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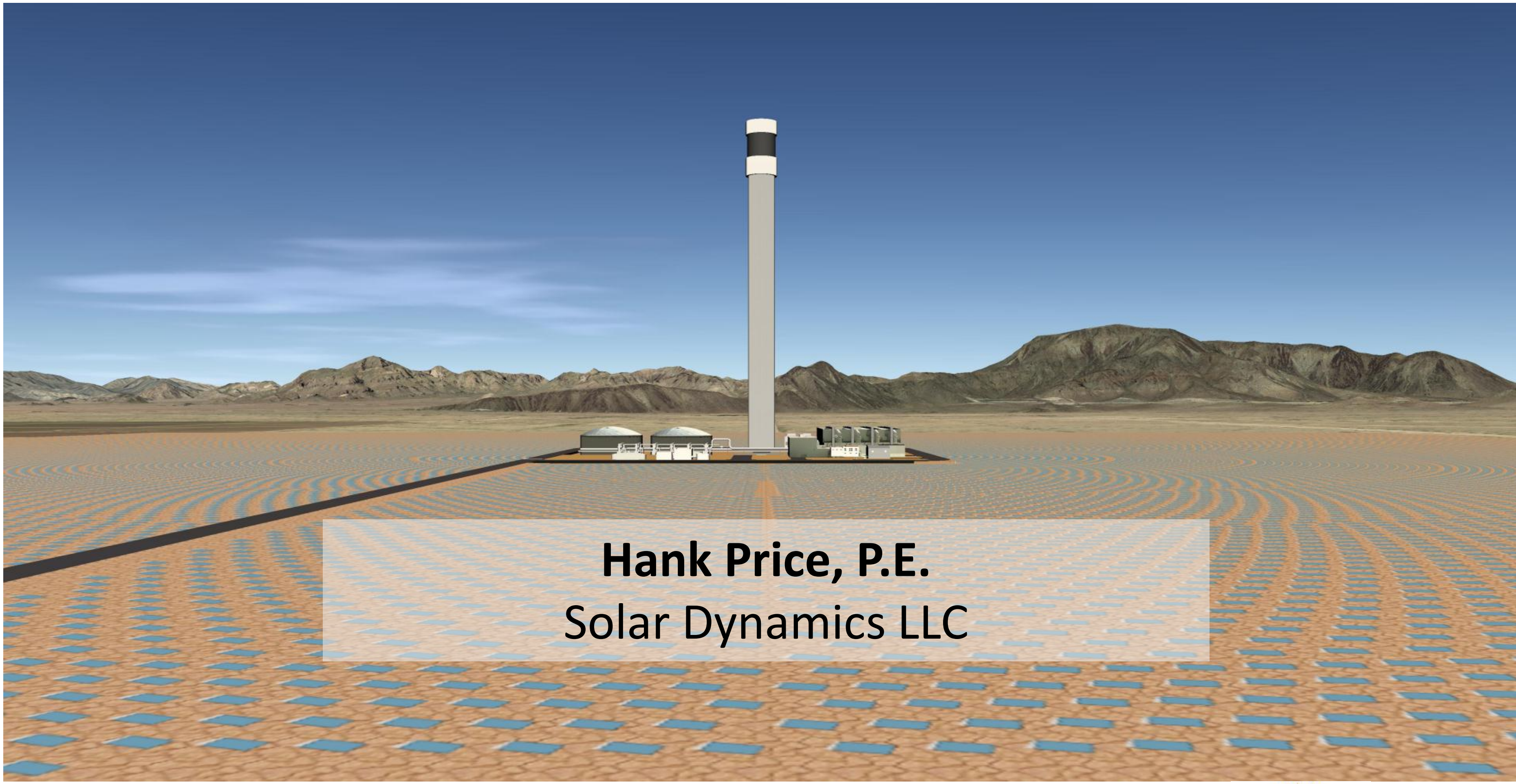
Dispatchable Solar Power: Adapting CSP to modern grid needs



Hank Price, P.E.

Solar Dynamics LLC

Sargent & Lundy

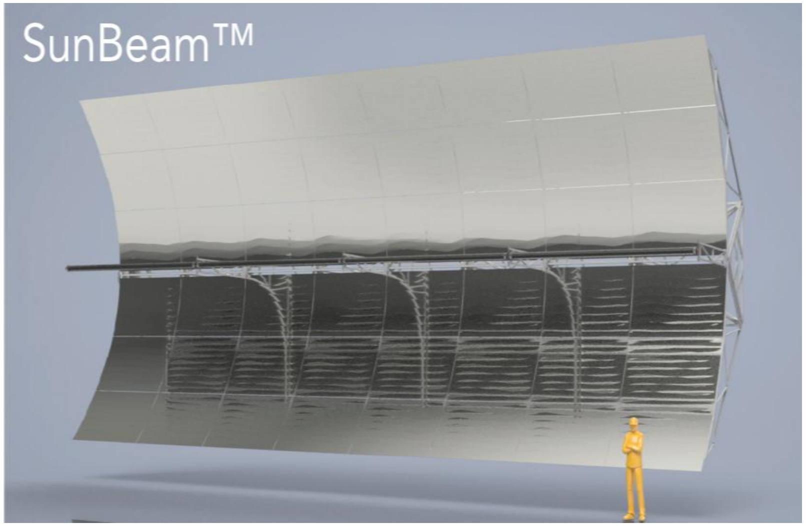
Morse Associates

BlüNebü

K&A

Who is Solar Dynamics?

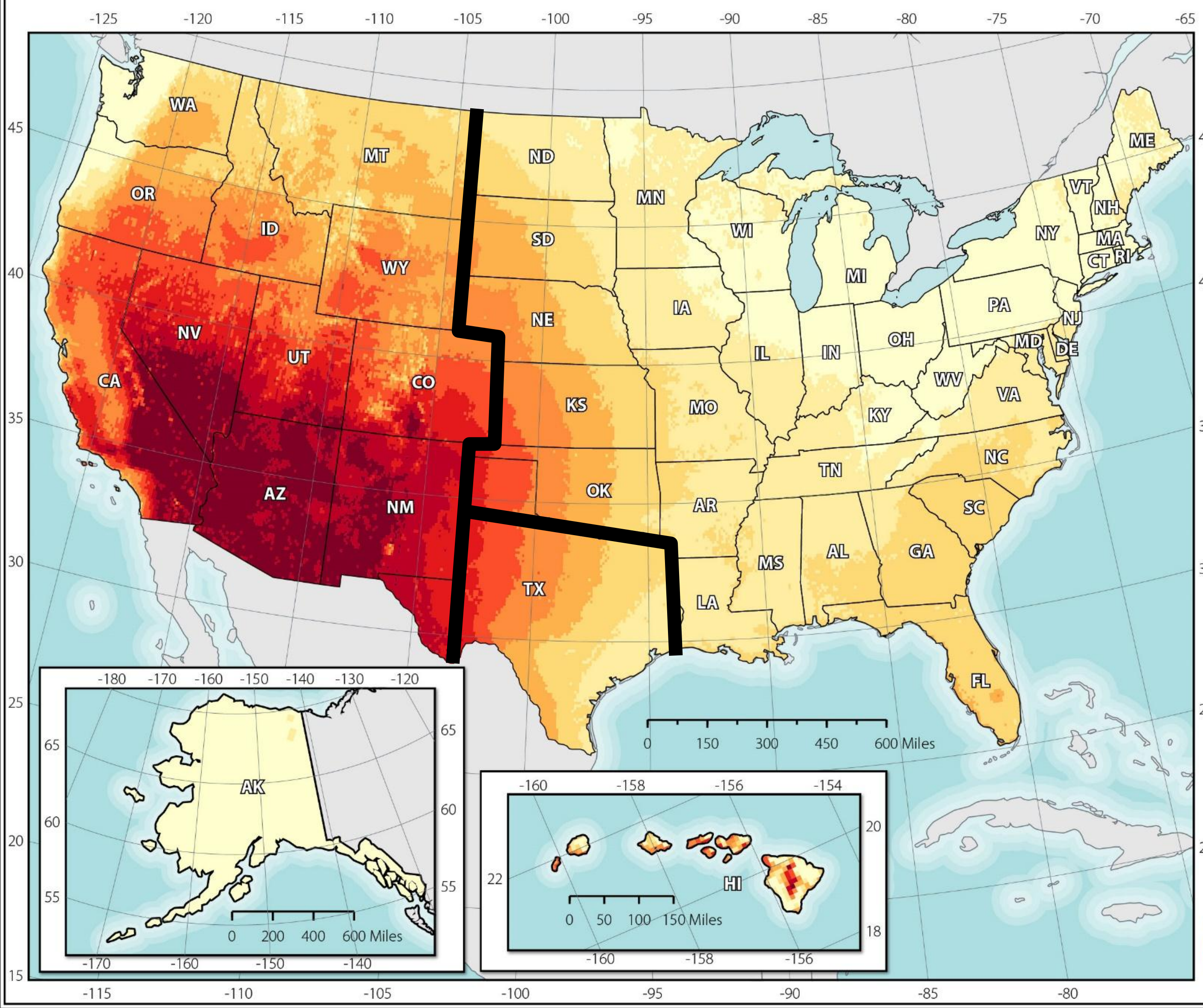
- Solar Dynamics is a new CSP technology company formed in 2016 by the former engineering and R&D management of Abengoa Solar USA
- We have four U.S. DOE SunShot contracts
  - Dispatchable Solar Power Plant (MS Tower Peaker)
  - Advanced Large Aperture Trough Collector (SunBeam collector)
  - Autonomous Drop-In-Place Heliostat (2nd generation ROP heliostat)
  - SMART MS Trough



ATLAS Parabolic Trough – 8.2 m Aperture, 200 m Long

ROP Heliostat – 18 m^2

Concentrating Solar Resource of the United States



kWh/m²/Day

kWh/m²/Day
> 2740
2550 – 2740
2370 – 2550
2190 – 2370
2010 – 2190
1825 – 2010
1640 – 1825
1460 – 1640
< 1460

Annual average direct normal solar resource data are shown. The data for Hawaii and the 48 contiguous states are a 10km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2009.

