Solar Energy Utilization in the United States

For the American Nuclear Society
Nor Cal
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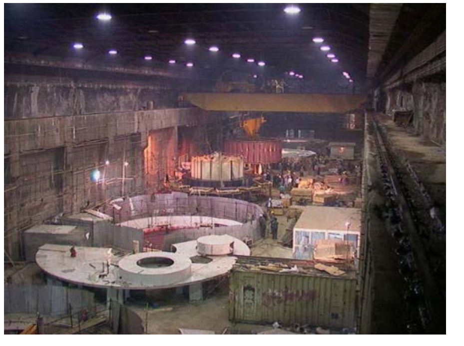
February 21, 2013

Professional Experience

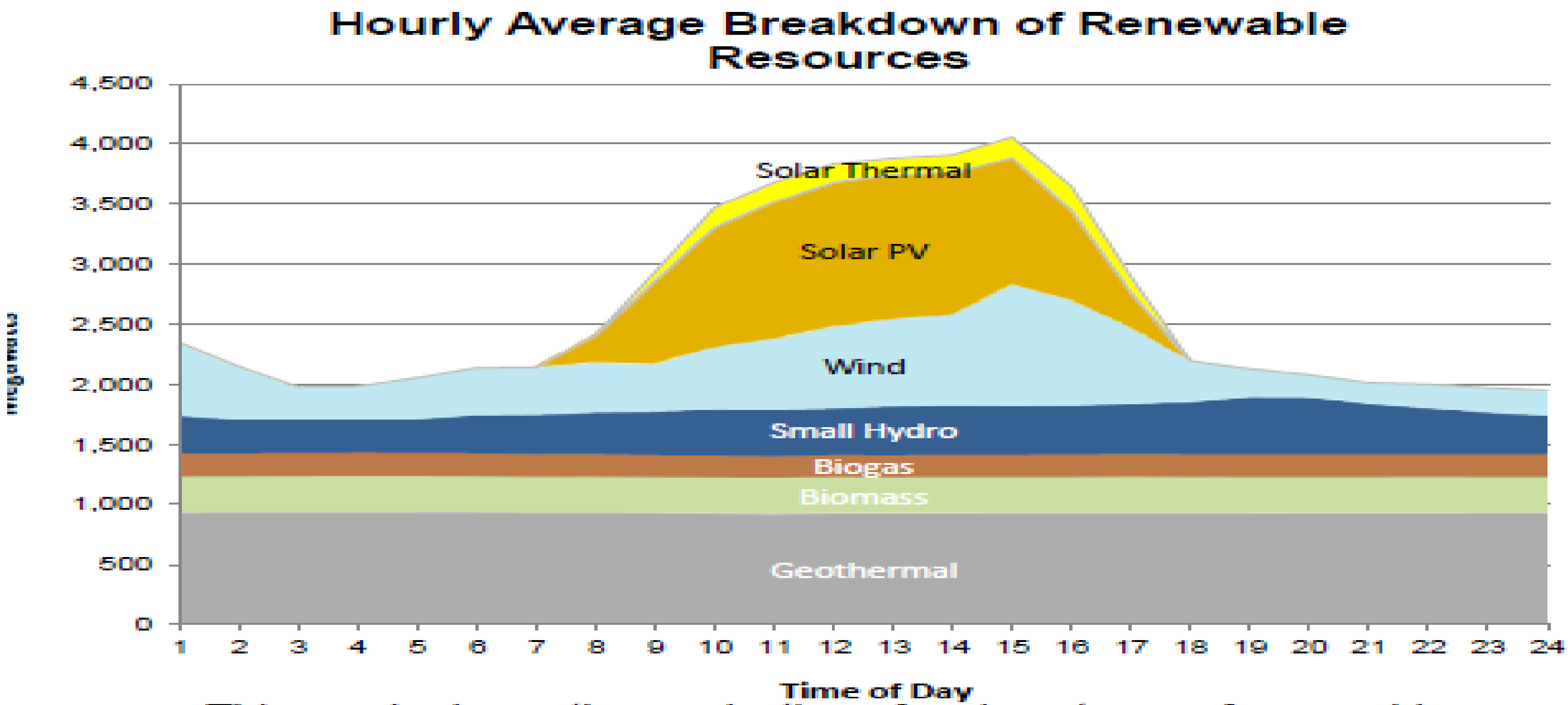
- 20 years project engineer experience, including the overall engineering of:
  - *Hydro electric power*
  - *Gas turbines*
  - *Steam turbines*
  - *CSP solar steam turbine*
  - *Photovoltaic power*
- Project Engineering experience with world's largest hydrogen generation plant: 220 MMSCFD (million standard cubic feet per day)
- Power Projects: 50- 1000 MW
- Mechanical design and fabrication background



