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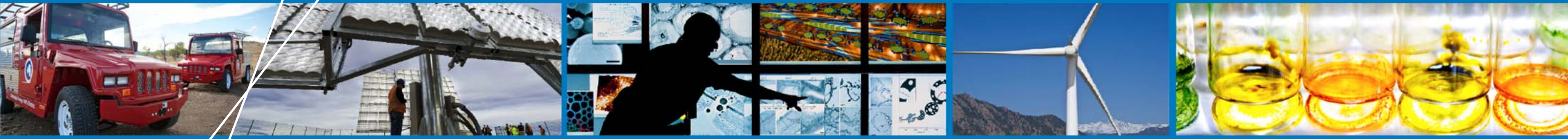
An Analysis of Concentrating Solar Power with Thermal Energy Storage in a California 33% Renewable Scenario (Report Summary)



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March 2013

NREL/PR-6A20-58470

Motivation

- 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?

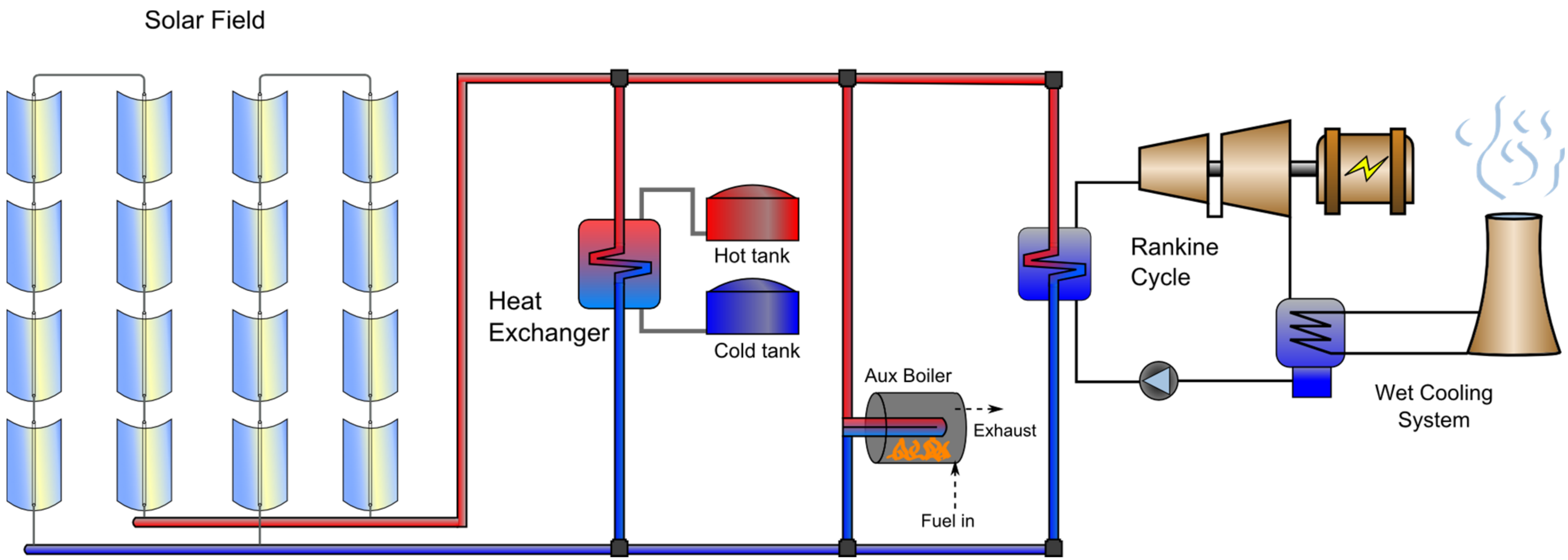
Analytic Approaches

- 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

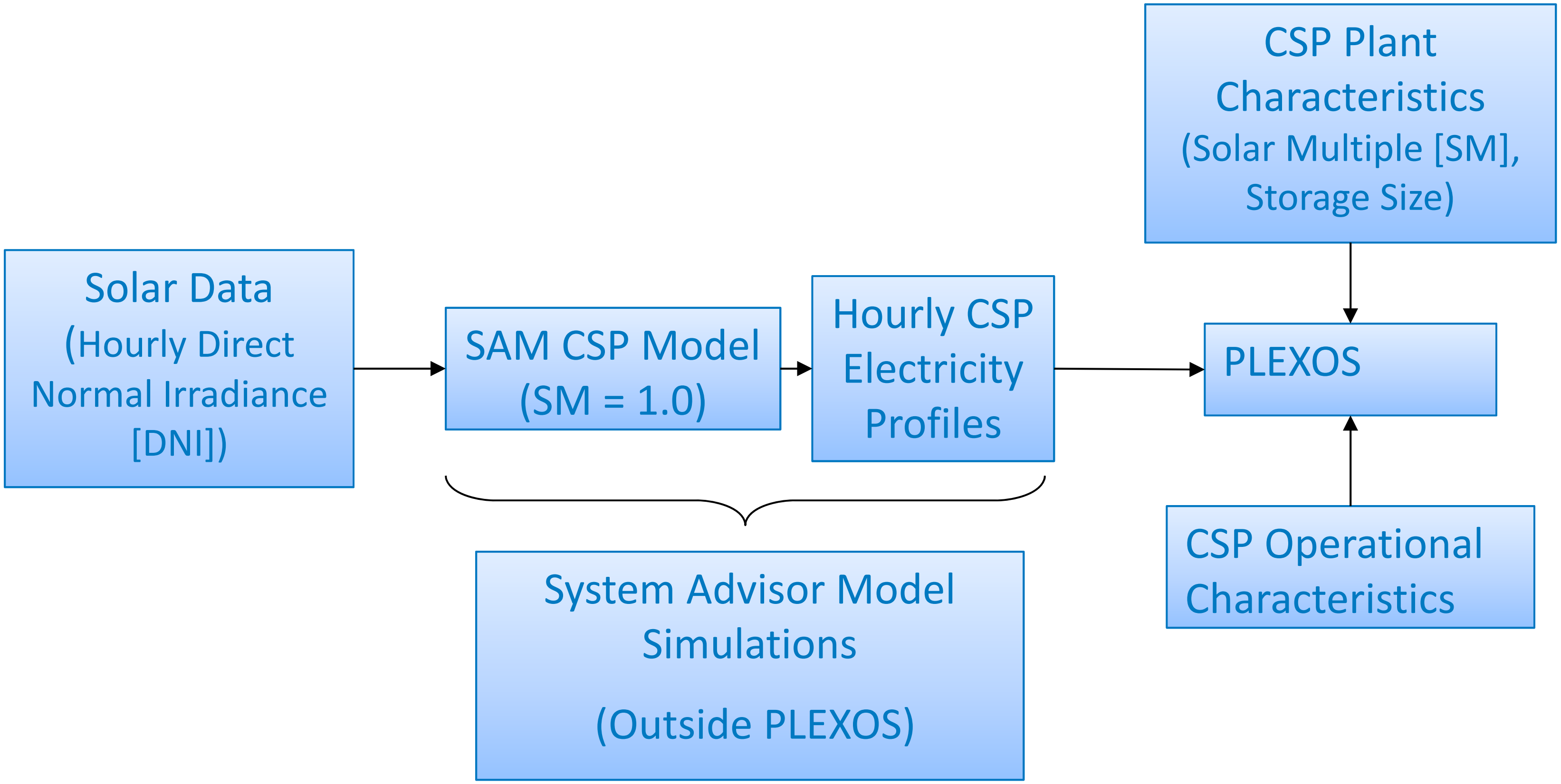
Previous Simulations of CSP in Grid Models in the U.S.

- GridView Simulations in RE Futures/SunShot Vision Studies (NREL 2012 and DOE 2012)
  - Demonstrated qualitatively the value of dispatchability
- Test System Simulation (Denholm & Hummon 2012)
  - Simulation of CSP in a small system
- Mills & Wiser 2012
  - Used a reduced-form dispatch of CSP in the California grid

