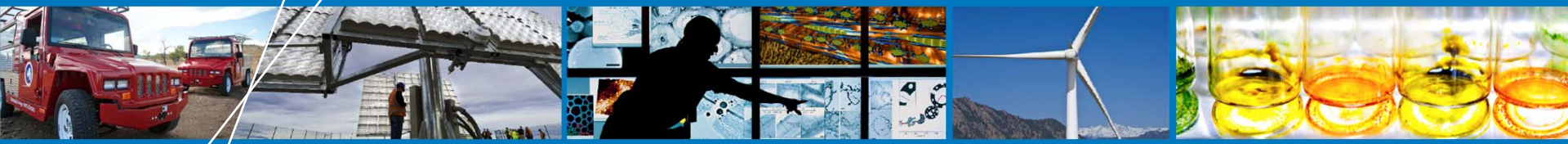
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Summary of:

Simulating the Value of Concentrating Solar Power with Thermal Energy Storage in a Production Cost Model



Paul Denholm

Marissa Hummon

November 2012

NREL/PR-6A20-57376

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.

Motivation

- Implement CSP with thermal energy storage (TES) in a commercial production cost model
- Evaluate the optimal dispatch of CSP with TES
  - How would a plant actually be used to minimize system production cost?
- Quantify the value of CSP w/TES under scenarios of low and high penetrations of variable wind and PV

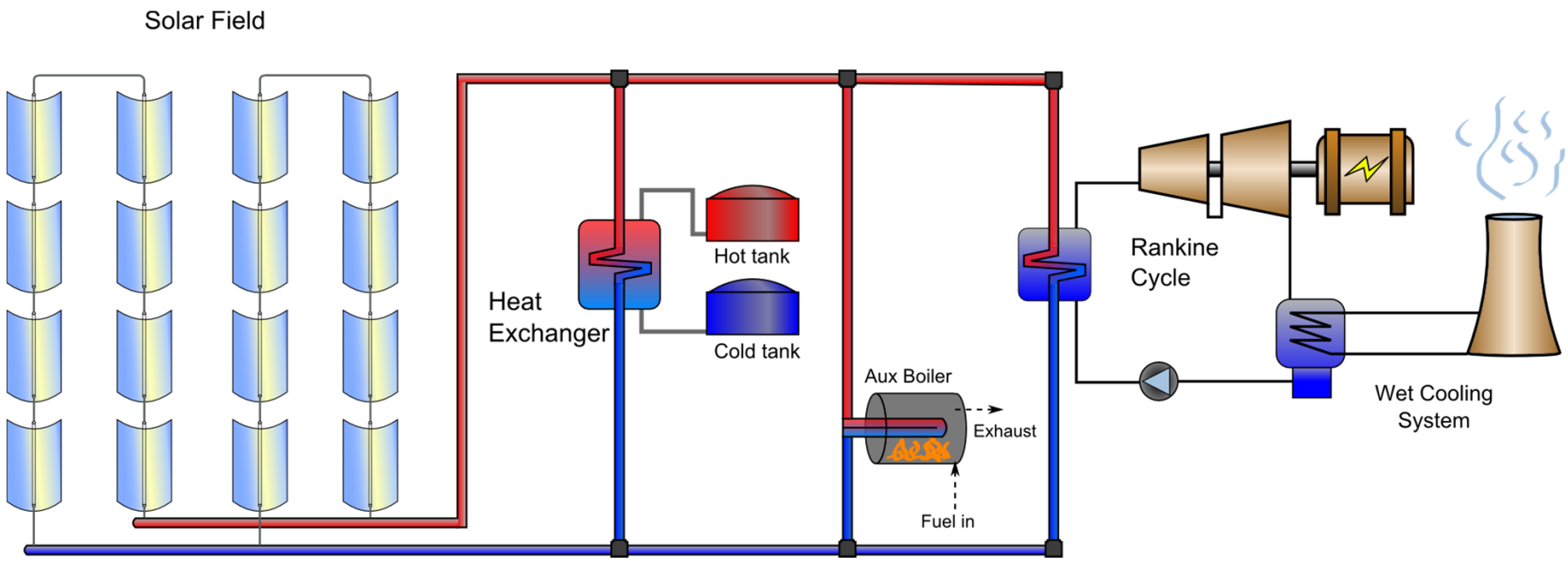
Analytic Approaches

- Price-Taker
  - Simulates a relatively small CSP plant that does not affect prices
  - Dispatch 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 be used to simulate future grid mixes
  - Can evaluate interaction of CSP with the grid
  - Can be costly and time consuming to develop and implement

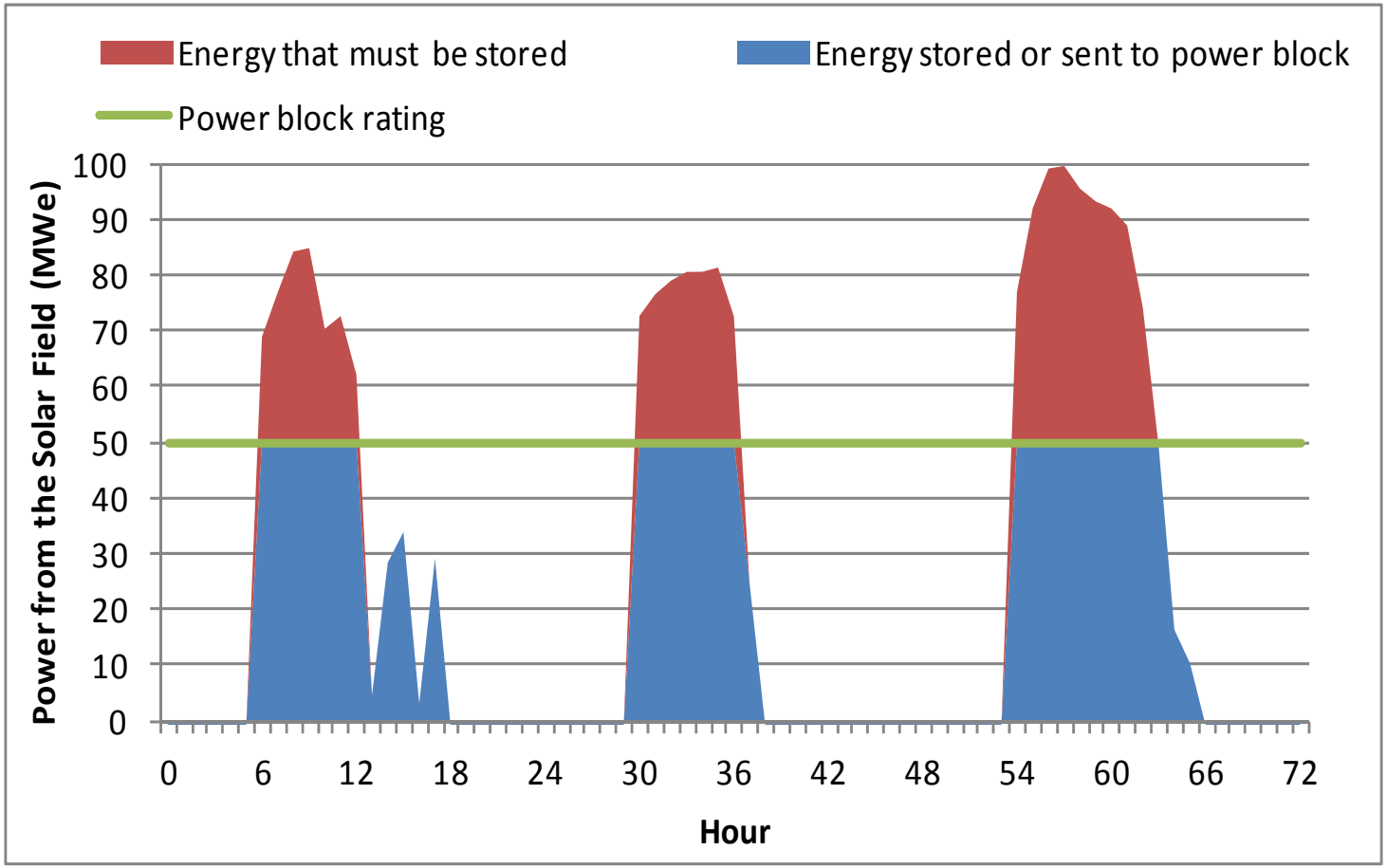
Previous Simulations of CSP in Grid Models

- GridView Simulations in RE Futures/Solar Vision Studies (NREL 2012 and DOE 2012)
  - Demonstrated qualitatively the value of dispatchability
- Mills & Wiser 2012
  - Used a reduced form dispatch of CSP in the California grid