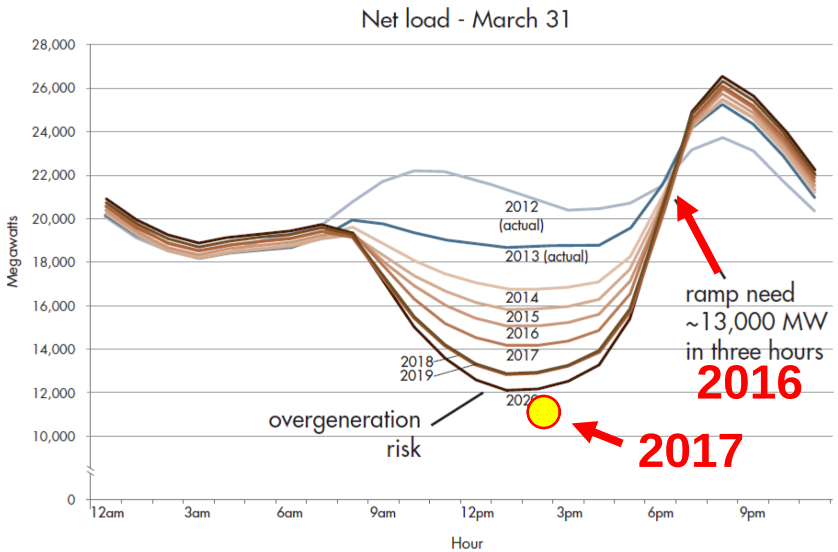
The data for Alaska are a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.
Billy J. Roberts
19 September 2012

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Flexible Generation Needed

- The California "Duck Curve" is a sign of success in terms of achieving a meaningful contribution of renewable power on the grid.
- Managing the Duck is one of the key challenges to moving to higher renewable contributions on the grid.
- Utilities are responding by:
  - Closing baseload plants.
  - Adding flexible or "Peaking" natural gas resources.



CAISO Duck Curve

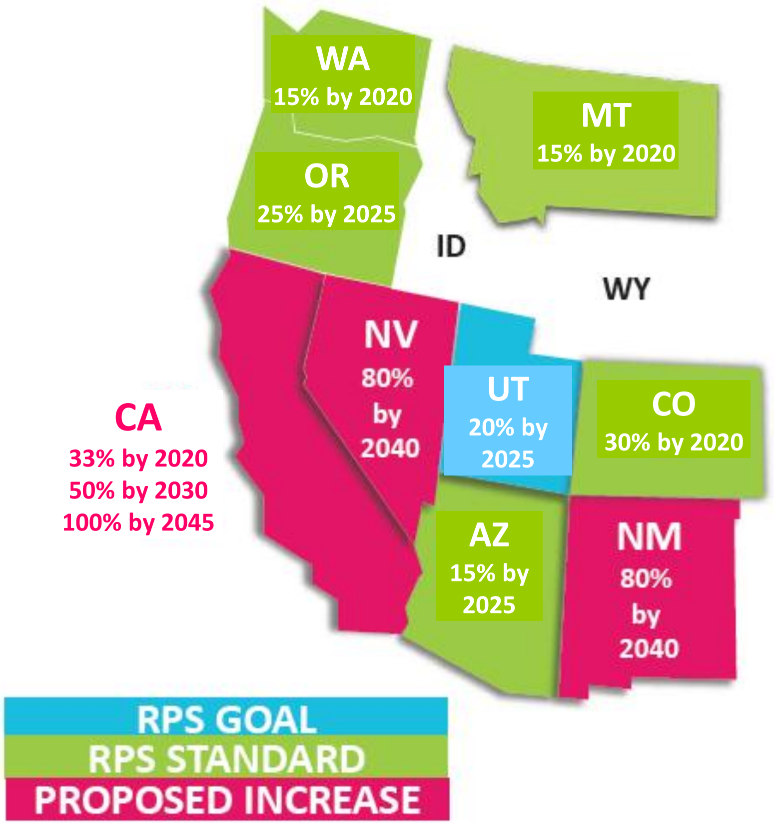
The CAISO indicates the duck is flying ahead of schedule.

- Ramp of 13 GW in Dec. 2016.
- Min. net load of 11 GW in Apr. 2017.

Decarbonizing the Power Sector

- Renewable deployment driven by both Federal and State policies.
  - Federal PTC & ITC drive economics
  - Federal ITC drives wind.
  - State RPS mandates drive PV deployment
- The Duck Curve problem occurs in 2020 when CA achieves 33% RPS.
- Western states proposing more aggressive RPS targets
  - California **100%** by 2045
  - Nevada **80%** by 2040
  - New Mexico **80%** by 2040

FIGURE ES-8. PROPOSED RENEWABLE PORTFOLIO STANDARD (RPS) INCREASES



Source: SNL – S&P Global Market Intelligence

How does DSP help California?

Example based on Actual 2016/2017 CAISO System Load

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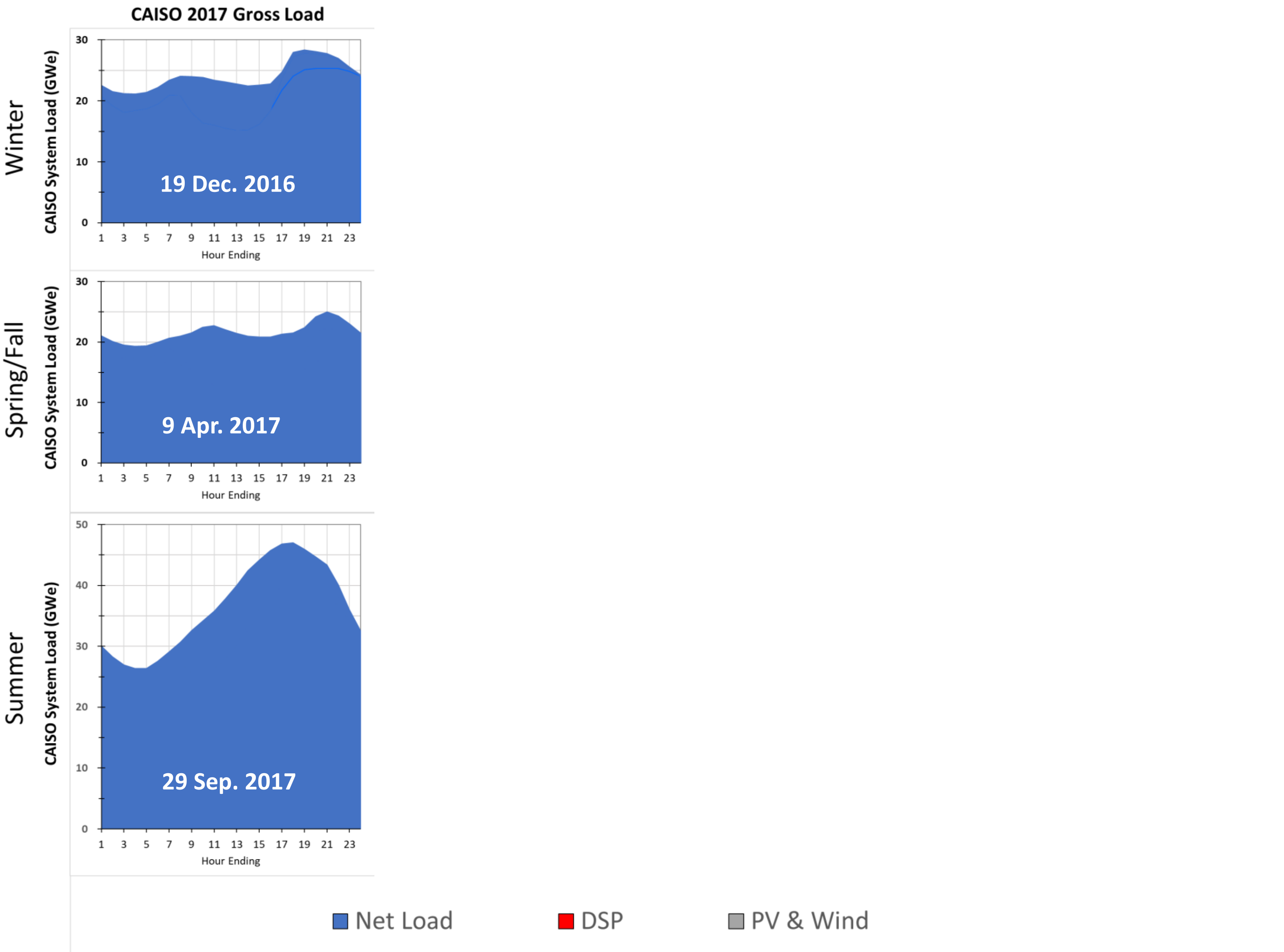
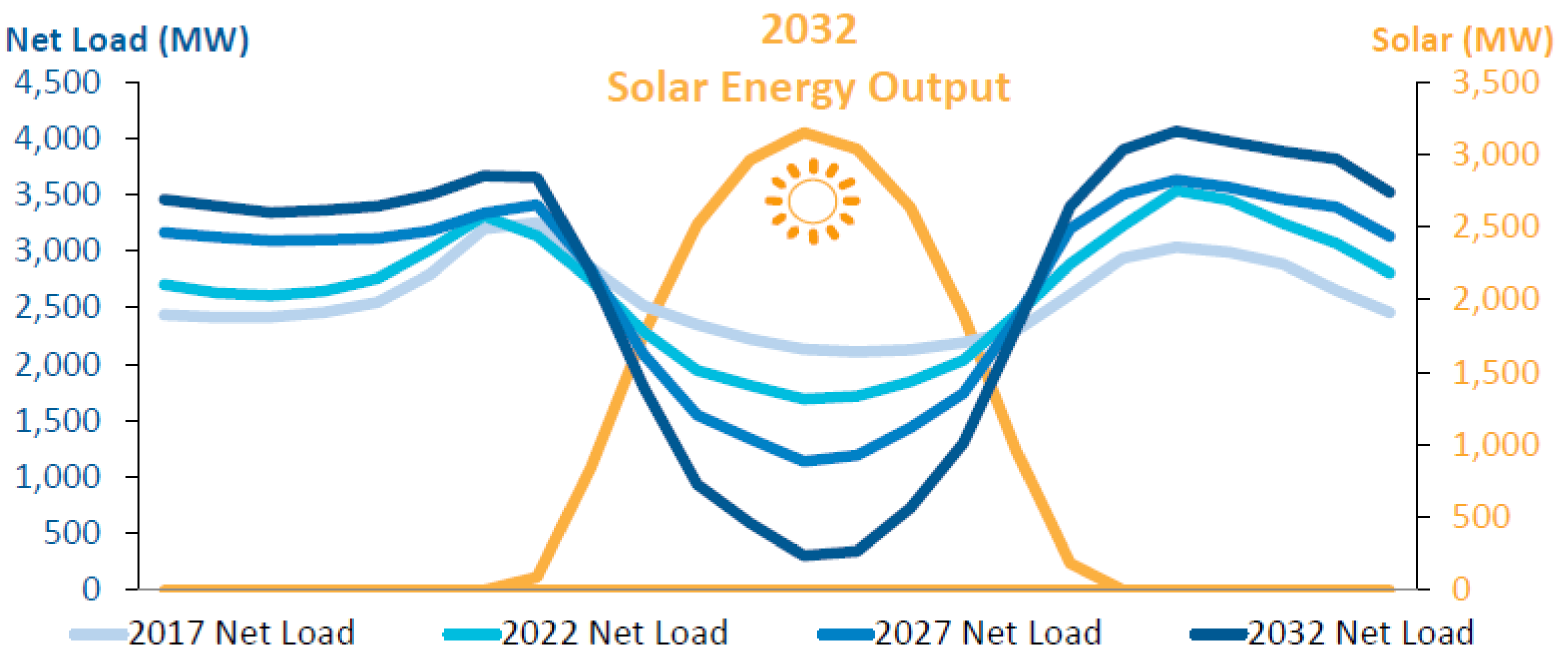