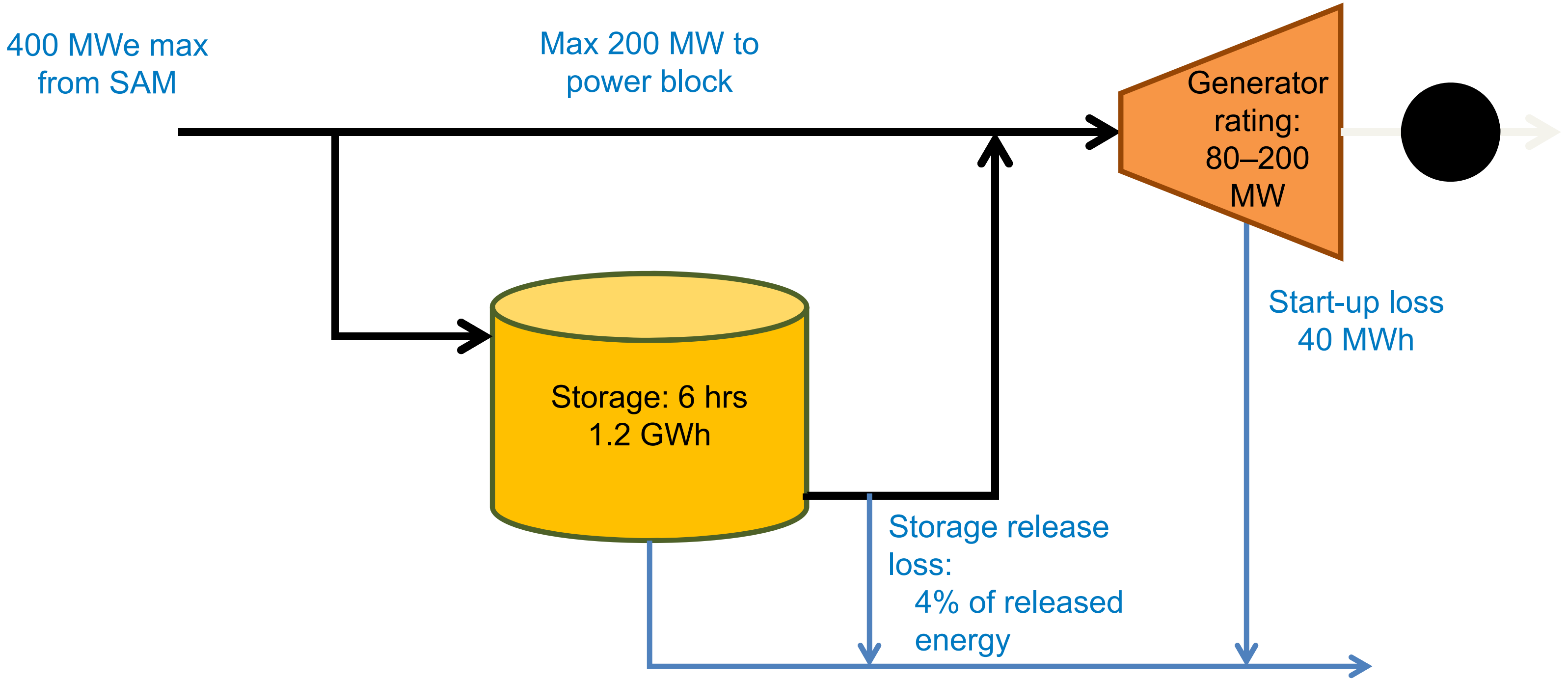
CSP with TES


Solar Field
Heat
Exchanger
Hot tank
Cold tank
Aux Boiler
Exhaust
Fuel in
Rankine
Cycle
Wet Cooling
System

Implementation of CSP with TES in PLEXOS



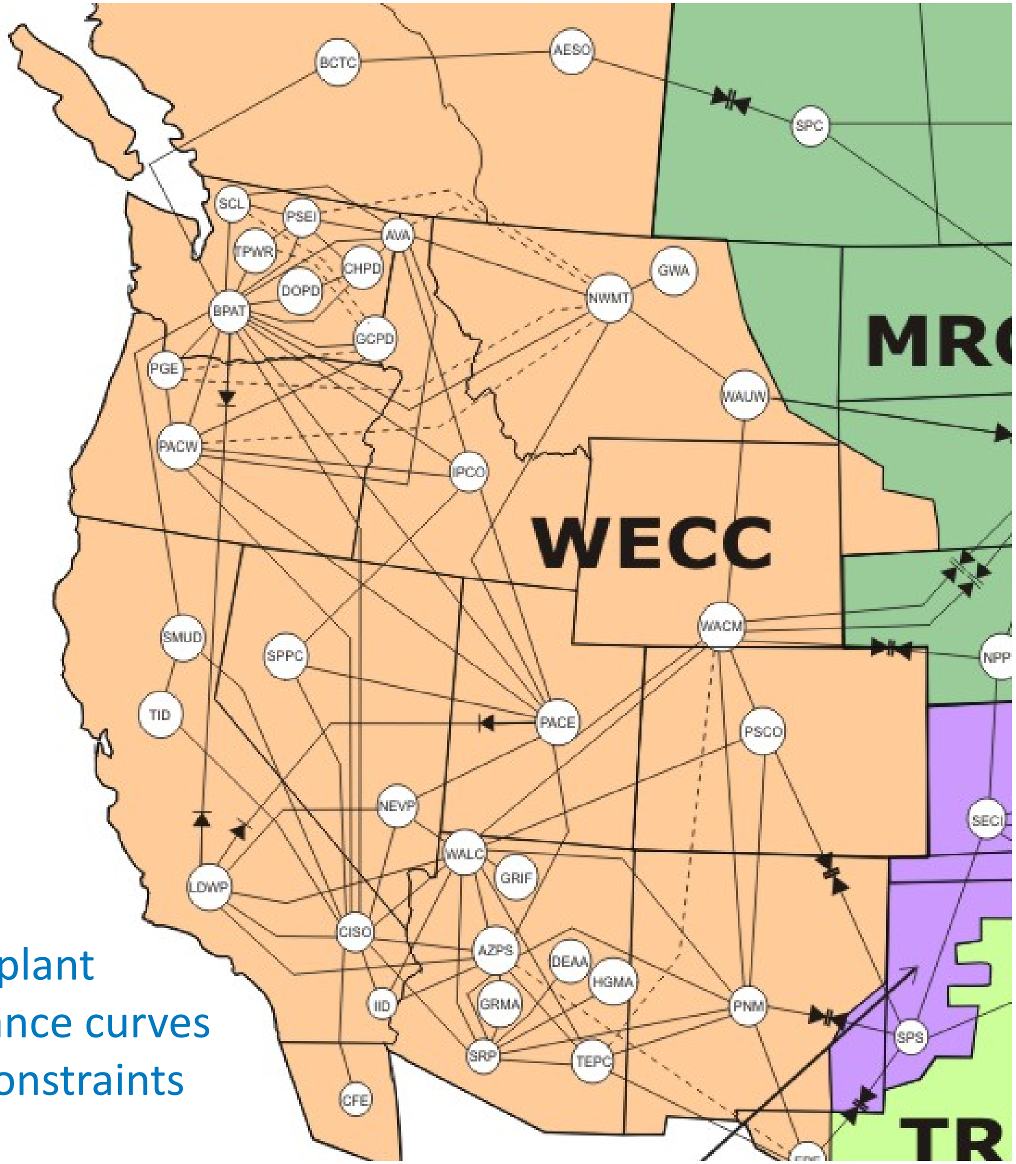
CSP Example Characteristics



Summary of analyzed system:

- Trough plant
- Wet cooled
- SM = 2.0
- 6 hours of storage (at discharge rating)

Geography



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

Reserves and Fuel Prices

- 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
- Fuel prices not modified
  - Natural gas prices varied by location, range from $5.6–$6.3/MMBtu in California
  - CAISO CO_2 cost of $36/ton

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

Comparison to CAISO Results

- Production cost of Environmentally Constrained case within 0.5% of CAISO results
  - We used a newer version of PLEXOS