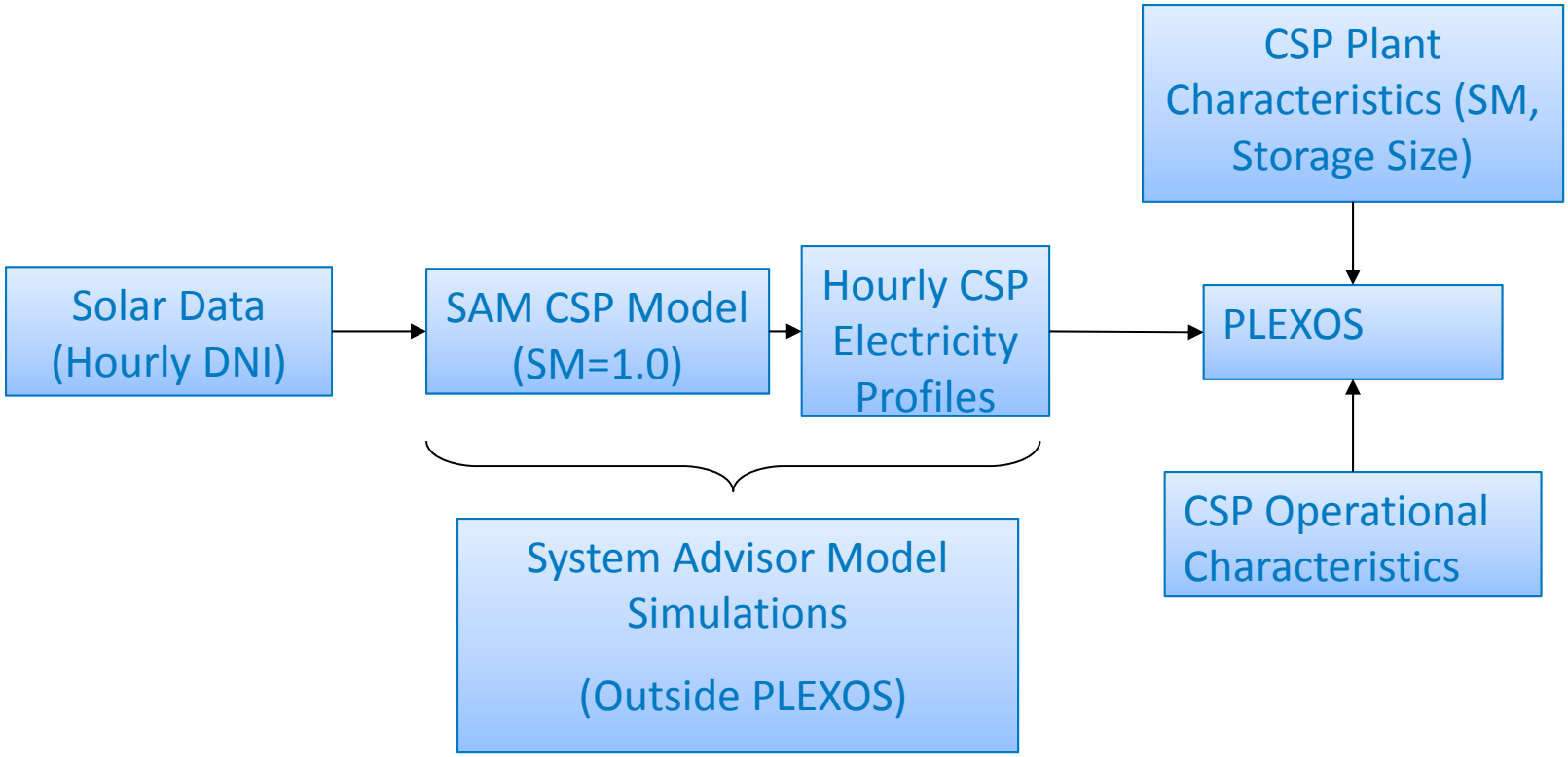
CSP with TES


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

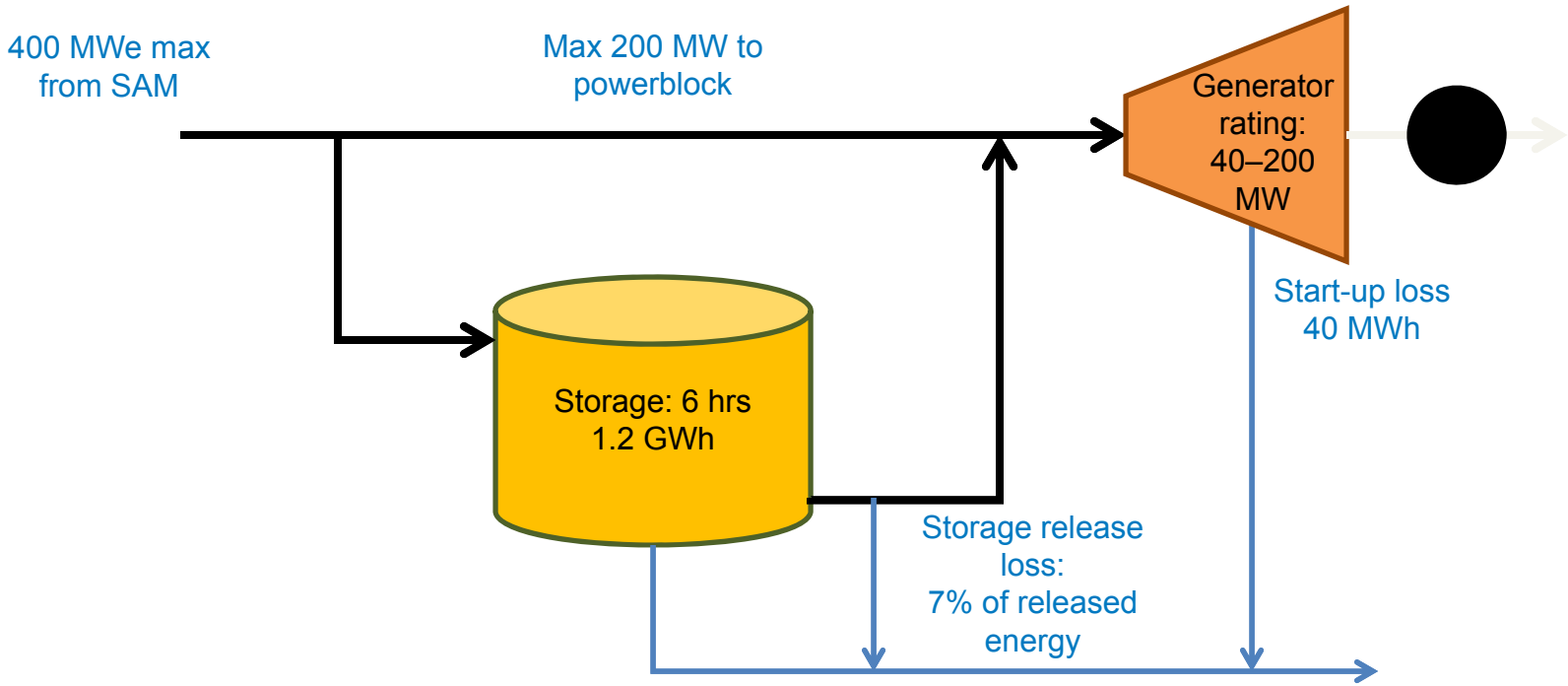
Importance of Solar Multiple



Implementation of CSP w/TES in PLEXOS



CSP Example Characteristics



Summary of analyzed system:

- Trough Plant
- Wet Cooled
- SM = 2.0
- 6 hours of storage (at discharge rating)

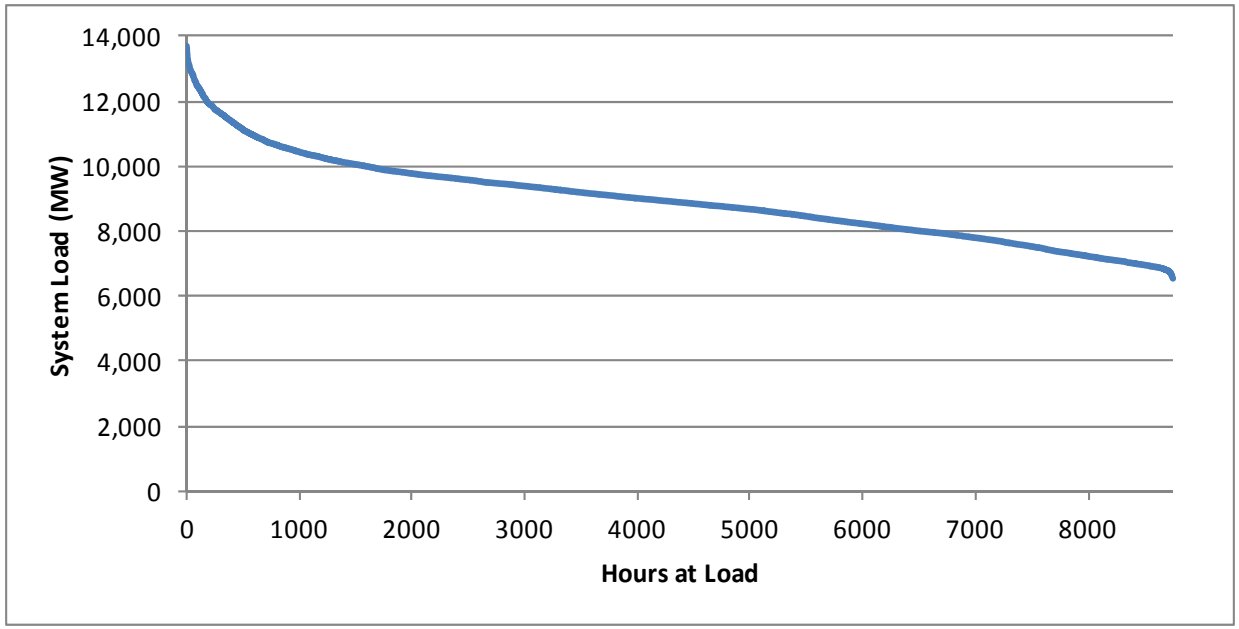
Base System Characteristics

- Used publicly available data from Transmission Expansion Policy Planning Committee (TEPPC) 2020 model
- Data includes plant capacities, heat rates, outage rates (planned and forced), and several operational parameters, such as ramp rates
- Generator database was modified to include part-load heat rates based on Western Wind and Solar Integration Study Phase II (WWSIS II) study
- Total of 201 thermal and hydro generators
- Start-up costs were added using the start-up fuel requirements in the generator database plus the operations and maintenance (O&M) related costs based on estimates prepared for the WWSIS II study
- Adjusted the generator mix to achieve a generator planning reserve margin of 15% by adding a total of 1,450 MW (690 MW of combustion turbines and 760 MW of combined cycle units)