Earth Climate: A global solar power plant

Fuel source: ~ 240 W/m2 solar flux (average annual)

CAISO (2/16/2013)



This graph shows the production of various types of renewable generation across the day.

System Peak Demand (MW) 28,658
*one minute average

Time: 18:21

CAISO (2/16/2013)

24-Hour Renewables Production

Renewable Resources	Peak Production Time	Peak Production (MW)	Daily Production (MWh)
Solar Thermal	15:16	205	1,363
Solar	11:49	1,209	8,774
Wind	14:47	1,050	10,858
Small Hydro	18:14	475	8,808
Biogas	23:02	200	4,727
Biomass	16:23	310	7,239
Geothermal	5:44	929	21,195
Total Renewables			**62,964**

Total 24-Hour System Demand (MWh): *594,216*

CA Renewable Portfolio Standard
33% by 2020

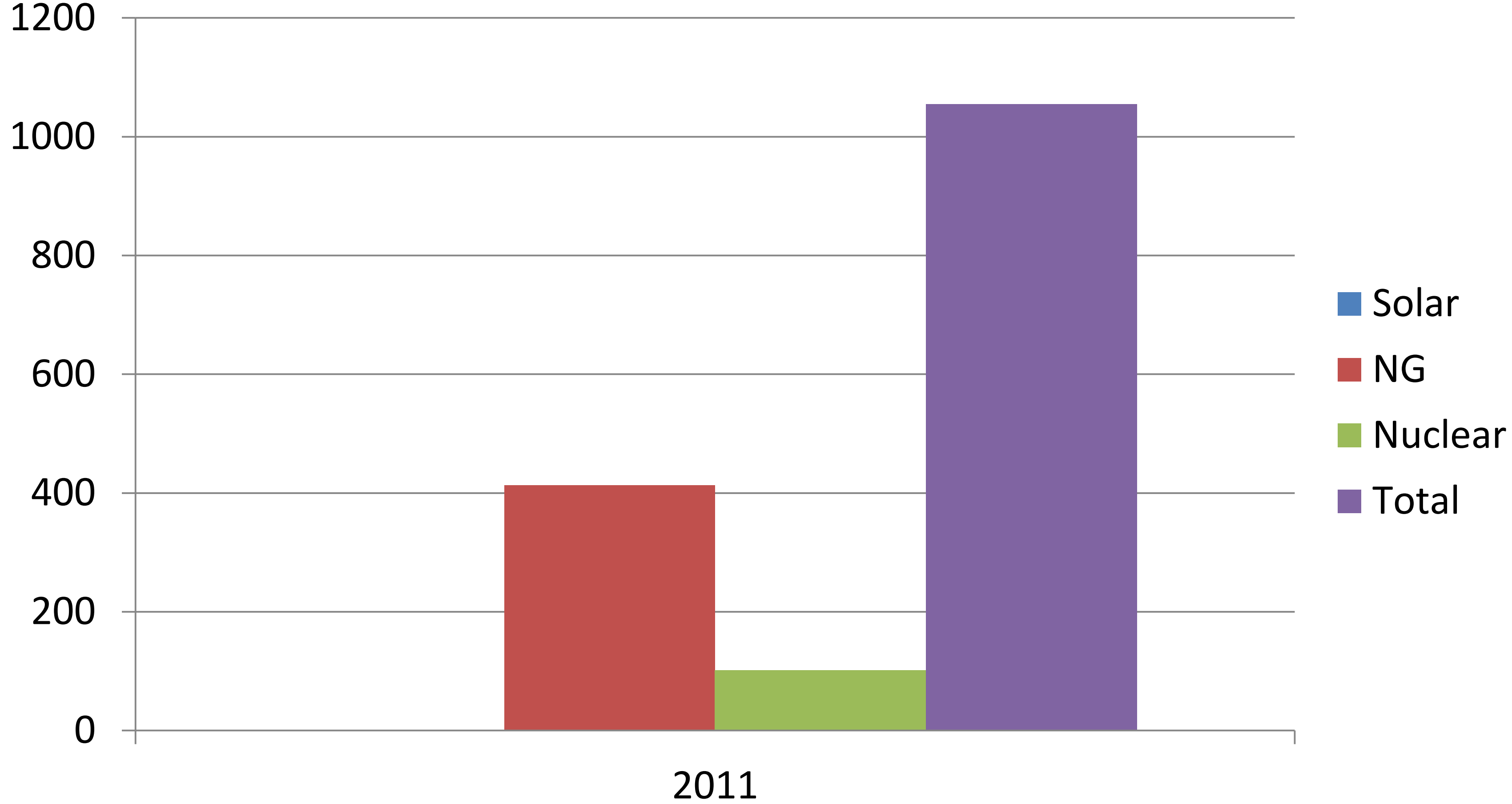
- Established in 2002 and accelerated in 2006.
- It is procurement program requiring utilities, and other electric service providers to increase their annual use of (eligible) renewable generation sources.