APS Load Shape

FIGURE ES-7. INCREASING IMPACT OF NON-CURTAILABLE SOLAR ON APS NET LOAD SHAPES



Source: APS 2017 Integrated Resource Plan

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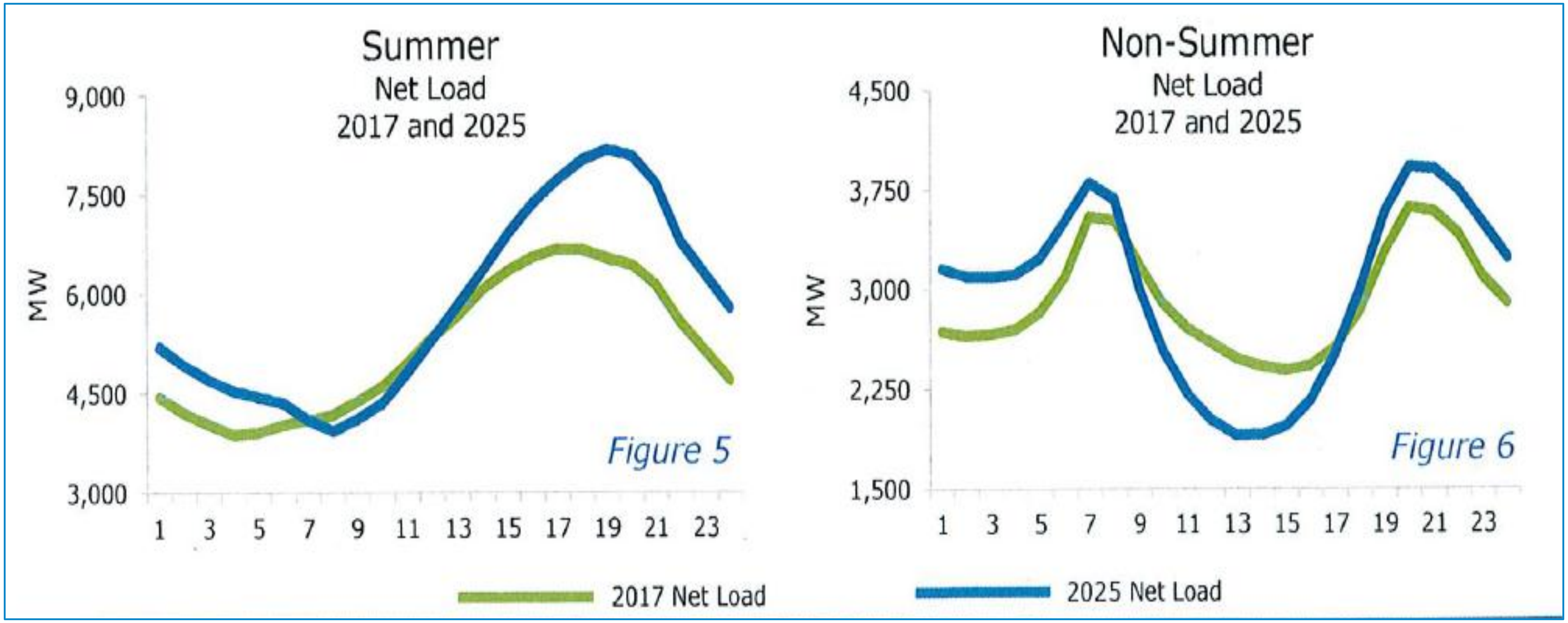
Arizona Seasonal Load Patterns

- Arizona Public Service (APS) Evolving Usage Patterns
  - Duck curve during non-summer periods. Creating dual peak in morning and evening and reducing daytime belly.
  - Variable energy resources reduce daytime but have no effect on reducing peak load at the end of the day. Summer peak Is increasing and shifting later in the day.

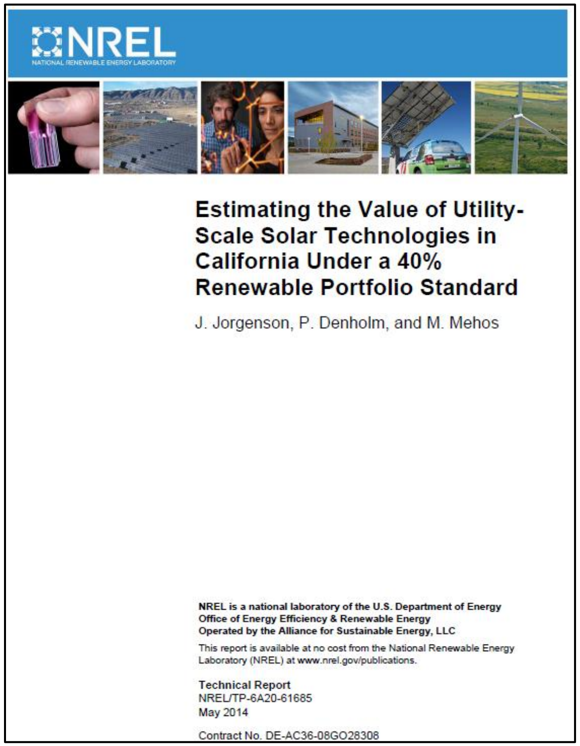


Source: APS 2017 IRP IRP_Stakeholder_Presentations.pdf

Market Assessment

- California
  - Replacing Once Through Cooling (>10GW of replacements by 2030)
  - Moving to 50% RPS by 2030
  - Proposed 100% RPS by 2045
- Arizona
  - Adding 4000 MW of new capacity over next 15 years.
  - 2017 Peaking Capacity RFP (400-700 MW)
- Other Conclusions
  - Today demand is for flexible resources.
  - There is no demand for baseload CSP plants today but this could change in future.