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

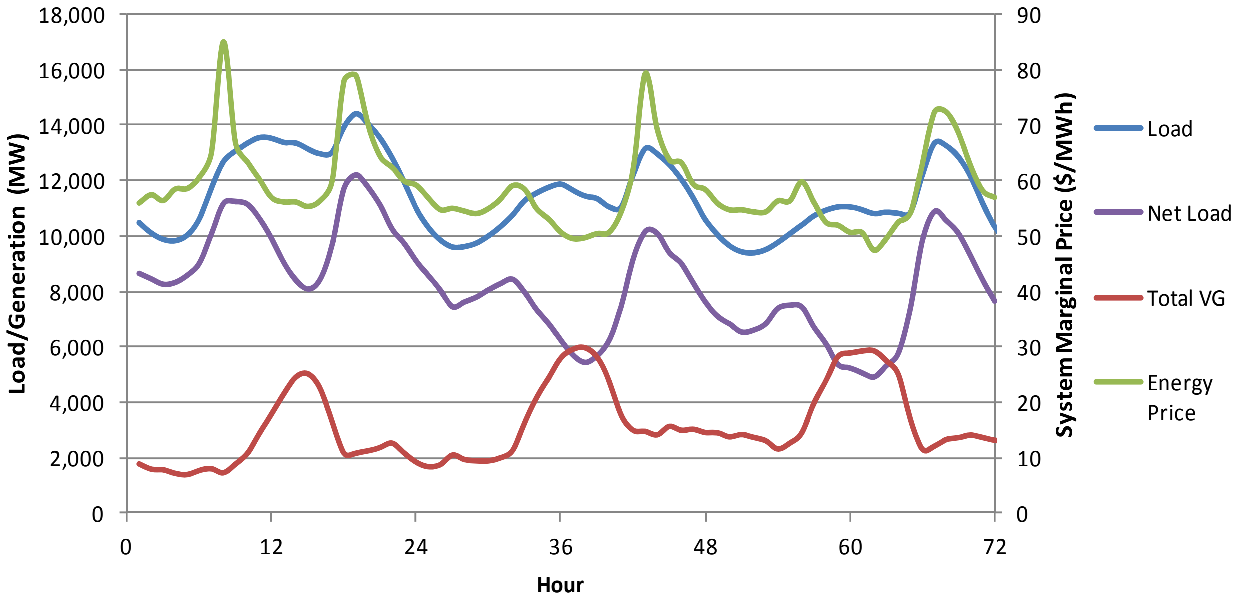
Operational Value Results

PLEXOS generates hour sources of costs for system operation:

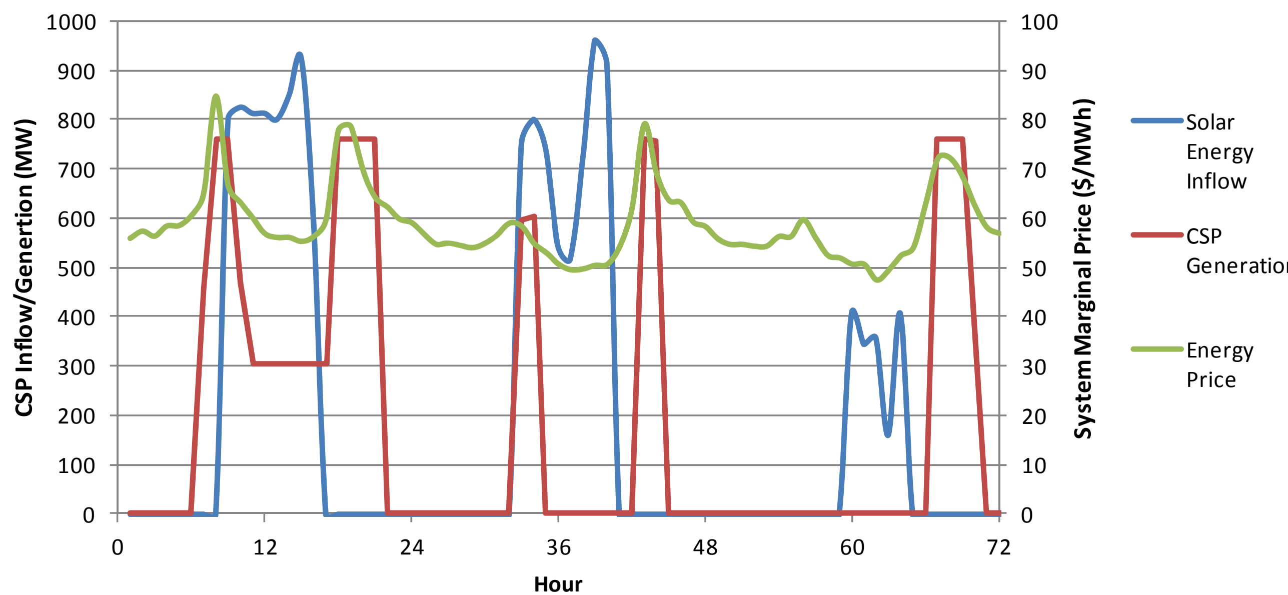
1. Operational fuel
2. Variable operations and maintenance (O&M)
3. Startup (fuel + start O&M)
4. Emissions