Base System 2020 Characteristics

Generator Characteristics

	System Capacity (MW)
Coal	6,178
Combined Cycle (CC)	3,724
Gas Turbine/Gas Steam	4,045
Hydro	773
Pumped Storage	560
Other	513
Total	15,793



2020 load duration curve
Peak demand of 13.7 GW
Annual demand of 79.0 TWh

Scenarios

- 2 Scenarios – Low RE and high RE
  - Low RE case – 13% energy from wind and solar
  - High RE case – 35% energy from wind and solar

System Capacity (MW)		
	Low RE Scenario	High RE Scenario
Wind Capacity (MW)	3,054	6,489
Wind Energy (GWh)	9,791	20,210
Solar Capacity (MW)	395	3,630
Solar Energy (GWh)	625	6,493

Reserves & Fuel Prices

- Three classes of ancillary service requirements were included (Contingency, Regulation, Flexibility)
  - Contingency based on existing single largest contingency
  - Regulation and flexibility requirements based on variation of net load using WWSIS II methods

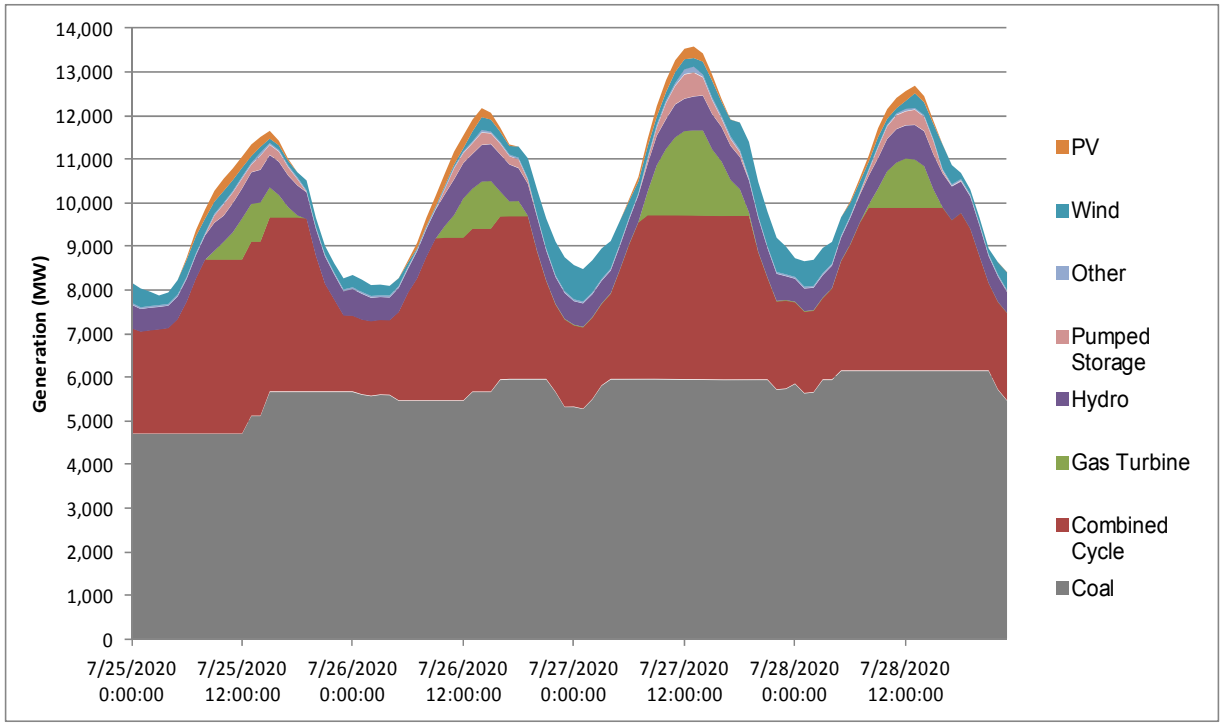
- Fuel prices were derived from the TEPPC 2020 database.
  - Coal prices were $1.42/MMBTU for all plants
  - Natural gas prices varied by plant, generation weighted average of $4.1/MMBTU.
  - Sensitivity to natural gas price was also analyzed

Base Case (no CSP) Results

	Low RE	High RE
Total Production Cost (M$)	1,491.37	1,024.38
Average Production Cost ($/MWh)	18.9	13.0
Total Generation (GWH)	78,957	79,098
Generation Mix		
Coal	58.8%	52.0%
Gas Combined Cycle (CC)	20.7%	7.2%
Gas Combustion Turbine (CT)/Gas Steam	1.4%	1.1%
Hydro	4.8%	4.8%
Wind	12.4%	25.5%
Solar PV	0.8%	8.2%
Other	1.1%	1.2%
Fuel Use (1,000 MMBTU)		
Coal	490,923	434,426
Gas	140,447	53,928

Base System Low RE Summer Dispatch

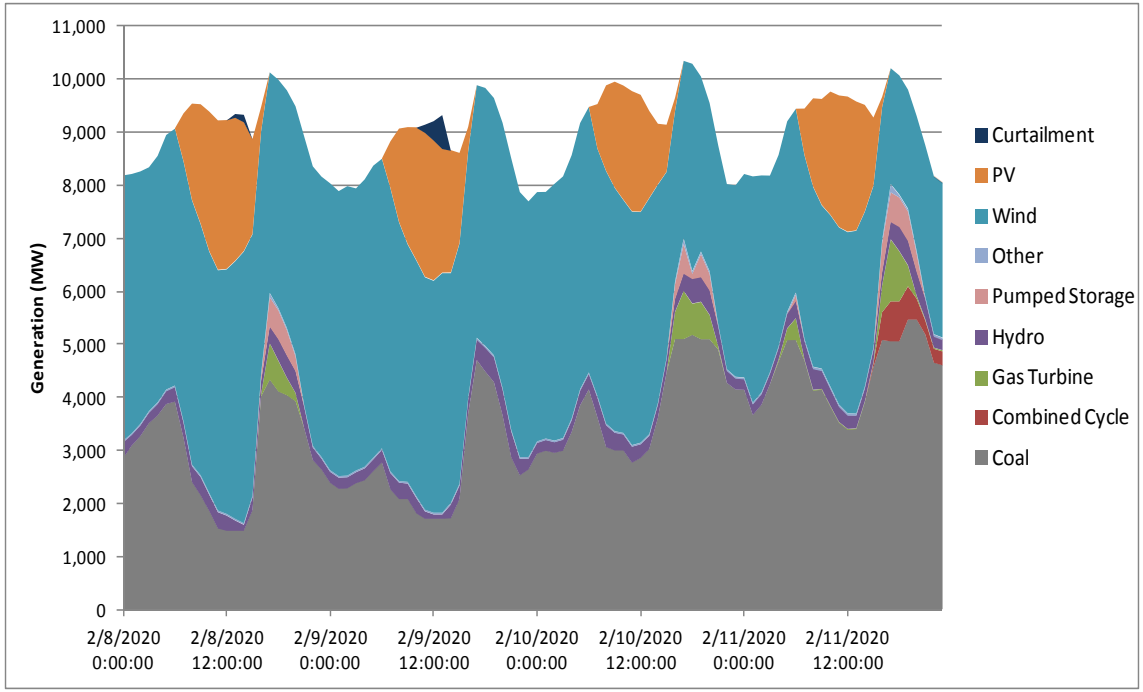
- PV has high capacity value
- Displaces highest cost generators