NREL Analysis on the Value of CSP with TES



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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

J. Jorgenson, P. Denholm, and M. Mehos

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

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-6A20-61685
May 2014

Contract No. DE-AC36-08GO28308

Total Value for different configurations of CSP+TES

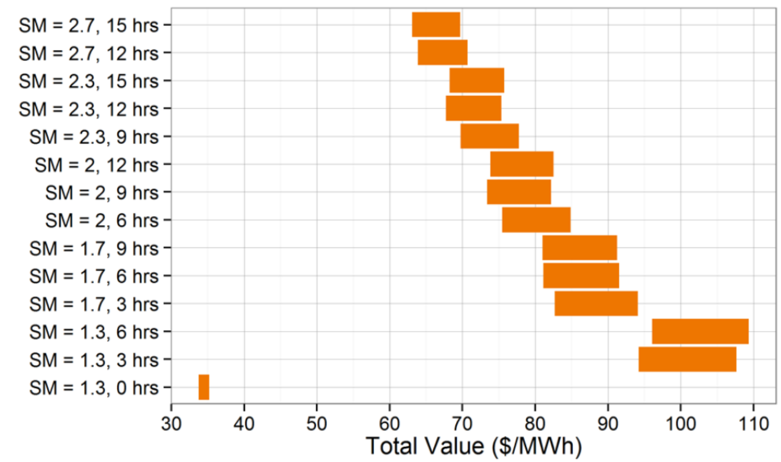
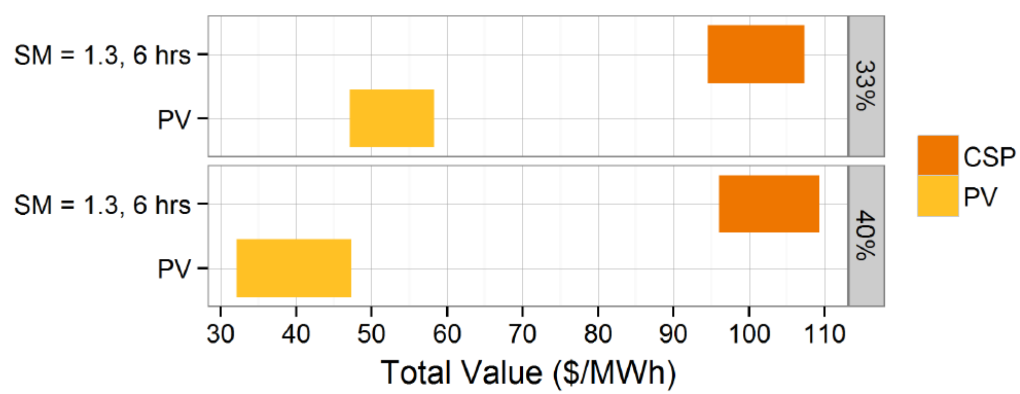


Figure 18. Total operational and capacity value of several configurations of CSP-TES in the 40% RPS scenario

Total Value (capacity + operational value) for PV and CSP+TES



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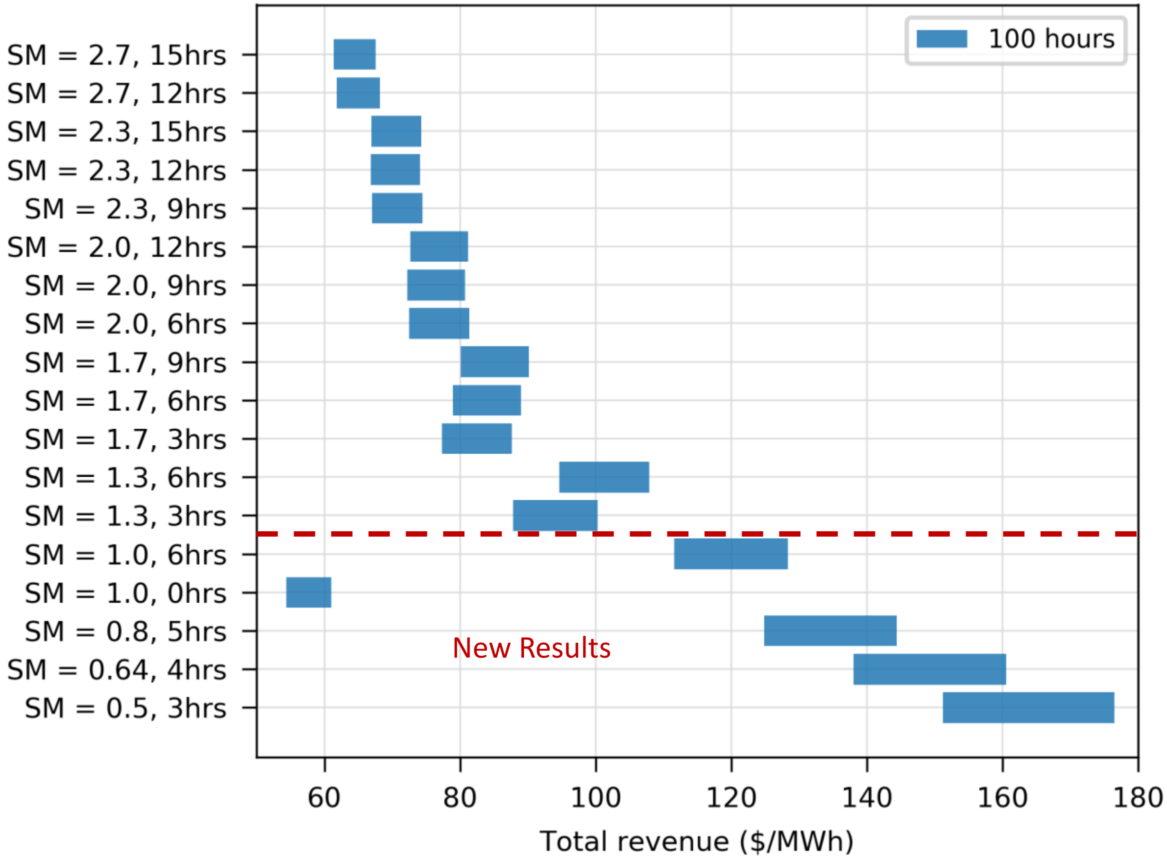
Updated NREL Analysis on the Value of CSP with TES

J. Martinek, J. Jorgenson, M. Mehos – Sept. 2017



Original Source: J. Jorgenson, P. Denholm, and M. Mehos, **"Estimating the Value of Utility Scale Solar Technologies in California Under a 40% Renewable Portfolio Standard**," NREL/TP-6A20-61685, May 2014

Dispatchable Solar Power Plant - Project Objectives

Develop conceptual design for a molten-salt tower dispatchable solar power plant.

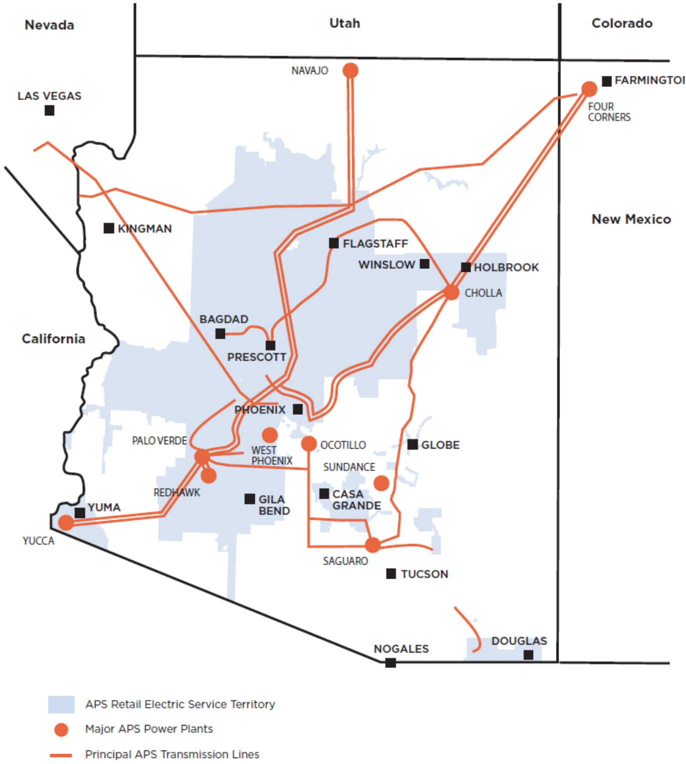
- Market Assessment
- DSP Design to Meet Operational Requirements
  - Fast Starts & Ramps
  - Store solar energy during the day
  - Dispatch power anytime during next 24 hrs
- Cost Reduction
  - Standardized design
  - Compressed EPC schedule
  - New low cost heliostats
- Commercialization
  - Conceptual engineering design and EPC cost estimate (Sargent & Lundy)
  - Vendors identified for all key equipment
  - Outreach to Developers, EPCs, Utilities
  - Address tower sensitive development issues
  - Assess economics of real project

Example: Arizona Public Service (APS)

APS 2017 Peaking Capacity RFP:

- Needs flexible summer capacity beginning **June 1, 2021.**
  - **36 – 42 months from PPA to COD**
- Driven by retiring contracts, growth in variable renewable generation, and growth in demand
- Peaking capacity for 400-700 MW from existing or new facilities.
- Flexible dispatchable summer resources have highest value – June to September from 3pm to 9pm.
- APS will not accept proposals that require APS to take energy during the "**No Must Take Energy**"

FIGURE 1-1. APS SERVICE TERRITORY MAP



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APS 2017 Peaking Capacity RFP

APS Thermal (Fossil) Tolling Power Purchase Agreement

- Maximum of 20 year term for Tolling PPA
- Capable of operating for 4 hours at 114F and 20% RH at 100% contract capacity.
- Dispatchable by APS with AGC (load following capability)
- Must have access to natural gas pipeline, all required water rights, and emission allowances.
- Any carbon allowances for the facility must be passed through to APS at no charge.

APS Preferences:

- Prefer connection to both pipelines
- Resource is capable of stable operation at a minimum operating level of 25% loading and without exceeding emissions limits.
- Capable of at least 2 starts per day.
- Faster ramp rates better
- Resources with shorter minimum run, min down, and start-up times better.
- Resource capable of being online and dispatchable in 10 minutes or less (quick start).
- Shorter term transactions are preferred.