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

January Price and Dispatch

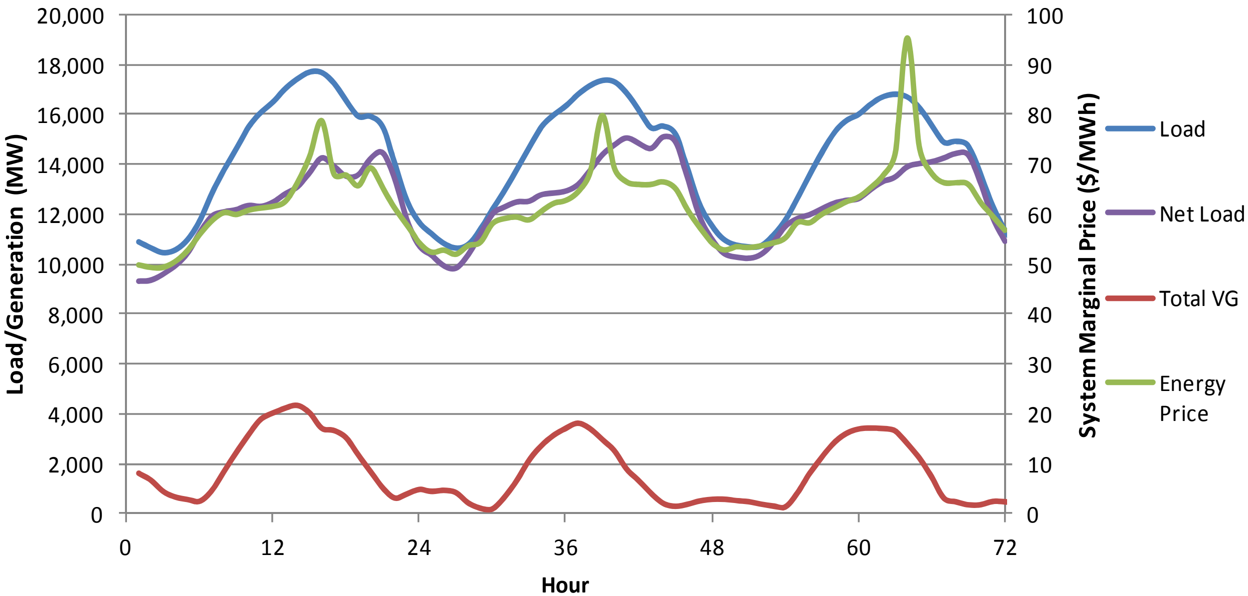


System net load and marginal price for January 31–February 2



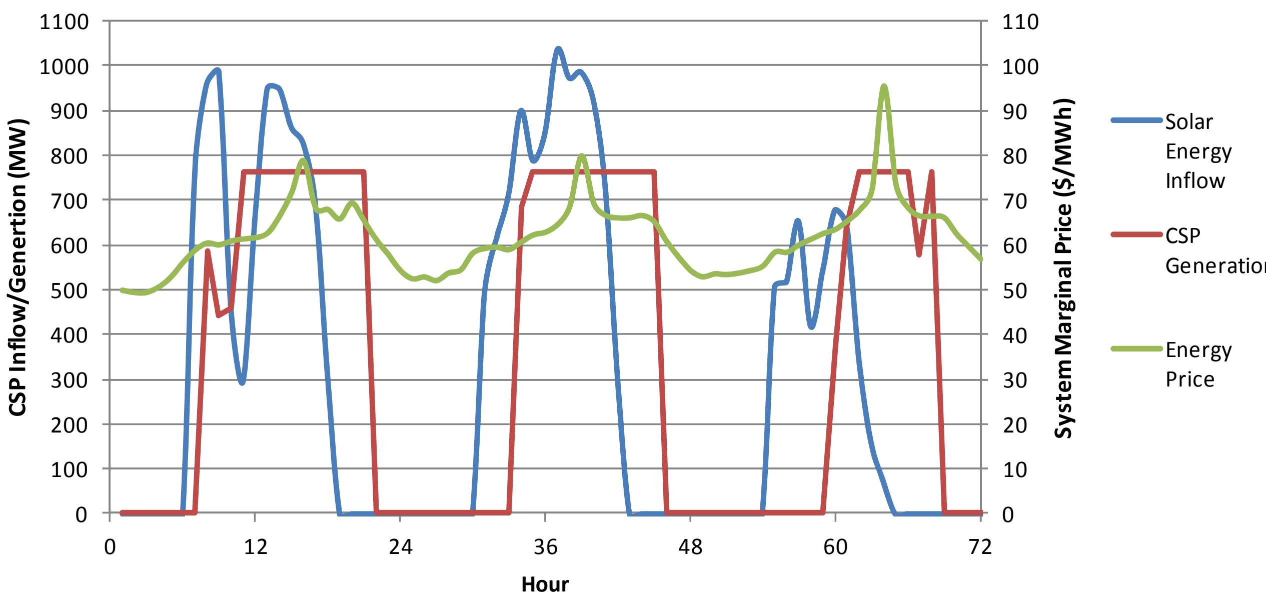
System marginal price and corresponding CSP generation on January 31–February 2