Dispatch stack during the period of July 25–28 in the low RE Case

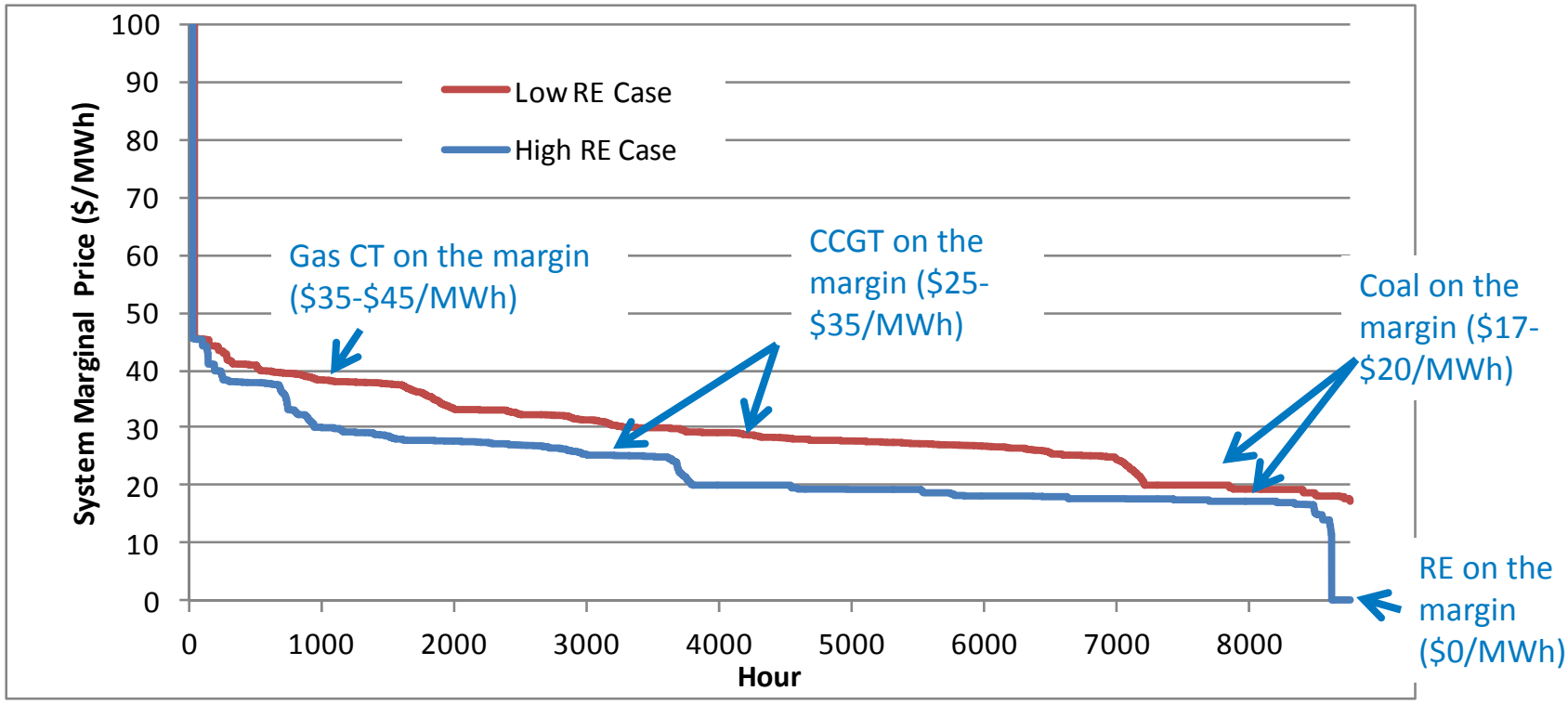
Base System High RE Winter Dispatch

- PV has low capacity value
- Wind and solar displace a greater amount of low cost coal
- Some mid-day curtailment
- Ramp rates of net load increases substantially



Dispatch stack during the period of February 8-11 in the high RE Case

Marginal Dispatch Costs



System marginal price duration curve in the PSCO balancing area for the two cases

CSP Scenarios

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

1. CSP plant with 6 hours of storage
   - 300 MW, SM=2.0
   - Generates about 1,070 GWh, or enough to provide about 1.4% of the test system demand
2. CSP no storage
   - 568-MW, SM = 1.3
3. Solar PV
   - About 580 MW, 1-axis tracking.
   - This plant also required additional reserves due to uncertainty and variability
4. Flat block (baseload) resource.
   - 123 MW of constant output with zero fuel costs

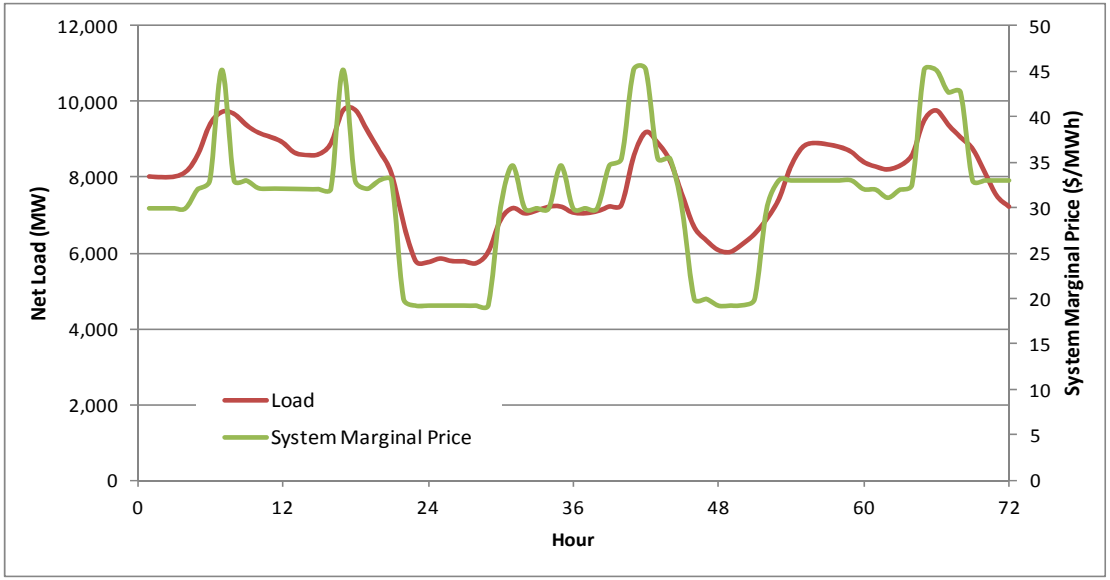
Operational Value Results

PLEXOS generates three sources of costs for system operation:

1. Operational fuel
2. Variable O&M
3. Startup (fuel + start O&M)

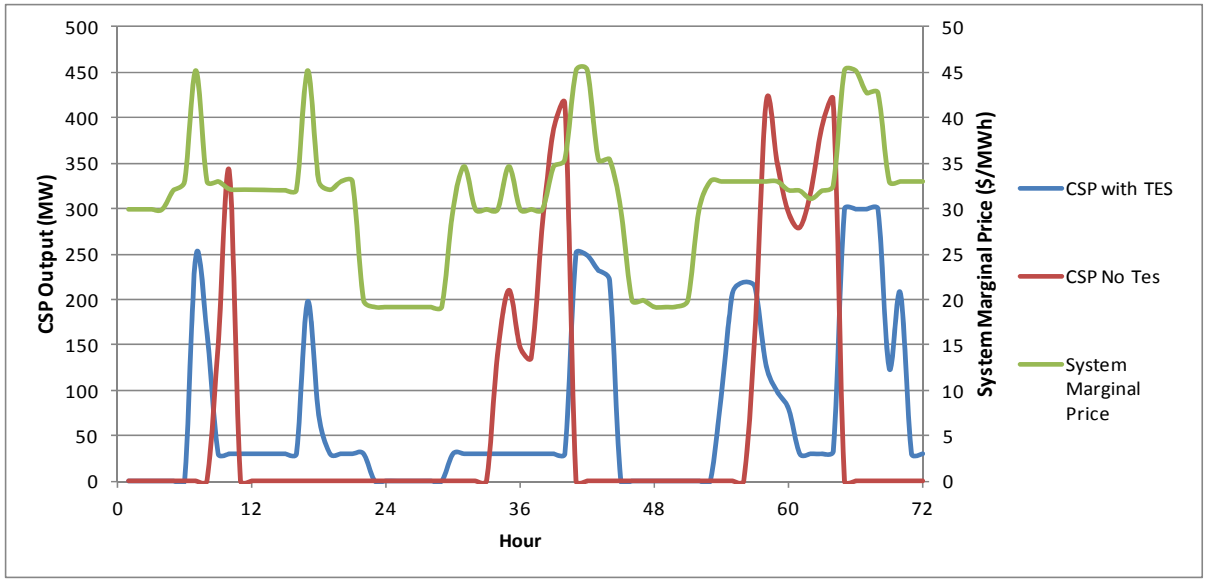
Examining dispatch can explain the origin and differences of these costs.

January Price and Dispatch – Low RE Case



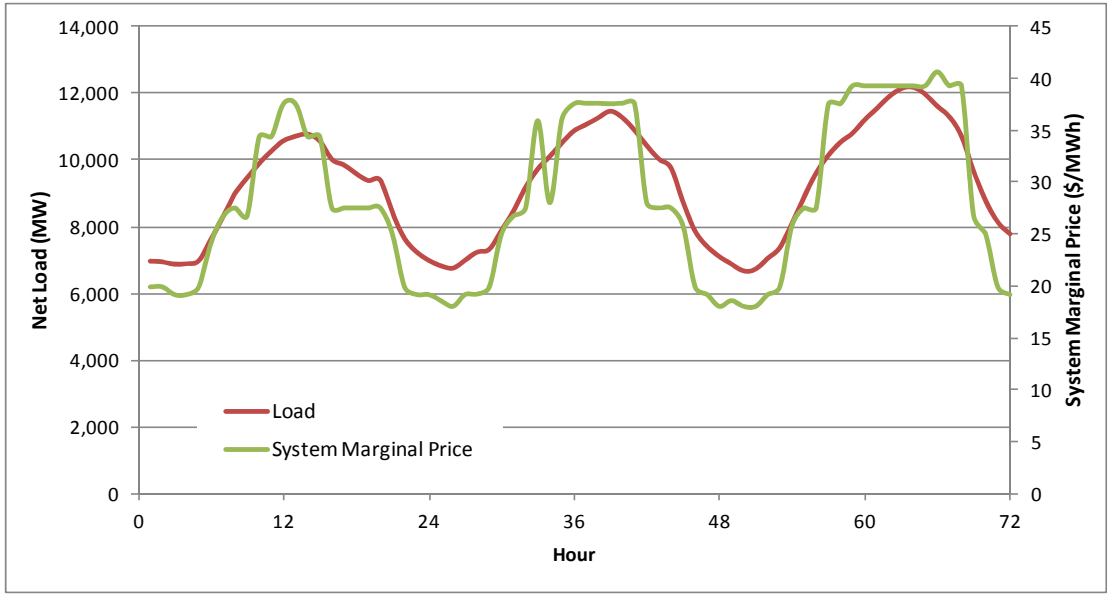
System net load and marginal price for January 22–24

