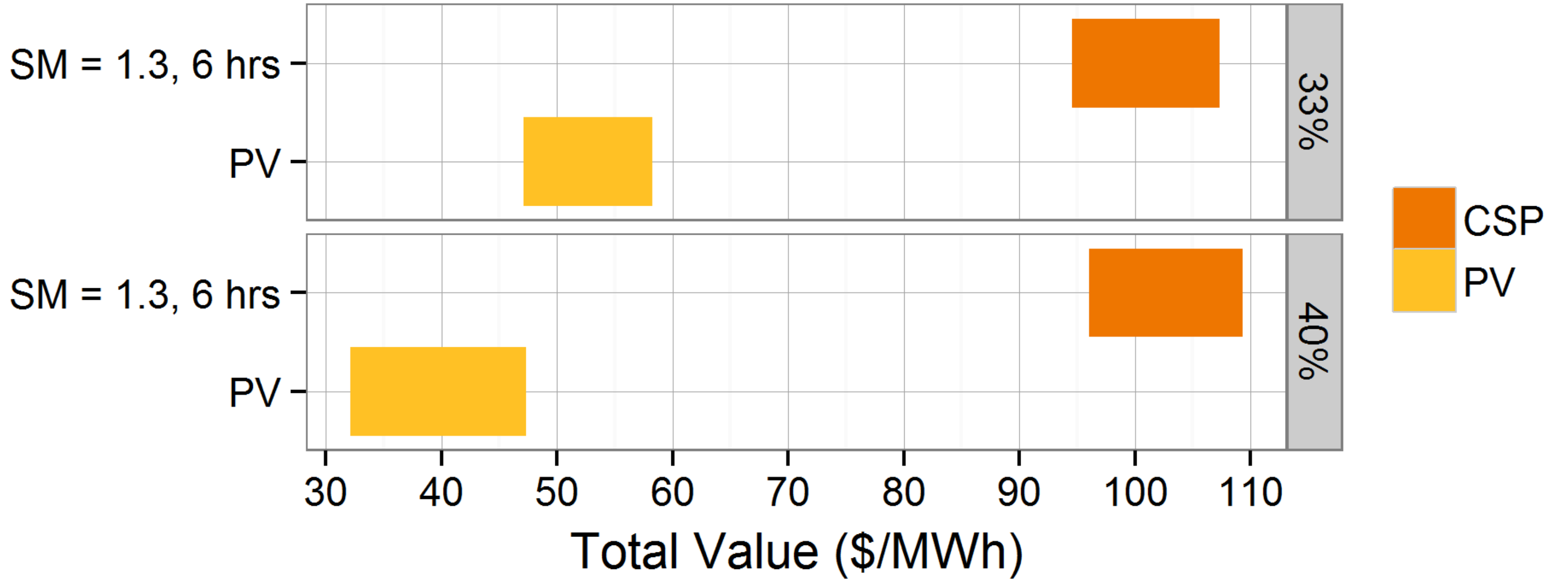
- Applying the cost of a new combustion turbine in California ($150/kW-y or $190/kW-y) to the effective capacity (capacity credit multiplied by nameplate capacity) leads to a range of capacity values in $/MWh

($/MWh)	33% RPS	
	Lower Estimate	**Upper Estimate**
PV	15.2	26.3
CSP-TES	47.9	60.8
($/MWh)	**40% RPS**	
	Lower Estimate	**Upper Estimate**
PV	2.36	17.6
CSP-TES	49.8	63.1

Capacity value for solar technologies

- Adding the capacity values (previous slide) to the operational values from before, the total values for each technology become:

($/MWh)	33% RPS	
	Lower Estimate	**Upper Estimate**
PV	47.1	58.2
CSP-TES	94.6	107
($/MWh)	**40% RPS**	
	Lower Estimate	**Upper Estimate**
PV	32.2	47.4
CSP-TES	96.0	109