June Price and Dispatch

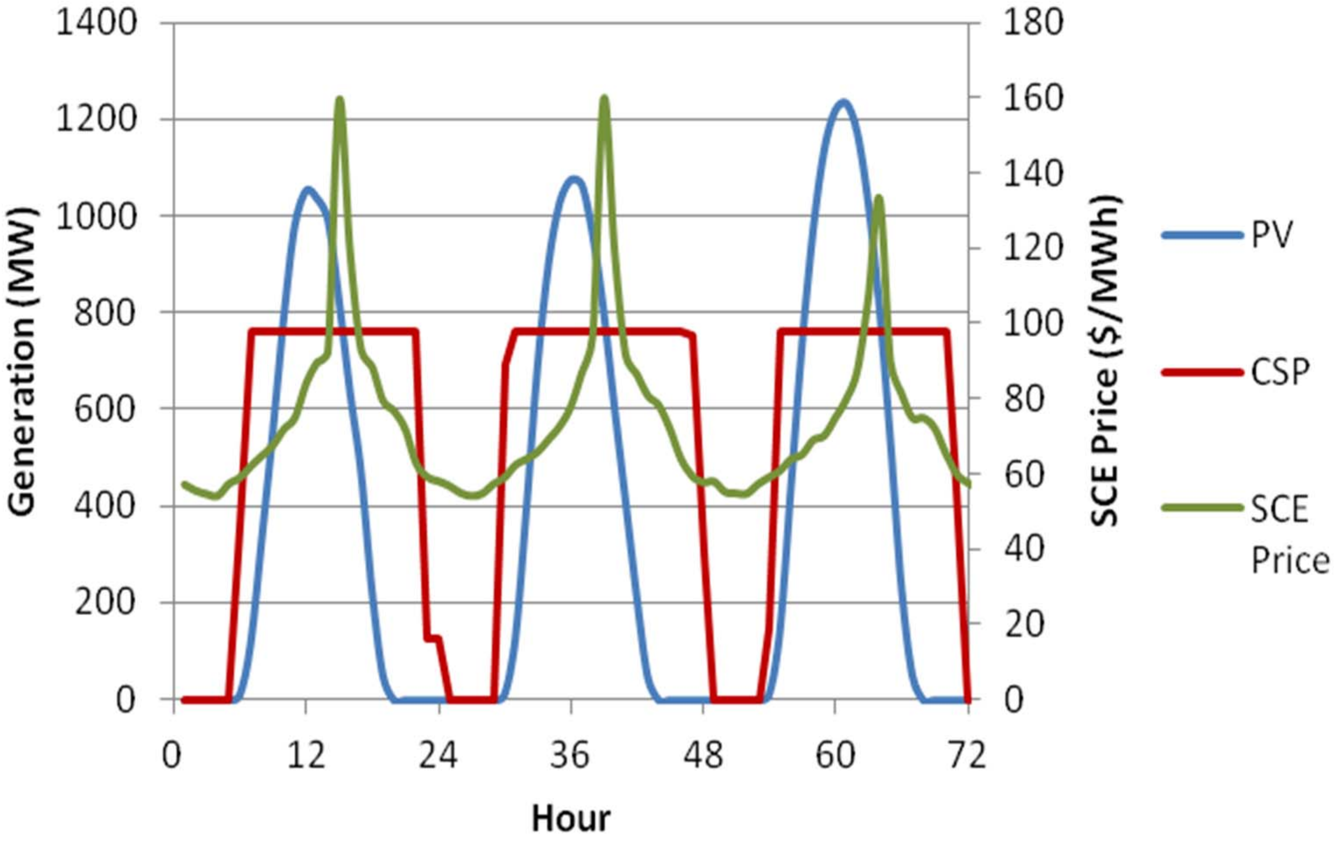


System net load and marginal price for June 24–26

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



Challenges of Higher Solar Penetration

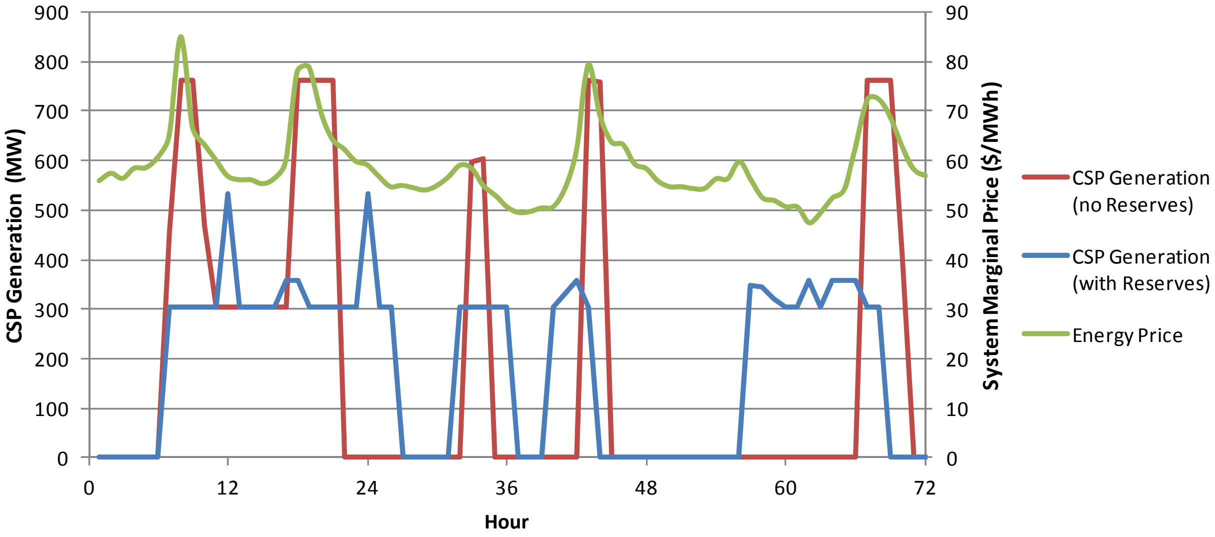


System marginal price and corresponding CSP generation on July 21–23. Short price spike partially driven by decrease in PV output.