System marginal price and corresponding CSP generation on January 22–24



- CSP dispatched to periods of highest price

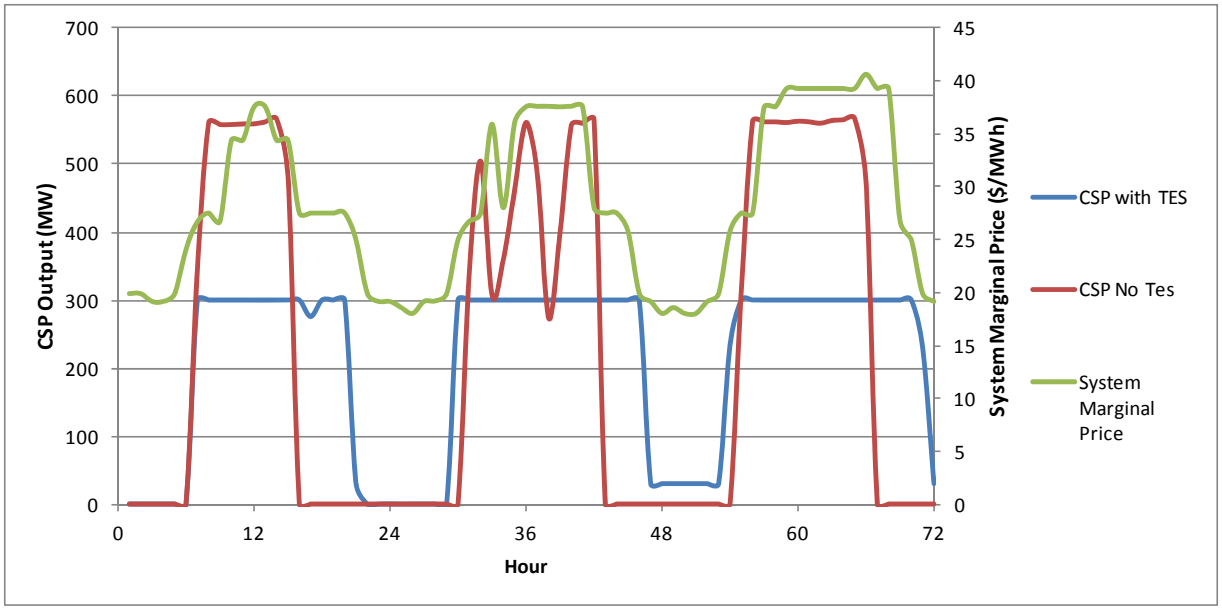
July Price and Dispatch – Low RE Case



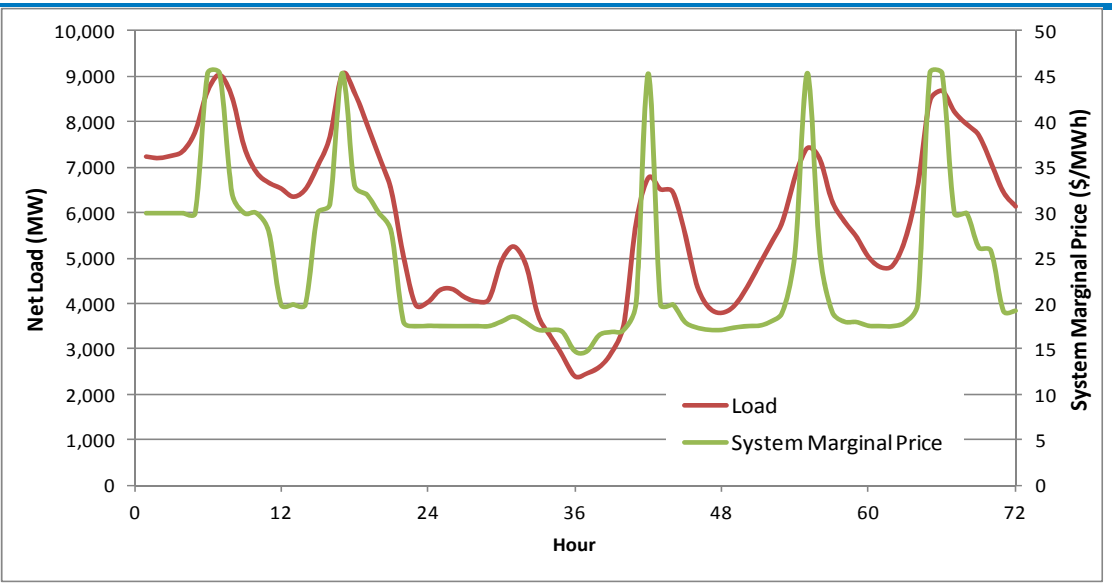
System net load and marginal price for July 14–16

System marginal price and corresponding CSP generation on July 14–16

- At low RE penetration CSP w/o storage is largely coincident with periods of high demand and high price

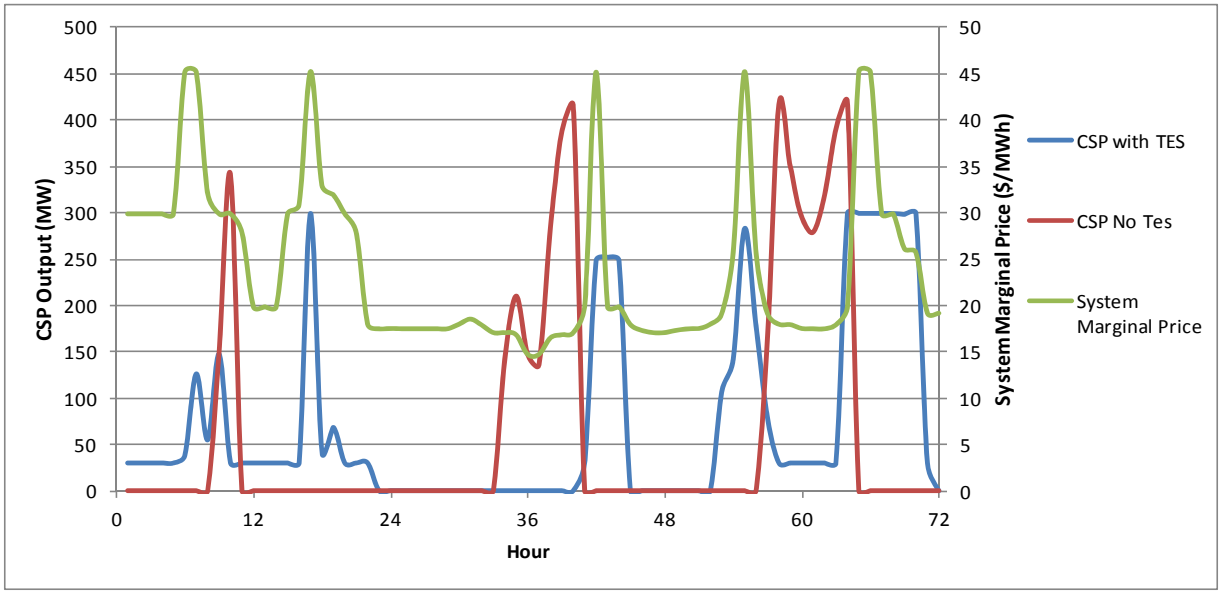


January Price and Dispatch – High RE Case



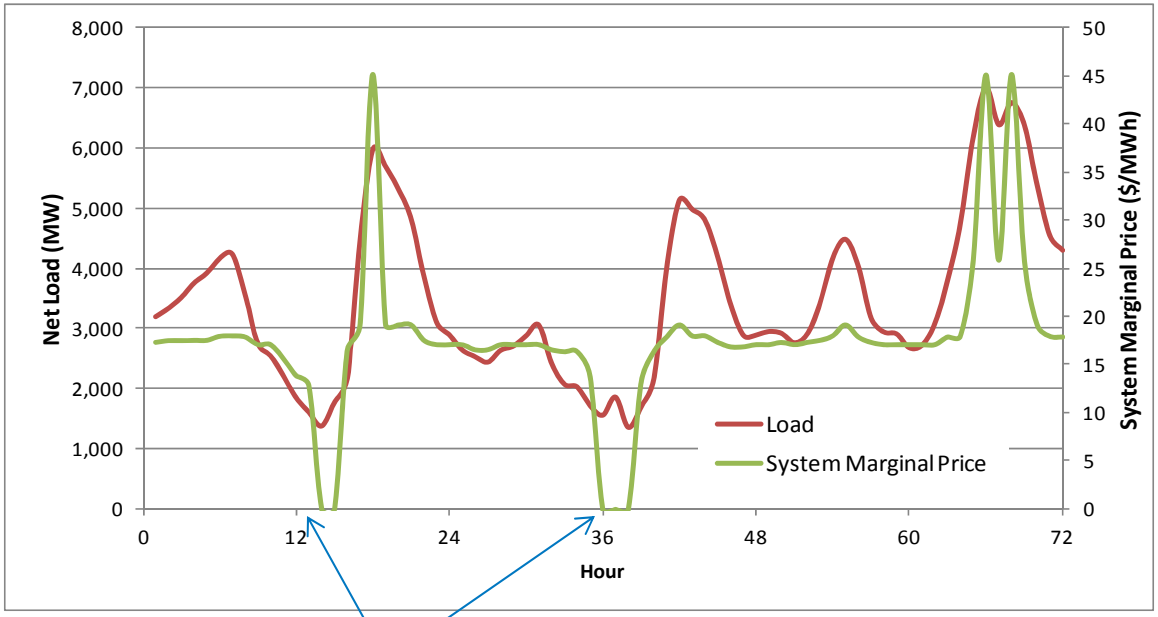
System net load and marginal price for January 22–24