APS indicated that a DSP Plant could be bid as a “Solar Peaker” and contract under a modified “solar” tolling agreement

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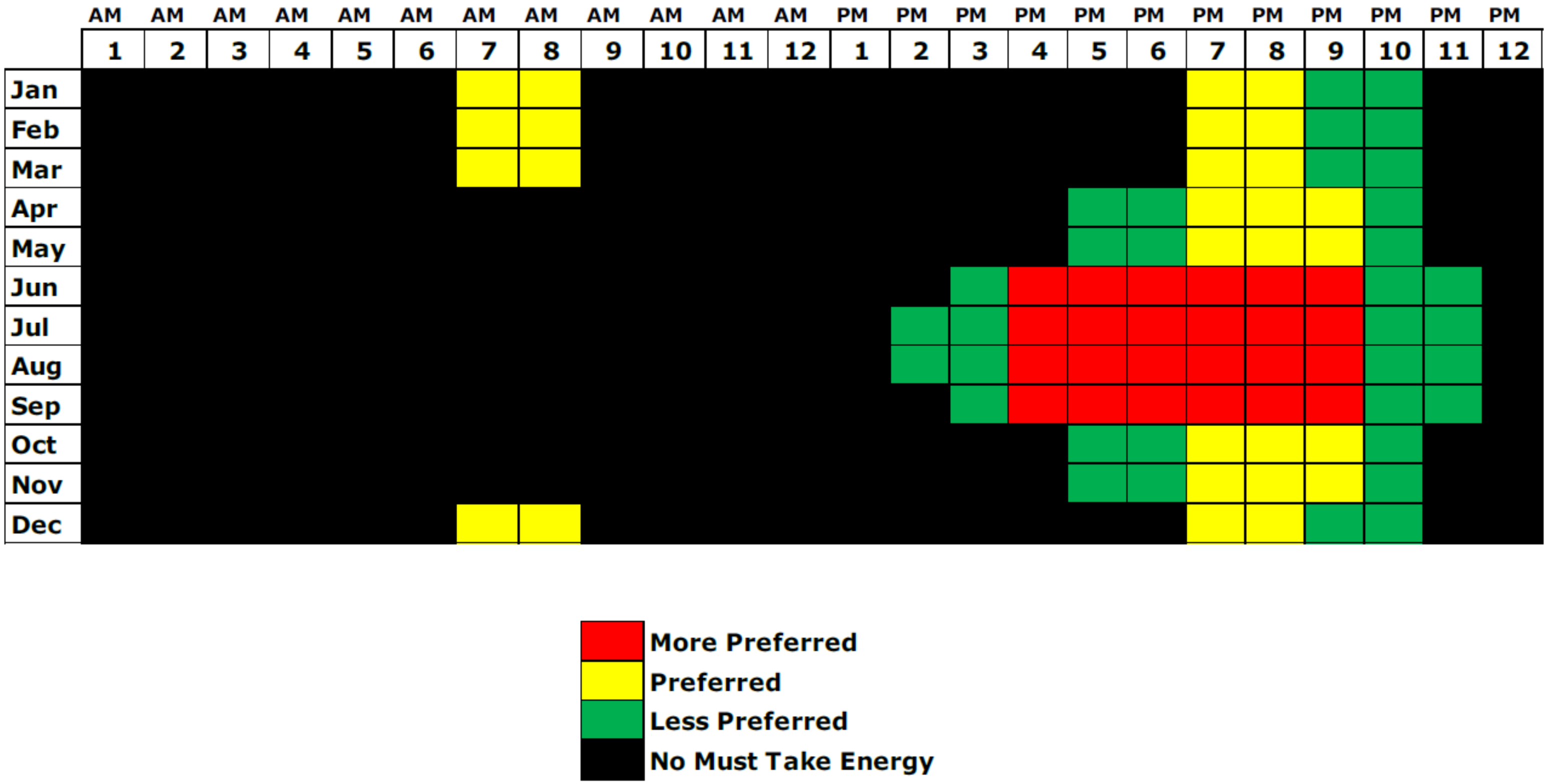
APS 2017 Peaking Capacity RFP

Time of Day Relative Net Load Heat Map



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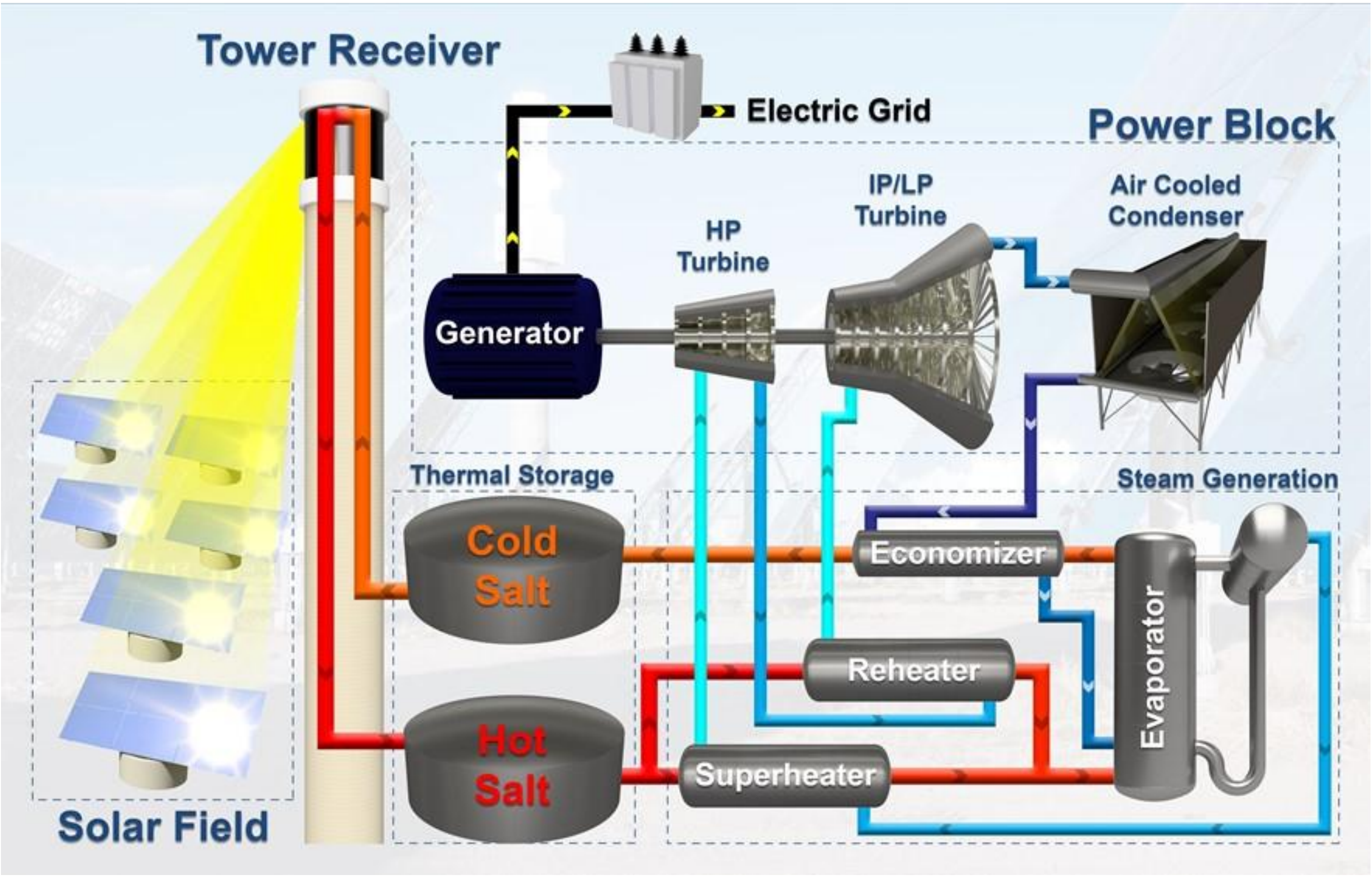
The Dispatchable Solar Power (DSP) Plant