Operation with Reserves

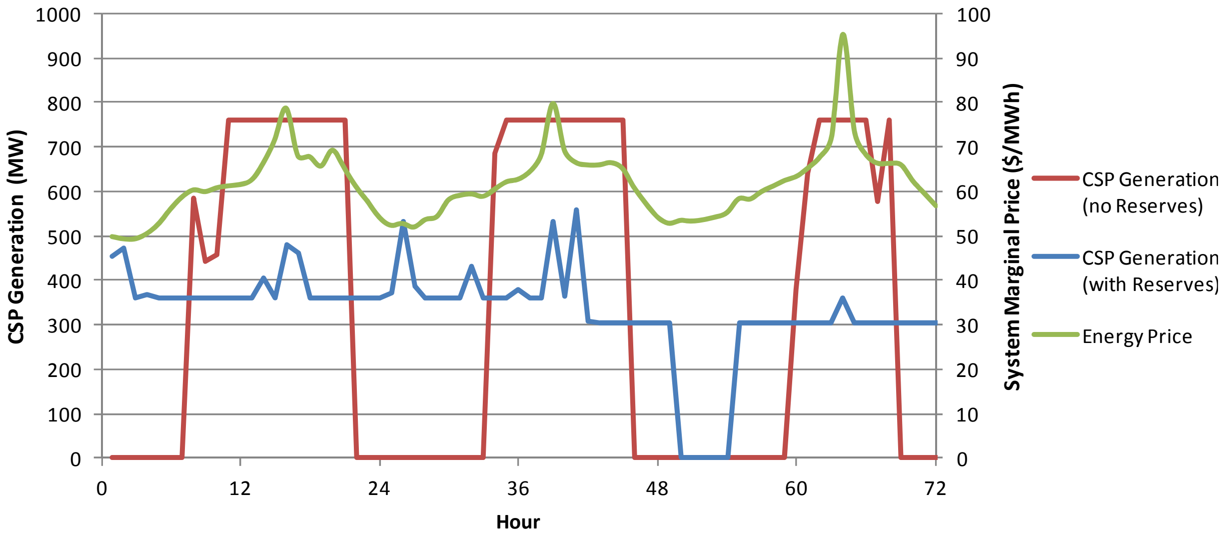
- Much more part-load operation
  - Plant without reserves operates at full output during about 66% of on-line hours
  - Plant providing reserves operates at full output during about 11% of on-line hours
- Stays on line longer
  - 25% fewer starts
- Operates at lower output even when price is high

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



Operation with Reserves

Hour	SCE Energy Marginal Price ($/MWh)	CSP Energy-Only Dispatch (MW)	**Energy-Only Value ($K)**	CSP Energy Dispatch w/Reserves (MW)	Energy Value w/Reserve Dispatch ($K)	CAISO Avg. Reserve Price ($/MWh)	CSP Up Reserve Dispatch (MW)	Reserve Value ($K)	**Total Value with Reserves ($K)**
1	49.8	-	-	453	22.5	8.9	309	2.8	25.3
2	49.3	-	-	474	23.3	5.5	288	1.6	24.9
3	49.3	-	-	359	17.7	13.4	403	5.4	23.1
4	50.5	-	-	368	18.6	6.0	394	2.4	21.0
5	52.6	-	-	359	18.9	11.8	403	4.7	23.6
6	55.9	-	-	359	20.1	15.3	403	6.2	26.2
7	58.6	-	-	359	21.0	9.6	403	3.9	24.9
8	60.3	585	35.2	359	21.6	19.4	403	7.8	29.5
9	59.9	444	26.6	359	21.5	19.0	403	7.7	29.2
10	60.7	459	27.9	359	21.8	19.9	403	8.0	29.8
11	61.2	762	46.6	359	22.0	20.3	403	8.2	30.1
12	61.5	762	46.9	359	22.1	20.6	403	8.3	30.4
13	62.5	762	47.6	359	22.4	21.6	403	8.7	31.1
14	66.2	762	50.4	406	26.8	25.4	356	9.0	35.9
15	71.5	762	54.5	359	25.7	21.7	403	8.7	34.4
16	78.6	762	59.9	481	37.8	28.1	281	7.9	45.7
17	68.0	762	51.8	460	31.3	17.3	302	5.2	36.5
18	67.8	762	51.6	359	24.3	17.2	403	6.9	31.3
19	65.6	762	50.0	359	23.6	14.9	403	6.0	29.6
20	69.2	762	52.7	359	24.8	20.1	403	8.1	32.9
21	65.2	762	49.7	359	23.4	15.5	403	6.2	29.6
22	61.0	-	-	359	21.9	20.2	403	8.1	30.1
23	57.7	-	-	359	20.7	16.9	403	6.8	27.5
24	54.2	-	-	359	19.4	13.7	403	5.5	25.0
Total		**9,870**	**651.4**	**9,103**	**553.3**		**9,185**	**154.3**	**707.6**

Provision of reserves + energy generates more revenue than only energy
(even with less energy sales on this day)