System marginal price and corresponding CSP generation on January 22–24



- RE has suppressed marginal prices. Prices are more volatile due to variability

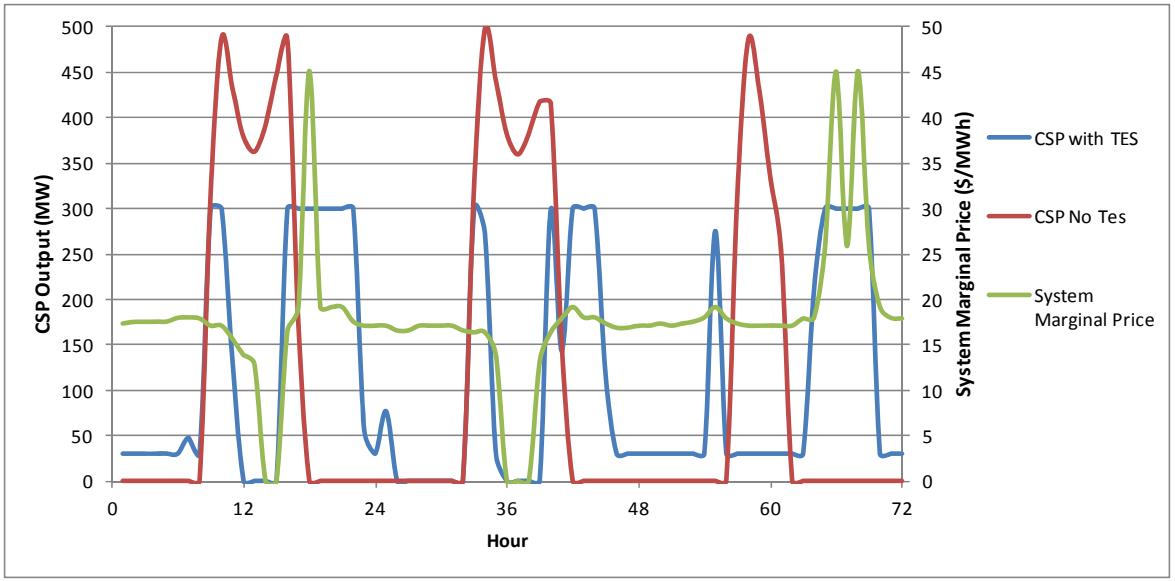
Curtailment in High RE Case



System net load and marginal price for Feb 8-10

Marginal price is zero

System marginal price and corresponding CSP generation on Feb 8-10



- About 5% of the additional PV and about 6% of the CSP without storage has zero value and is effectively curtailed

Avoided Generation

Avoided Thermal Generation (kWh/kWh)								
	Low RE Scenario				High RE Scenario			
	Flat Block	PV	CSP (no TES)	CSP (6-hr TES)	Flat Block	PV	CSP (no TES)	CSP (6-hr TES)
Coal	0.09	-0.06	-0.03	-0.08	0.55	0.50	0.52	0.17
Gas Combined Cycle	0.78	0.99	0.91	0.79	0.39	0.50	0.39	0.72
Gas Turbine/ Steam	0.10	0.09	0.11	0.27	0.05	-0.02	-0.01	0.11
Total	0.98	1.03	1.00	1.02	0.99	0.97	0.90	1.04

Avoided generation may not equal 1.00 due to curtailment and changes in pumped storage operation

Effect of curtailment

Avoided Fuel

Avoided Fuel (MMBTU/MWh)								
	Low RE Scenario				High RE Scenario			
	Flat Block	PV	CSP (no TES)	CSP (6-hr TES)	Flat Block	PV	CSP (no TES)	CSP (6-hr TES)
Coal	1.1	-0.7	-0.7	-0.9	5.8	5.2	5.4	1.9
Gas	7.4	8.9	8.9	9.7	3.5	3.6	2.9	7.1
Total	8.5	8.2	8.2	8.8	9.3	8.8	8.3	9.0

Able to displace more gas

Higher avoided fuel rate due to greater displacement of coal

Avoided Starts

Avoided Starts (Total/%)								
	Low RE Scenario				High RE Scenario			
	Flat Block	PV	CSP (no TES)	CSP (6-hr TES)	Flat Block	PV	CSP (no TES)	CSP (6-hr TES)
Coal	3/ 0.4%	-1/ -1.1%	-5/ -0.7%	-8/ -1.1%	-16/ -2.2%	4/ 0.6%	-3/ -0.4%	-18/ -2.5%
Combined Cycle	-77/ -6.3%	18/ 1.5%	53/ 4.3%	56/ 4.6%	9/ 1.2%	17/ 2.2%	-56/ -7.2%	129/ 16.5%
Gas Turbine/ Steam	362/ 4.6%	-412/ -5.2%	-271/ -3.4%	1,099/ 13.8%	432/ 4.1%	-640/ -6.1%	-361/ -3.4%	871/ 8.3%

Reduction in starts due to dispatchability

Total Operational Value

Production Value ($/MWh)								
	Low RE				High RE			
	Flat Block	PV	CSP (no TES)	CSP (6-hr TES)	Flat Block	PV	CSP (no TES)	CSP (6-hr TES)
Fuel	31.7	35.2	33.9	37.7	22.6	21.2	18.7	31.1
Variable O&M	1.2	1.0	1.0	0.8	2.1	2.0	1.9	1.4
Start	0.4	0.4	0.6	3.5	0.5	-0.9	-1.7	3.1
Total	33.3	36.6	35.5	42.1	25.2	22.3	18.9	35.6

Significant findings:

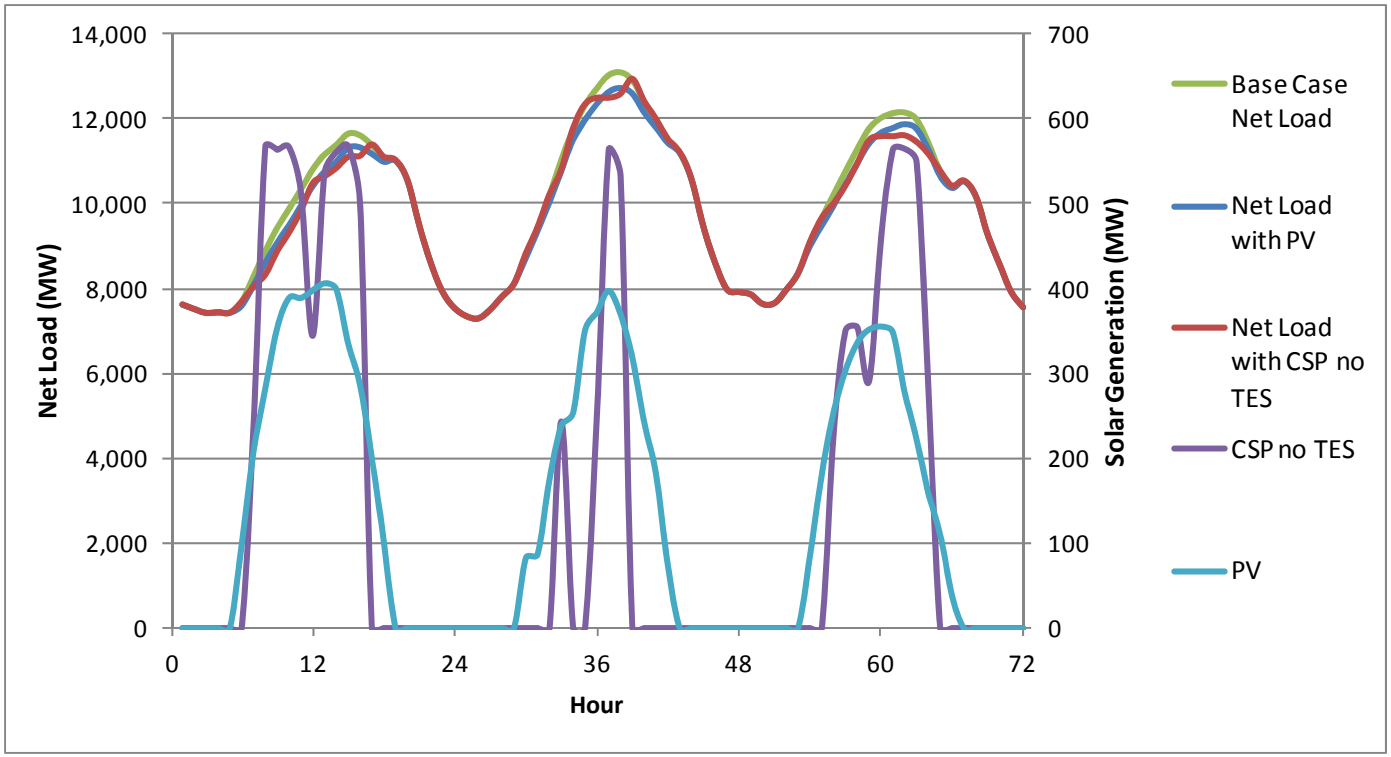
- At low penetration, the value of solar generation technologies is greater than the constant (flat block) resource
- The value of all generation decreases as a function of renewable penetration, but the value of non-dispatchable solar resources decreases at a greater rate than the flat block or dispatchable CSP
- The value of CSP with storage is higher than solar technologies without storage