California Solar Energy Potential

- High direct normal incident solar radiation
- Access/proximity to transmission lines
- Large urban areas
- Most populous State in the US.

Electric Net Summer Capacity (x1000 MW)

Total (All Sectors), 2011 values ***(EIA, Annual Energy Review 2011)***



Solar vs. Conventional Power Plant:
similarities/differences

Similarities

- Single/multiple generation sources
- Fit for utility scale
- Controllable output
- Dispatch-able
- Support the base load (CSP)
- Scalable (n x MW)

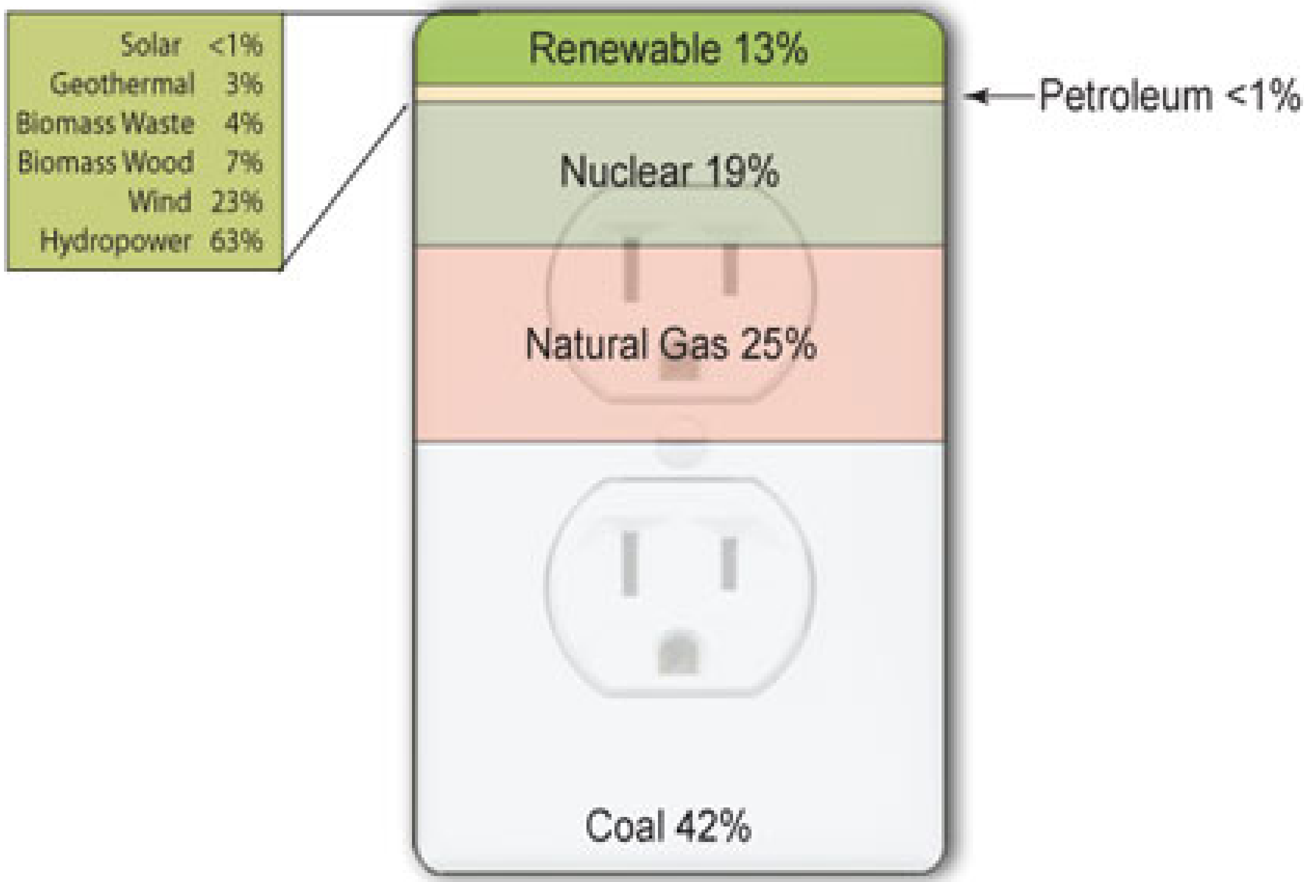
Differences

- **Costly (LCOE high)**
- Subject to solar irradiation
- Need sunlight, clear skies
- Variable output (PV)
- Low capacity factor (<2000 hours/year)
- Zero cost of fuel,
- Low O&M cost
- Large footprints (~ 5 acres /1 MW)

Existing Capacity by Energy Source (MW), *EIA 2011*

Energy Source	Number of Generators	Generator Nameplate Capacity	Net Summer Capacity	Net Winter Capacity
Coal	1,400	343,757	317,640	320,185
Petroleum	3,738	57,537	51,208	55,179
Natural Gas	5,574	477,387	415,191	448,456
Other Gases	91	2,202	1,934	1,919
Nuclear	104	107,001	101,419	103,507
Hydroelectric Conventional	4,048	78,194	78,652	78,107
Wind	781	45,982	45,676	45,689
Solar Thermal and Photovoltaic	326	1,564	1,524	**1,411**
Wood and Wood-Derived Fuels	345	8,014	7,077	7,151
Geothermal	226	3,500	2,409	2,596
Other Biomass	1,660	5,192	4,536	4,600
Hydroelectric Pumped Storage	154	20,816	22,293	22,268
Other Energy Sources	81	1,697	1,420	1,424
Total	18,530	1,153,149	1,051,251	**1,092,780**