Avoided Fuel

	Avoided Fuel per Unit of Delivered Energy (MMBtu/MWh)			
	Flat Block	PV	CSP (no Reserves)	CSP (with Reserves)
Coal	2.7	3.5	2.0	-0.6
Gas	5.3	4.3	6.2	9.7
Total	8.0	7.8	8.2	9.1

Operational value produced by different generator types in the CAISO "Environmentally Constrained" scenario

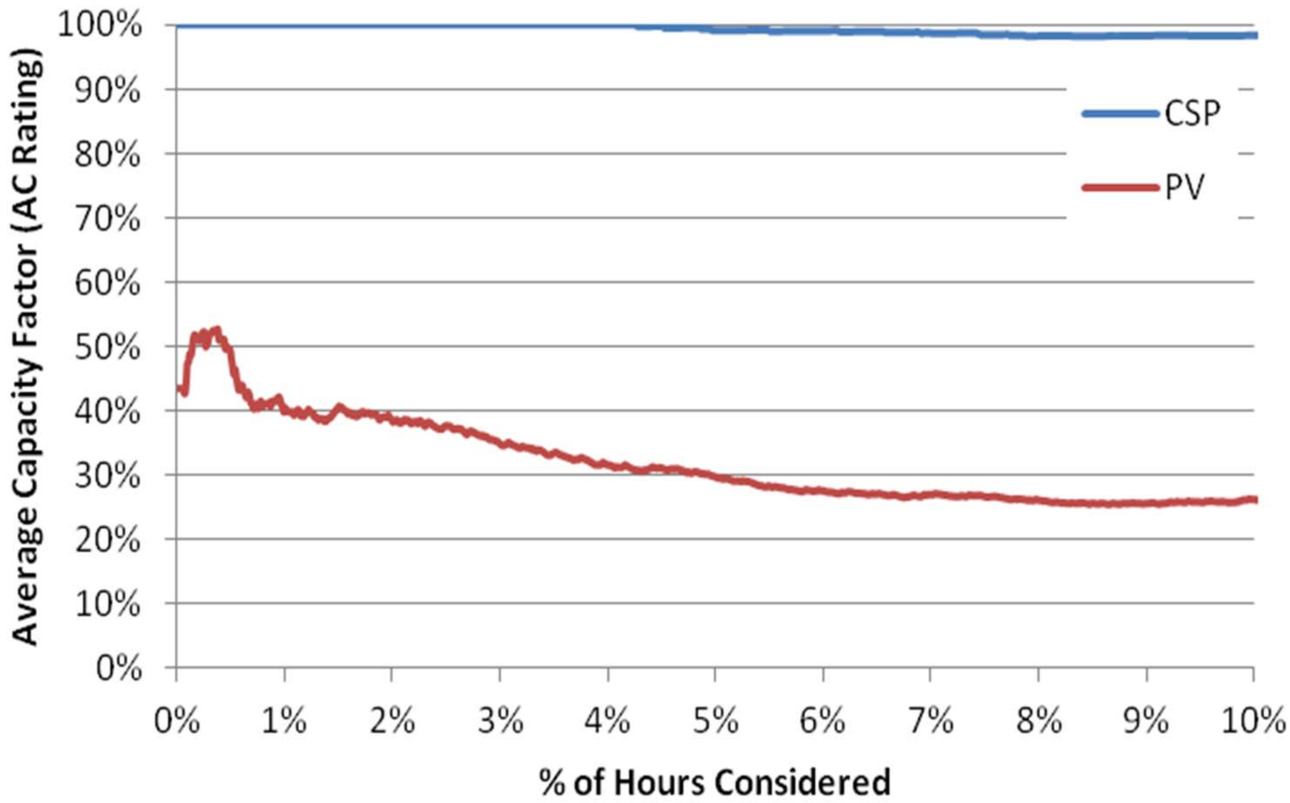
Total Operational Value

	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

	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

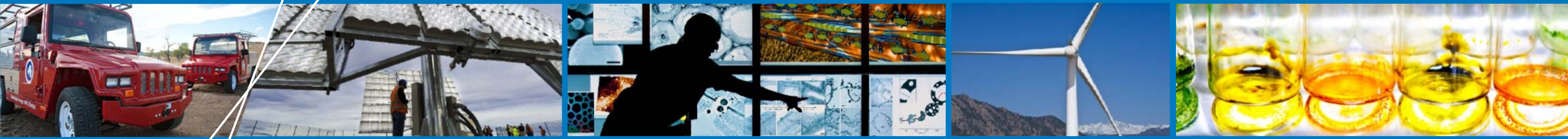
	Difference in Value per Unit of Delivered Energy for a CSP Plant Providing Reserves ($/MWh)		
	Baseload	PV	CSP (no Reserves)
Fuel	20.1	24.9	15.1
Variable O&M	1.3	1.6	0.8
Start	4.6	7.0	2.7
Emissions	-3.6	-4.4	-1.8
Capacity (Low / High)	7.3 / 20.8	2.8 / 8.1	0 / 0
Total (Low / High)	29.8 / 50.6	32.0 / 40.1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

Limitations and Next Steps

- Need to simulate dry-cooled towers
- Different CSP 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 was successfully implemented in a commercial simulation and planning tool
- To avoid the highest cost generation, simulated CSP plants shifted generation to the morning and evening in non-summer months and toward the end of the day in summer months
- CSP plants were dispatched during periods of highest net load, resulting in very high capacity value
- The difference in value in plants with and without storage is highly dependent on the penetration of other renewable energy sources, such as wind and PV



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