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

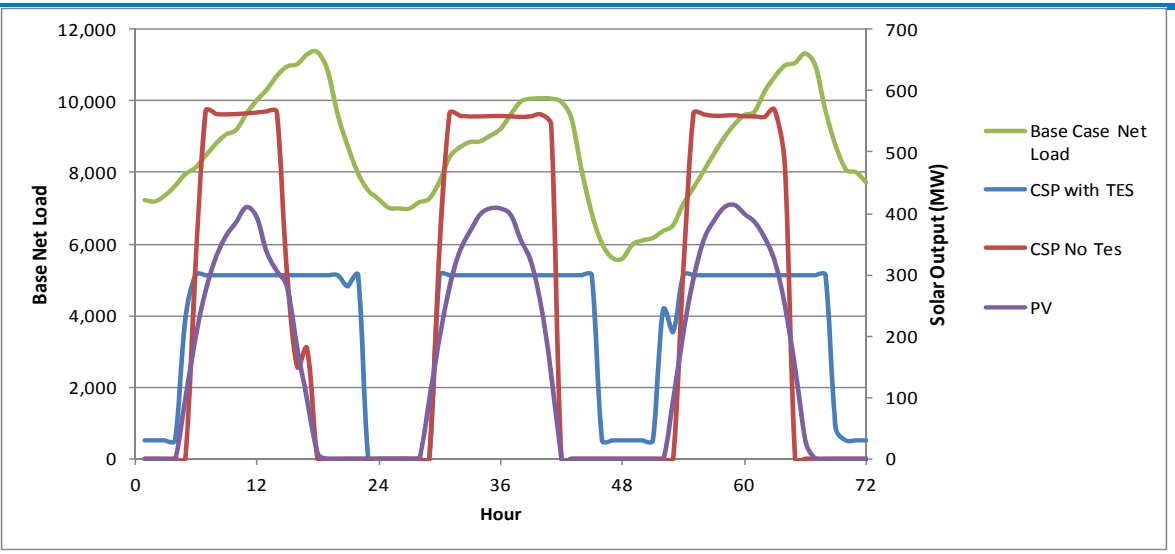
Capacity Value-Low RE

- At low penetration, the capacity credit of PV and CSP without TES is relatively high



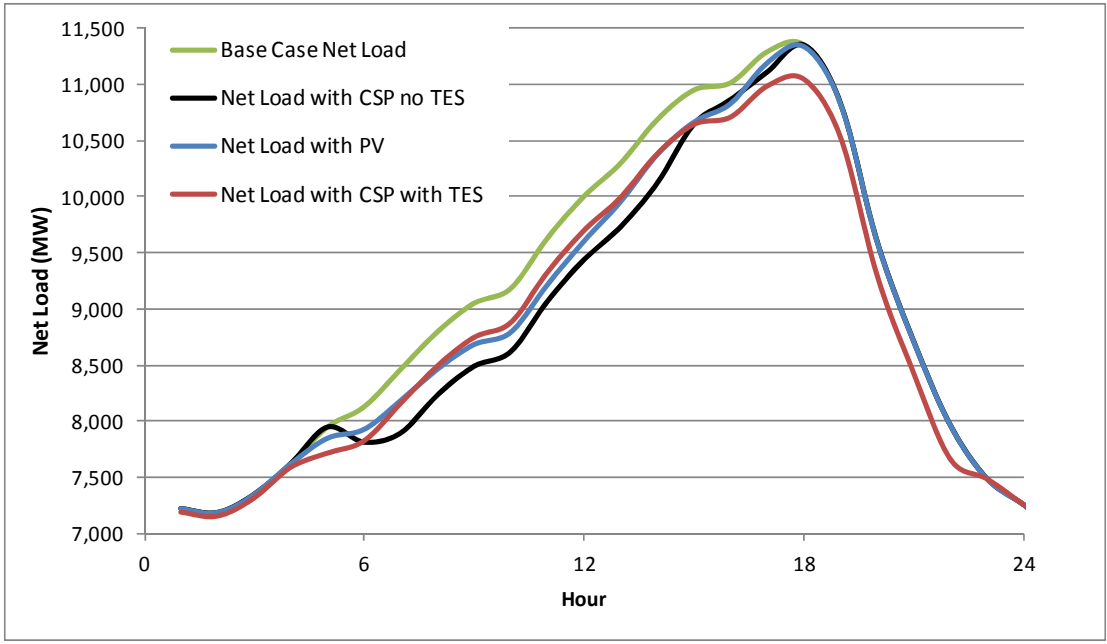
Correlation of demand and solar generation on a 3-day period starting July 26

Capacity Value –High RE Case



Correlation of demand and solar generation on a 3-day period starting July 17

Net demand with different solar generation types on July 17



- At high solar penetration the net load shifts to later and the capacity value of PV and or CSP decreases

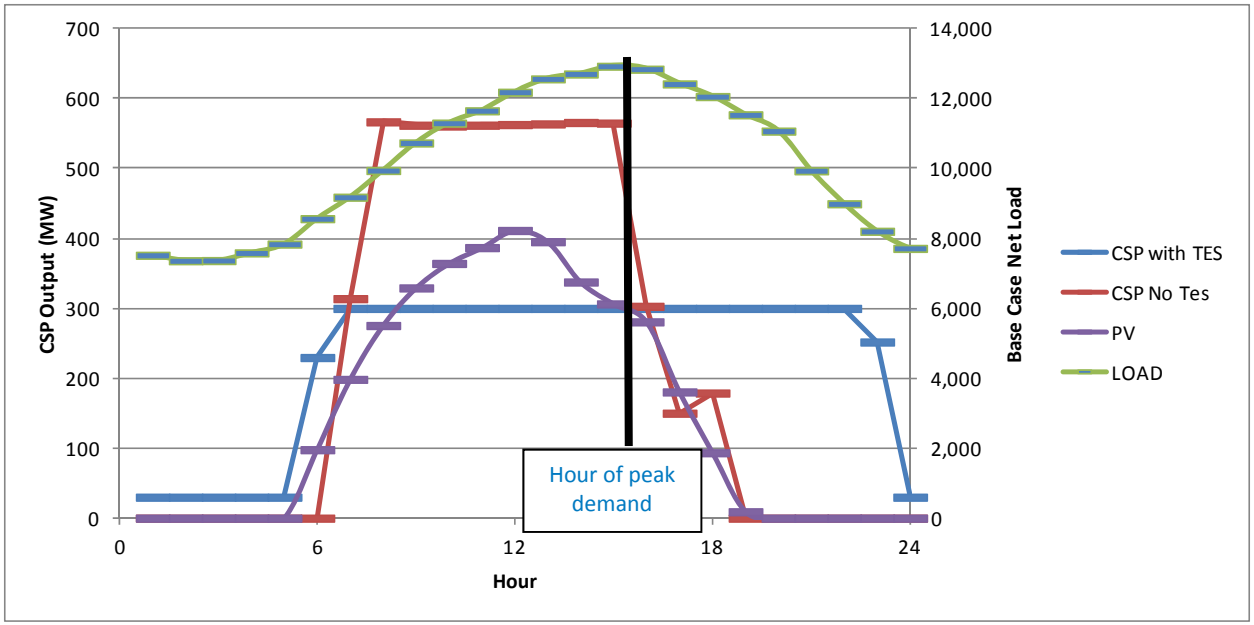
Capacity Value

	Low RE Scenario				High RE Scenario			
	Flat Block	PV	CSP (no TES)	CSP (6-hr TES)	Flat Block	PV	CSP (no TES)	CSP (6-hr TES)
Capacity Credit (%)	100	70	75	98	100	13	3	78
Capacity Value (Low/High) ($/kW)	77/147	54/103	58/110	76/144	77/147	10/19	3/5	60/115
Capacity Value (Low/High) ($/MWh)	8.8/ 16.8	29.7/ 56.6	29.1/ 55.3	21.2/ 40.4	8.8/ 16.8	5.3/ 10.1	1.3/ 2.4	17.1/ 32.6

"Low" case assumes the cost of new capacity is $77/kW-yr (about the cost of a gas CT)