A Molten-salt Tower Plant Designed to operate more flexibly



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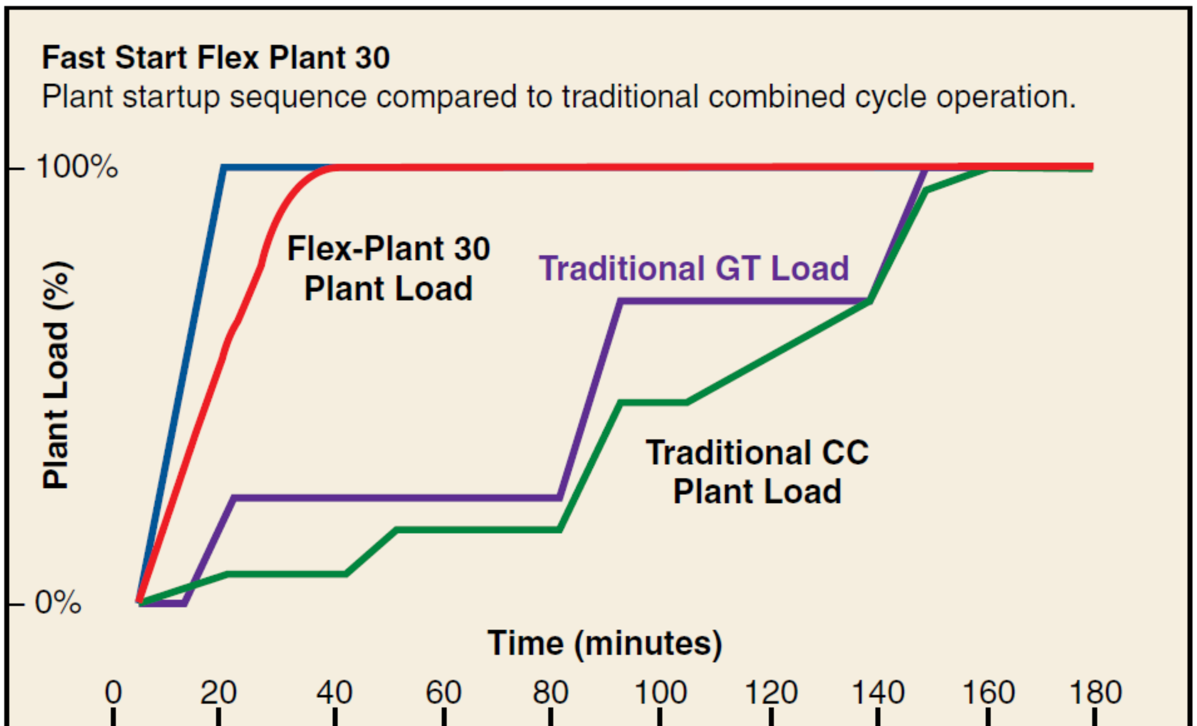
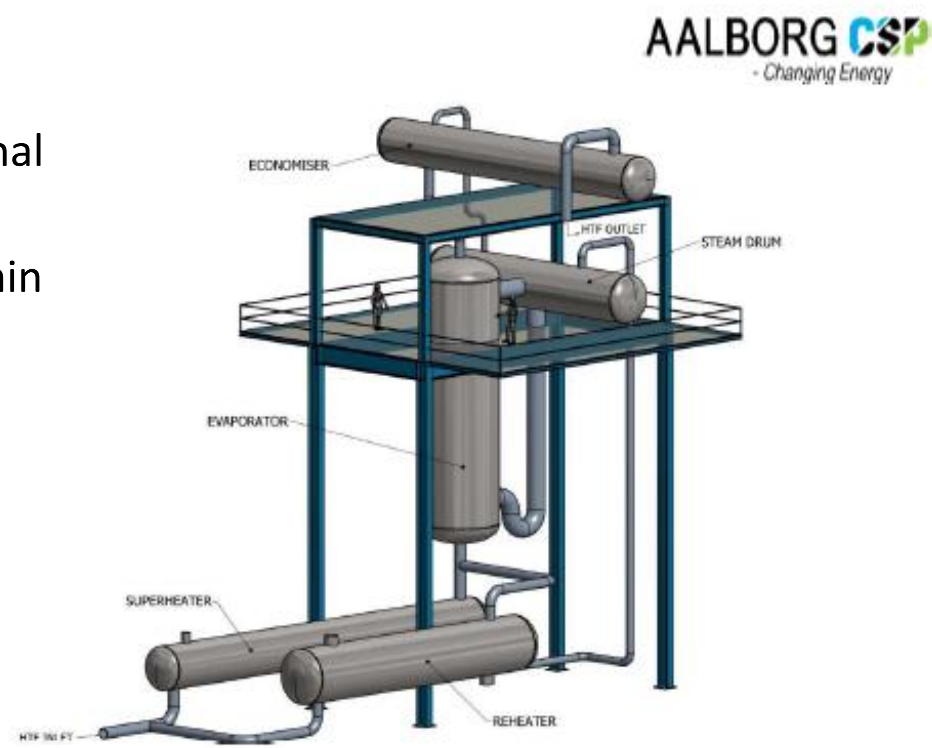
New Fast Start Siemens SST-700 Flex Plant 30

- Steam turbine Start-up
  - 30 minutes from Start to full capacity (normal daily start)
- High ramp rate
  - 10% per minute
- 25+ year life with multiple starts per day.



Steam Generator Design

- Aalborg Steam Generator
  - Header Coil HX
  - Allows 5x temperature gradients of conventional shell and tube HXs
  - Starts up in under 10 min
  - Modular design
  - Passive circulation
  - Salt drains back.



Typical steam generator layout with Natural circulation is shown above.
Two units are required for 50 MWe.

DSP Design

Configuration	Summer On-Peak 5 hours
Turbine Nominal Gross Power [$MW_{e,\ Gross}$]	**250**
Turbine Nominal Net Power [$MW_{e,\ Net}$]	**230**
Power cycle gross thermal efficiency [--]	**44.0%**
Power cycle cooling system	**hybrid**
Power cycle design ambient temperature [C]	**445**
Solar Receiver design duty [MWt]	**400**
Solar Multiple [---]	**0.65**
Tower Optical Height [m]	**168.5**
Total Heliostat Area [m2]	**685,316**
Heliostat Type	BSE V 2.4
Heliostat Size [m2]	20.8
Number of Heliostats	32,973
Solar Field Area [acres]	640
Storage Capacity [MWht]	3,000
Storage Capacity [hr]	5
Annual Gross Capacity Factor	**16.5%**
1^{st} year Net Generation [GWh]	**334.2**

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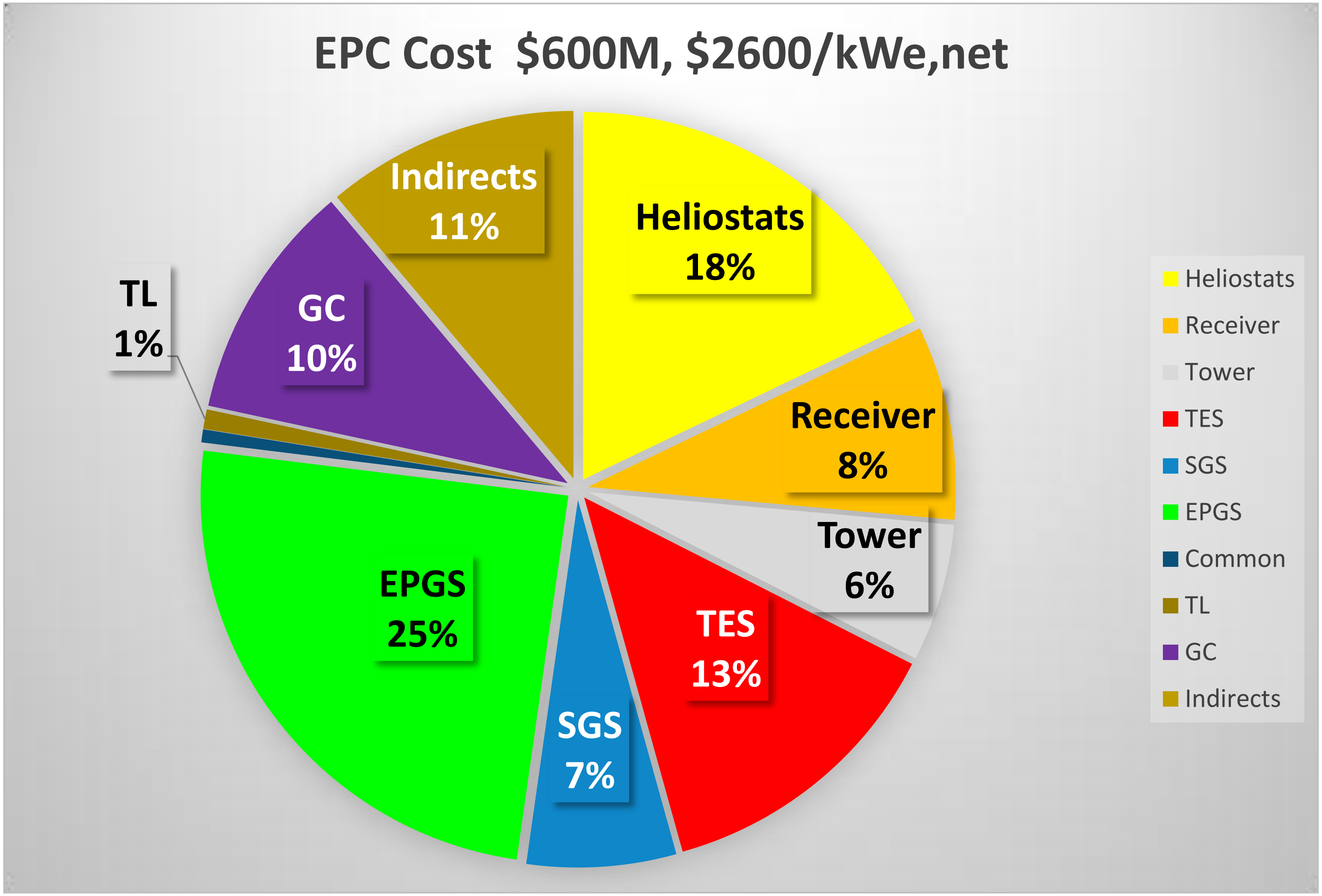
DSP Plant Cost