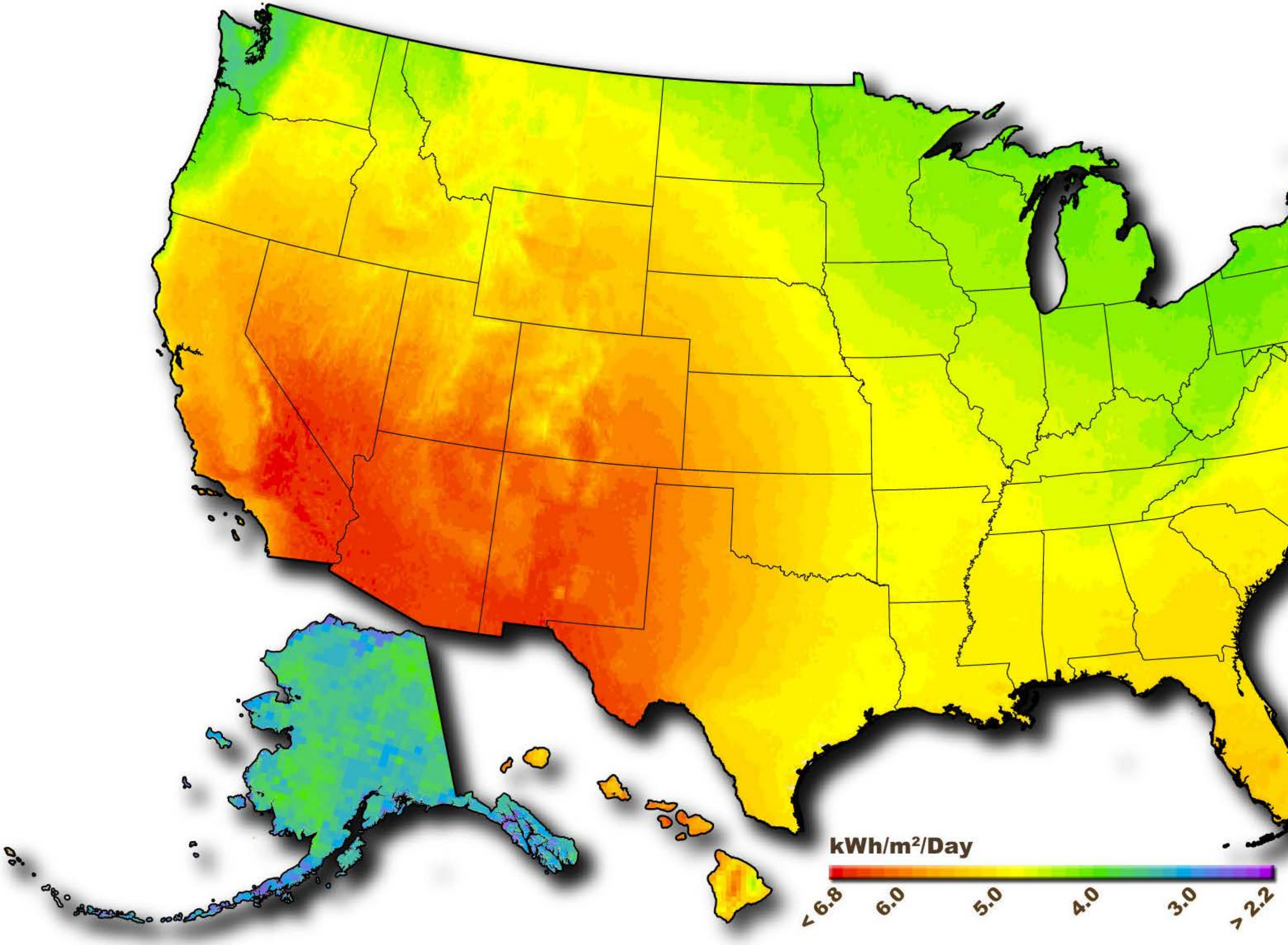
Sources of Electricity Generation, 2011



Note: Includes utility-scale generation only. Excludes most customer-sited generation, for example, residential and commercial rooftop solar installations

Source: U.S. Energy Information Administration, *Electric Power Monthly* (March 2012). Percentages based on Table 1.1, preliminary 2011 data.

U.S. Photovoltaic Solar Resource



Annual average solar resource data are shown for a tilt=latitude collector. The data for Hawaii and the 48 contiguous states are a 10 km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.