Capacity value for solar technologies

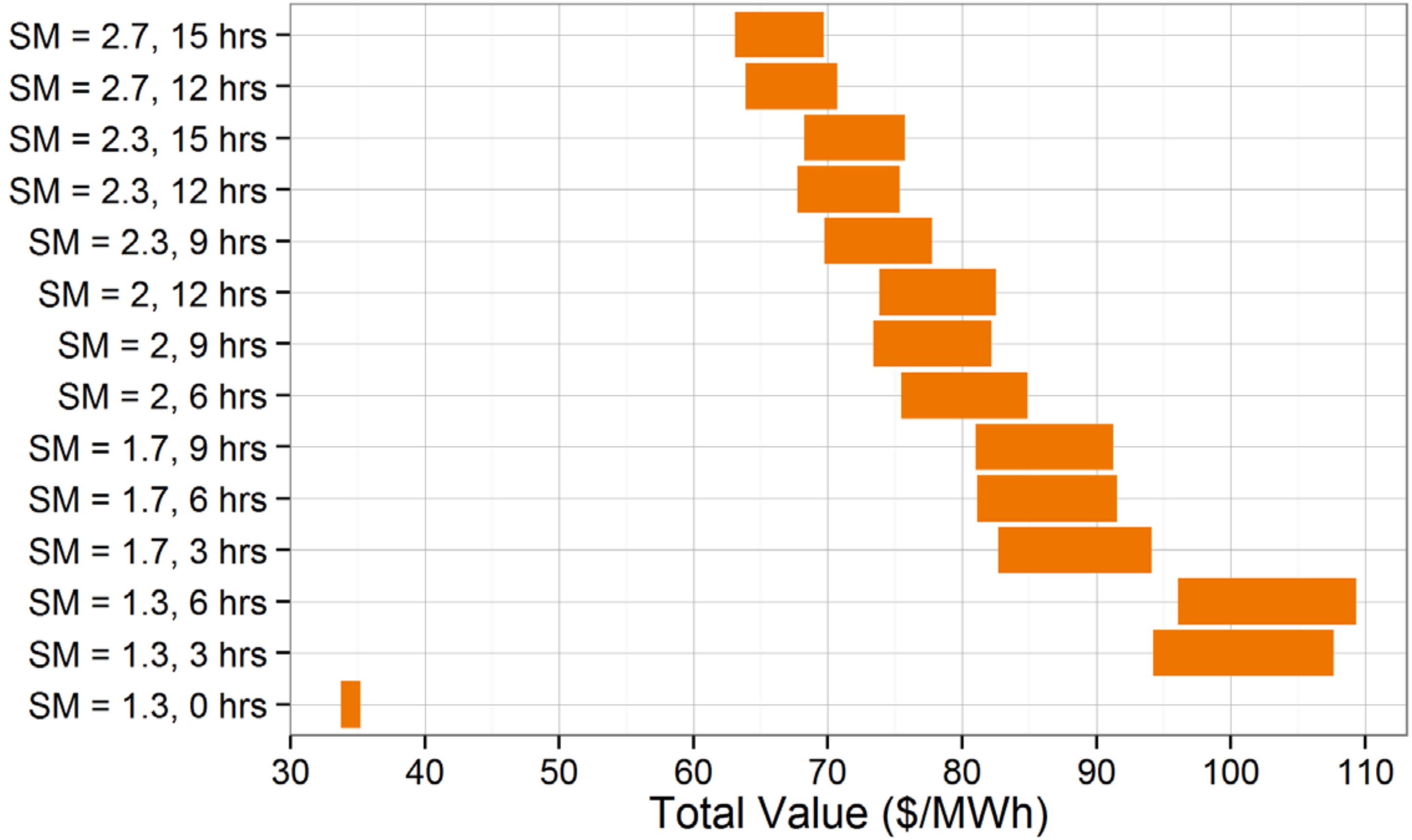
- Capacity credits for different configurations of CSP-TES in the 40% RPS case:

	Capacity Credit Including Dispatch and Useable Storage				
Hours of TES	SM				
	1.3	1.7	2	2.3	2.7
0	0.092				
3	0.946	0.979			
6	0.966	0.989	0.999		
9		0.995	1.00	1.00	
12			1.00	1.00	1.00
15				1.00	1.00

- All configurations of CSP **with thermal storage** exhibit very high capacity credit
- The capacity credit increases for plants with more storage, and with larger SMs

Capacity value for solar technologies

- **Total Value** (capacity + operational value) for different configurations of CSP-TES:



- Smaller SMs with storage show the highest total value
- Due largely to the higher assumed plant rating (see slide 16) and increased operational value

Conclusions

- The **operational value** in reduced generation costs for PV in a 33% RPS case is $31.9/MWh and is $46.6/MWh for CSP-TES
- The **operational value** for PV in a 40% RPS case is $29.8/MWh and $46.2/MWh for CSP-TES
- The operational value is sensitive to:
  - **The configuration of the CSP-TES plant.** Plants with large SMs reduced the value of CSP because the plant produces more energy during periods of low value. Adding sufficient storage capacity increases the value of CSP. Note that plants with smaller SMs and more storage capacity may be more expensive to build, and this interaction requires future analysis.
  - **Export capacity of California.** Reducing the export capacity of CAISO resulted in higher curtailment of PV, which slightly lowers its value to the system.
  - **Existing storage capacity.** Eliminating an existing 1,200-MW of energy storage increases the flexibility benefits of CSP, giving it a higher value

Conclusions

- A significant portion of CSP value appears to be derived from its ability to provide **firm system capacity.**
- The **total value** of CSP and PV (calculated as the sum of capacity and operational value) is:
  - **For PV in a 33% RPS: $**47.1/MWh - $58.2/MWh
  - **For CSP in a 33% RPS:** $94.6/MWh - $107/MWh
  - **For PV in a 40% RPS: $**32.2/MWh – $47.4/MWh
  - **For CSP in a 40% RPS:** $96.0/MWh - $109/MWh

Future Work

- More examination on the capacity value of PV and CSP, especially the interaction between the two
- System needs at shorter timescales (sub-hourly)
- Cost comparison of different configurations of CSP-TES plants

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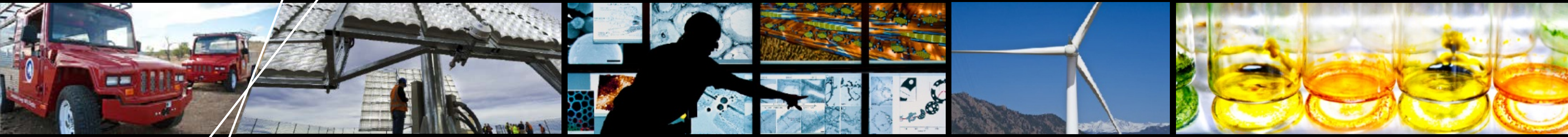
Learn more by downloading the full report: http://www.nrel.gov/docs/fy14osti/61685.pdf



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