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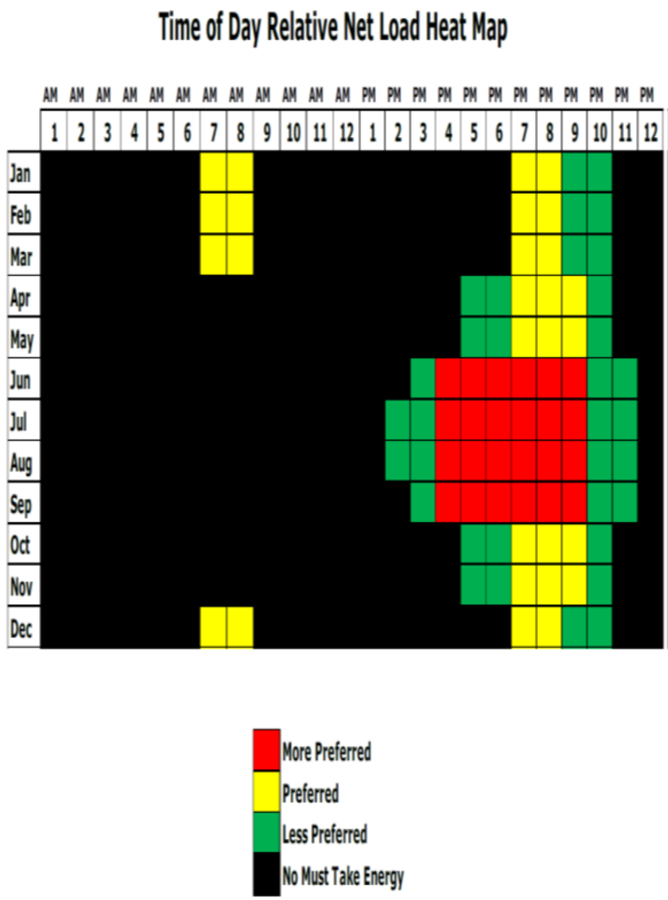
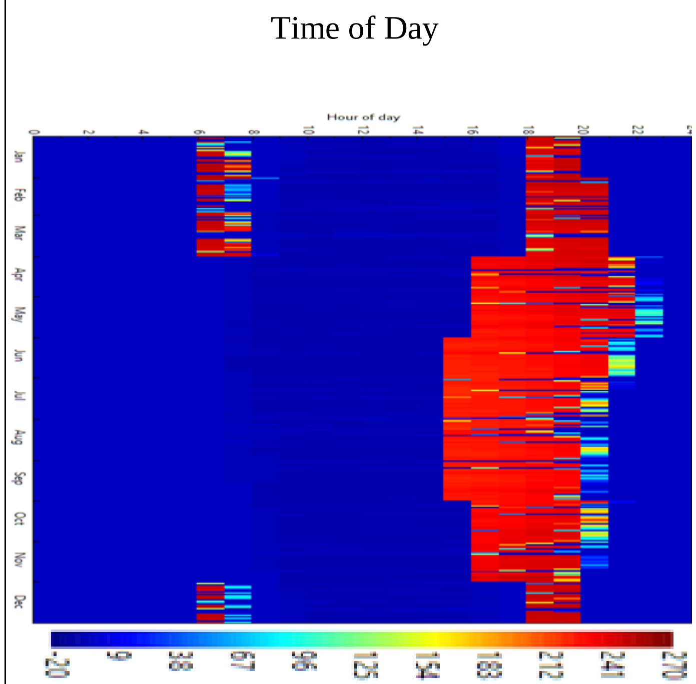
APS 2017 Peaking RFP TOD Periods and SAM Optimized DSP Dispatch Model



(a) APS Peaking Capacity TOD Periods



APS TOD Periods	CF	% of Gen
- More Preferred (5 hrs)	94%	38%
- Preferred	84%	48%
- Less Prefered	19%	13%
- No Must Take	0.2%	0.6%

(b) SAM DSP Plant Output

Projected on-peak performance for 2006-2015.

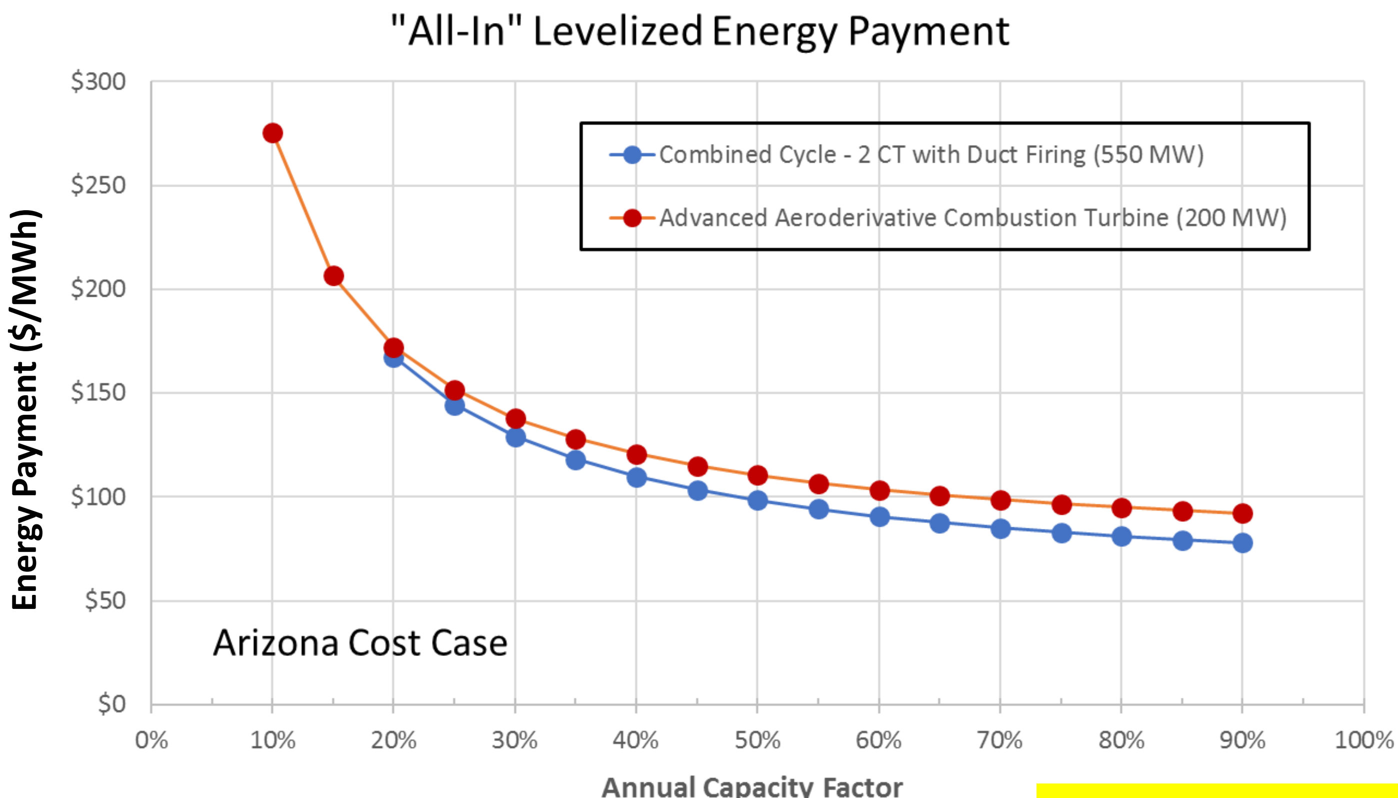
Peak Load Day Ranking	Net Design Capacity Factor (3-9pm) 2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Avg
1	100%	102%	76%	101%	52%	98%	101%	101%	41%	99%	87%
2	100%	99%	102%	65%	89%	80%	101%	78%	35%	95%	84%
3	70%	102%	101%	102%	65%	98%	101%	100%	99%	98%	94%
4	101%	102%	101%	100%	101%	99%	63%	101%	101%	82%	95%
5	101%	99%	100%	86%	78%	99%	101%	101%	94%	101%	96%
6	102%	85%	101%	77%	102%	99%	101%	87%	102%	102%	96%
7	101%	101%	102%	101%	101%	95%	101%	101%	101%	99%	100%
8	90%	100%	101%	101%	102%	101%	99%	92%	65%	102%	95%
9	103%	98%	101%	101%	102%	101%	102%	101%	102%	101%	101%
10	87%	101%	102%	69%	101%	96%	102%	98%	103%	102%	96%
11	97%	101%	101%	98%	80%	99%	101%	102%	103%	101%	98%
12	102%	102%	68%	99%	101%	98%	28%	69%	102%	75%	84%
13	103%	100%	102%	100%	102%	50%	102%	58%	93%	63%	87%
14	48%	99%	102%	101%	80%	101%	102%	79%	97%	102%	91%
15	99%	95%	101%	102%	102%	101%	102%	99%	101%	102%	100%
16	93%	102%	54%	101%	102%	100%	76%	96%	102%	100%	93%
17	102%	102%	102%	101%	102%	76%	100%	93%	103%	84%	96%
18	102%	100%	102%	100%	79%	102%	102%	100%	104%	102%	99%
19	102%	102%	95%	93%	102%	102%	100%	93%	86%	98%	97%
20	70%	101%	101%	101%	74%	101%	102%	100%	103%	85%	94%
Top 5 days	94%	101%	96%	91%	77%	95%	93%	96%	74%	95%	91%
Top 10 days	96%	99%	99%	90%	89%	97%	97%	96%	84%	98%	94%
Top 20 days	94%	100%	96%	95%	91%	95%	94%	92%	92%	95%	94%

Fossil Cost Analysis

- A new DSP plant will need to compete against a new fossil plant alternative.
- The CEC cost of generation (COG) model is used to estimate the cost of the fossil alternative to the DSP plant.
  - The COG model was developed and is maintained by the California Energy Commission to track the cost of generation for all new power technologies.