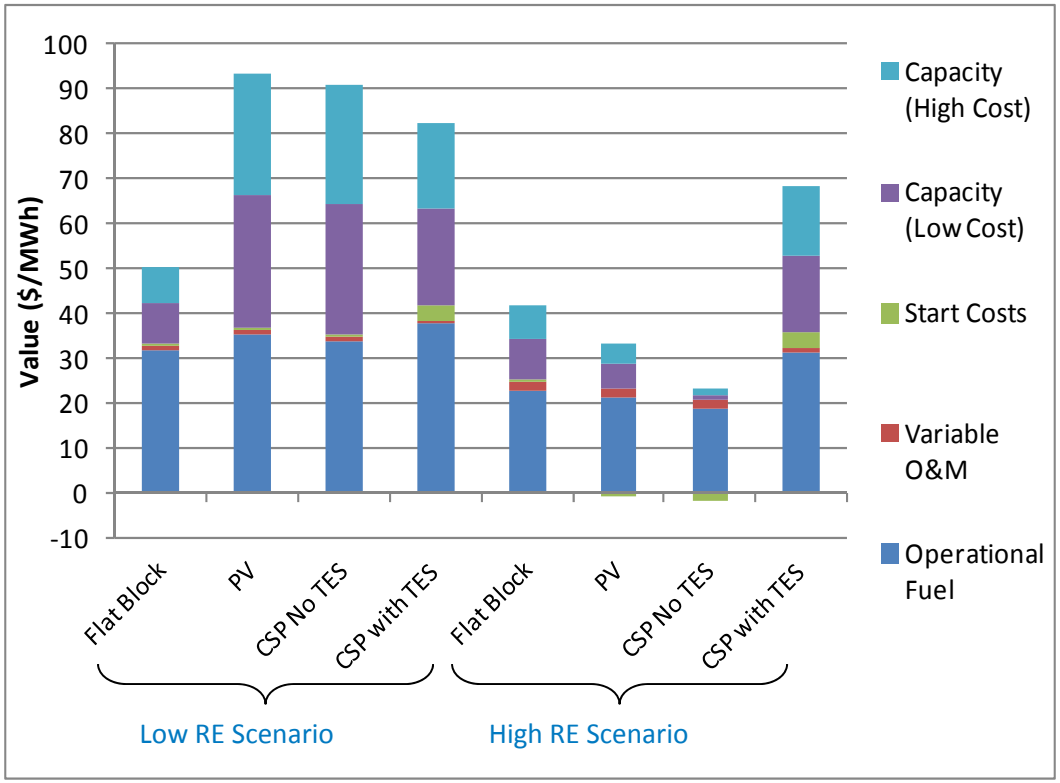
"High" case assumes the cost of new capacity is $147/kW-yr (about the cost of a gas CCGT)

Why can PV have higher capacity value than CSP?



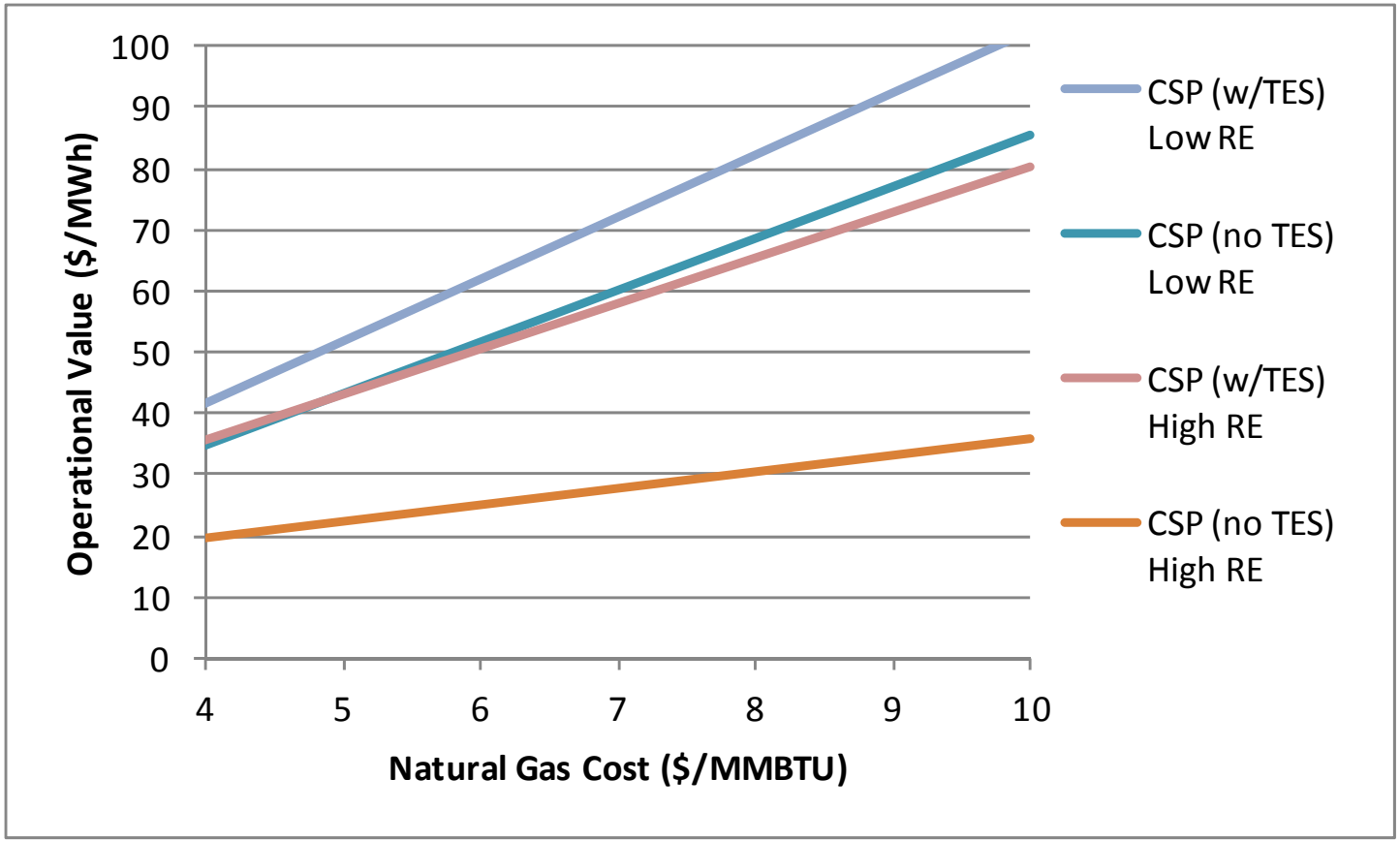
- PV can have a higher capacity value on a per unit of energy basis at low penetration due to the fact that CSP with storage and a SM>1 will have a lower power block rating.
  - In the low RE case, 300 MW of CSP w/TES with a 98% capacity value provides 294 MW of system capacity
  - 577 MW of PV with a 70% capacity value provides 404 MW
- This effect disappears in the high RE case where the capacity value of PV and CSP without storage is very low.

Total Operational and Capacity Value



Total value of generation sources in the test system

Sensitivity to Gas Prices



Gas cost is delivered price. Assumes no variation in price of coal.

Comparison to Previous Estimates

Previous Estimates of the Operational Value of CSP With and Without TES

Study Location	CSP Value ($/MWh)		Value Considered
	CSP (no TES)	CSP (with 6-hour TES)	
Arizona	47.0	50.5	Energy Only
New Mexico	61.2	66.2	Energy Only
California	58.5	67.9	Energy Only
Texas	89.4	98.4	Energy (with scarcity)
California	53.8 (energy)	56.3 (energy)	Energy + Capacity (Separate)

These studies used higher natural gas prices

When adjusting for gas price, results are similar to this study

Study Limitations

- This study did not evaluate the benefits of CSP providing ancillary services
- It did not simulation sub-hourly dispatch
- CSP plants are wet-cooled which over estimates performance in water restricted areas
- It did not consider tower-type CSP plants
- These issues will be considered in FY13

Conclusions

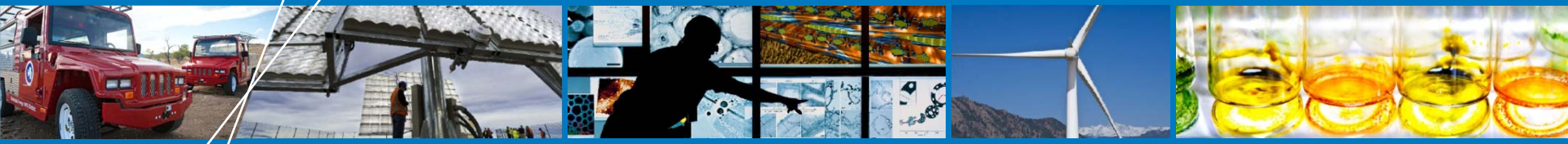
- CSP with thermal energy storage was successfully implemented in a commercial simulation and planning tool
- To avoid the highest cost generation, simulated CSP plants shifted generation to the morning and evening in non-summer months and toward the end of the day in summer months
- CSP plants were 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

Learn More

Download the full report at:
http://www.nrel.gov/docs/fy13osti/56731.pdf

Denholm, P.; Hummon, M. (2012). *Simulating the Value of Concentrating Solar Power with Thermal Energy Storage in a Production Cost Model*. TP-6A20-56731. Golden, CO: National Renewable Energy Laboratory.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



Contacts:

Paul Denholm (paul.denholm@nrel.gov)

Marissa Hummon (marissa.hummon@nrel.gov)