Start-Year = 2013 (Nominal $)	Size	Merchant		IOU		POU	
	MW	$/kW-Yr.	$/MWh	$/kW-Yr.	$/MWh	$/kW-Yr.	$/MWh
Generation Turbine 49.9 MW	49.9	275.66	662.81	185.13	2215.54	193.34	311.60
Generation Turbine 100 MW	100	273.83	660.52	183.47	2202.75	191.81	310.11
Generation Turbine - Advanced 200 MW	200	252.33	403.83	159.41	1266.91	200.67	215.62
Combined Cycle - 2 CTs No Duct Firing 500 MW	500	551.42	116.51	495.20	104.54	482.63	102.35
Combined Cycle - 2 CTs With Duct Firing 550 MW	550	548.14	115.81	492.86	104.05	481.32	102.08
Biomass Fluidized Bed Boiler 50 MW	50	812.34	122.04	941.97	141.53	820.03	123.54
Geothermal Binary 30 MW	30	561.31	90.63	743.97	120.21	519.74	84.98
Geothermal Flash 30 MW	30	653.36	112.48	851.61	146.72	627.91	109.50

COG Model Results – Energy PPA



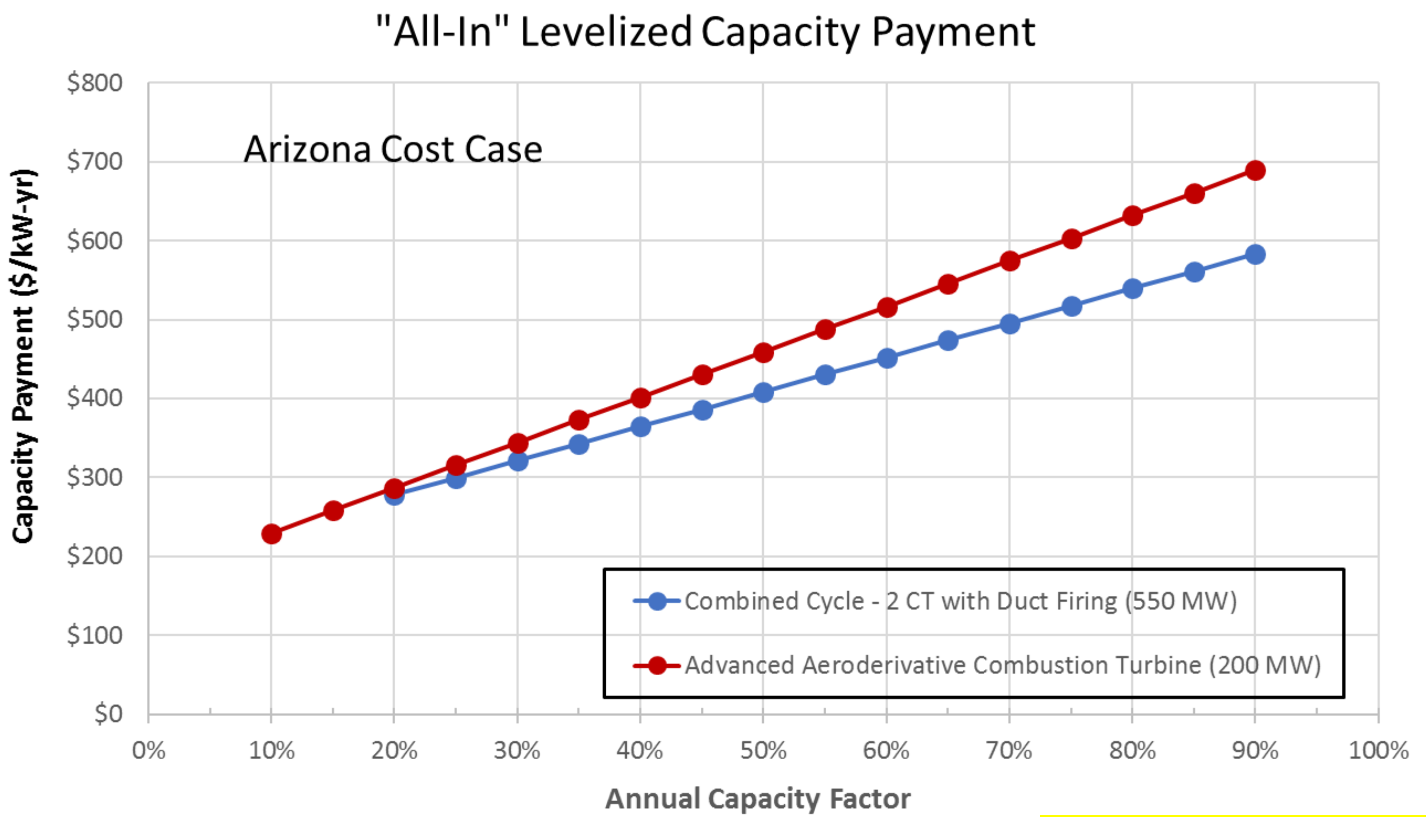
Assumptions:

1) Net Capacity: CC = 531 MW, CT = 192 MW
2) Gas Price: Low CA Average; CC = ~$35/MWh, CT = ~$45/MWh
3) CO2 Payment: Low CA; CC = $17/ MWh, CT = $24/MWh
4) Lifetime = 30 years, first year of operation : 2020
5) Capital Cost = AZ = 80% CA Average Prices
6) CEC Cog Model Website: http://energy.ca.gove/2014publications/CEC-200-2014-003/

All-In Cost Includes:

- **Capital Cost & Financing**
- **O&M & Insurance Costs**
- **Taxes (Incentives)**
- **Fuel Cost**
- **Carbon Cost**

COG Model Results – Capacity Tolling



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All-In Cost Includes:

- **Capital Cost & Financing**
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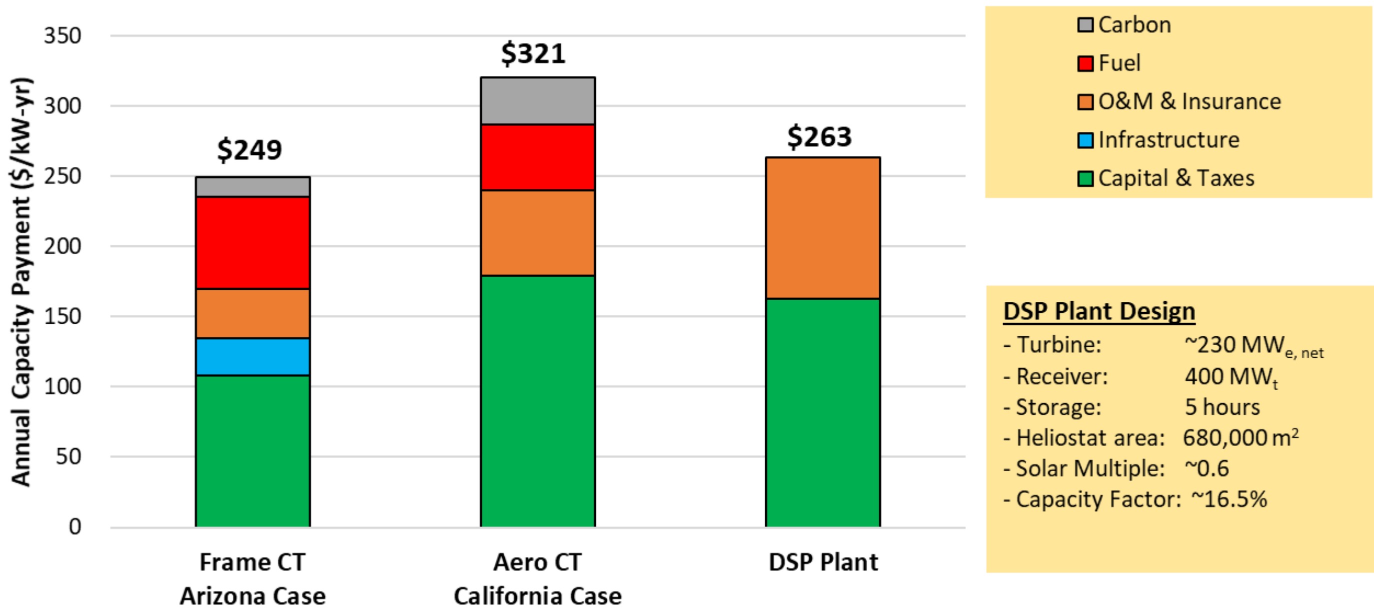
Capacity Cost Comparison [$/kW-yr]



~ $180/MWh

Assumptions:

1) Analysis conducted for peaking plants operating at 16.5% ann
2) Capacity payments based on all in cost including: capital, taxe cost methodology from: CEC-200-2014-003-SD, "Estimated Cost of new renewable and fossil generation in Calirornia," May 2014.
3) Assumes: 30-year project life for all plants.
4) Arizona Assumptions: GE Frame 7FA combustion turbine. Capital costs from WECC TEPPC 2014 assumptions. Fixed and variable costs from EIA AEO 2017 electric generator assumptions. Average operational heat rate and gas piping infrastructure for Arizona from APS. Carbon and natural gas pricing from APS 2017 IRP.
5) California Assumptions: GE LMS100 aeroderivatie combustion turbine capital & O&M cost, gas & carbon pricing from California capital costs from CEC-200-2014-003-SD.
6) DSP costs are based on current molten-salt tower technology and near-term heliostat

Conclusions

- There is an opportunity for CSP in the US market.
  - It is for a flexible capacity product.
- CSP plants can be designed for any number of configurations to match the system needs.
  - Peaker to baseload
  - The DSP design was optimized to the Arizona market.
- PV happens!
  - PV is cheap. It will likely be added to the system at some point. Make sure it is paid what it is worth.
  - Plan for how to accommodate PV on the system.
  - Morocco's PV for Daytime and CSP for Nighttime is a good example.
- LCOE is not a useful metric for comparing plants with different capabilities.
  - The cost of plants that provide energy only cannot be compared with plants that provide energy and capacity.
- There is probably no place better suited for CSP than Chile due to it's high solar resource and load profile.

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Thank you for your attention!

Questions?

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