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

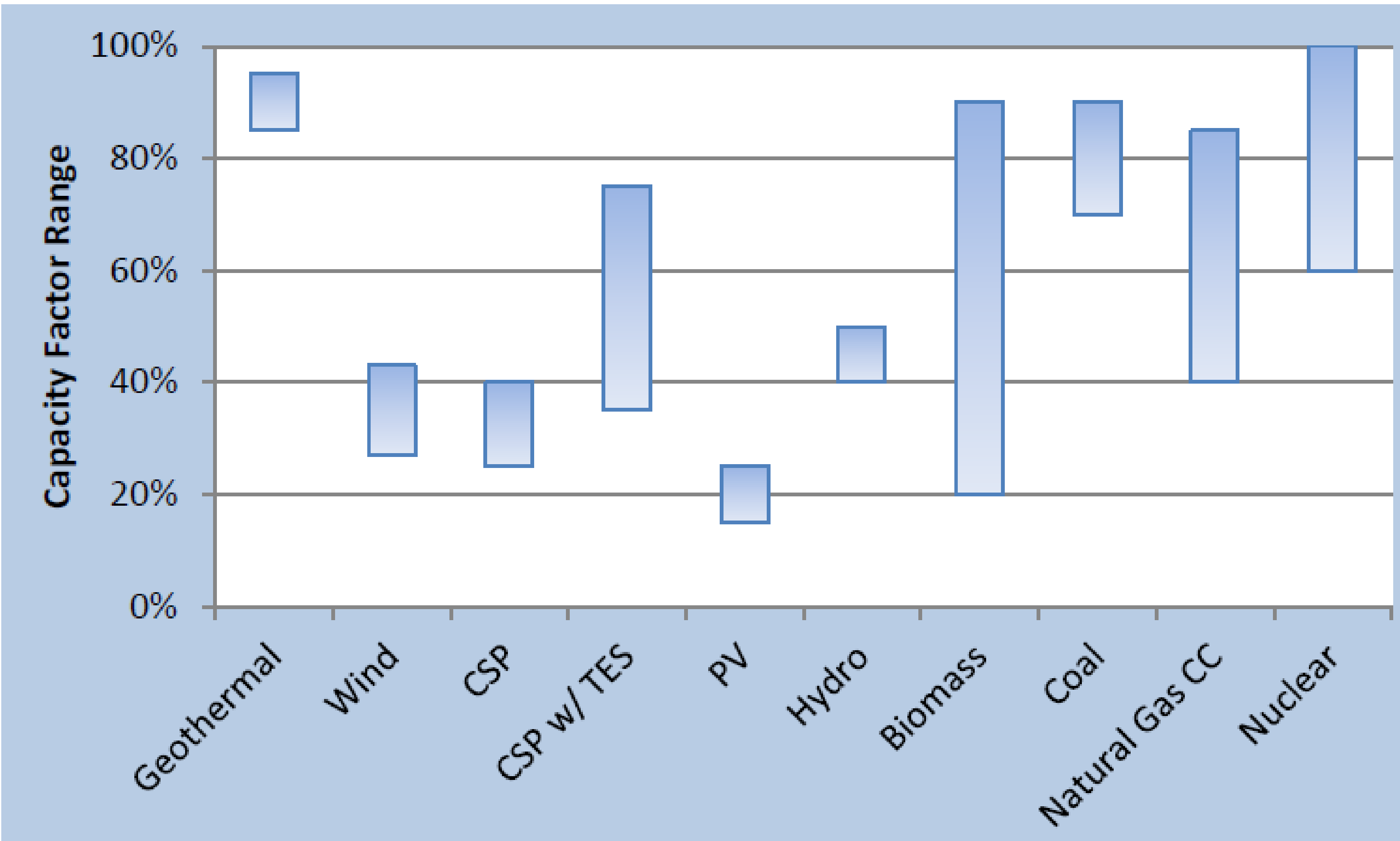
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Author: Billy Roberts - October 20, 2008

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.

Capacity Factor

CF= *(Actual annual output energy/name plate power at 8760 hr)*

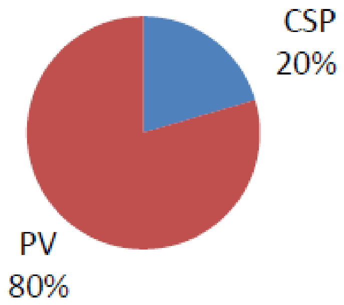


Utility-Scale Solar Projects in the United States

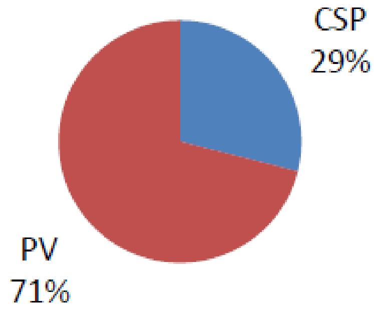
(SEIA Nov 2012)

Utility-Scale Project Capacity by Technology and Completion Status (MW)				
Technology	Operating	Under Construction	Under Development	Total
CSP	512	1,317	4,494	6,323
PV	1,992	3,239	20,579	25,811
Total	**2,505**	**4,556**	**25,073**	**32,134**

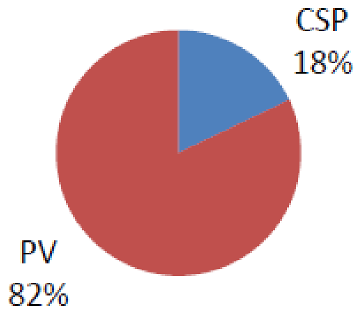
Operating Projects



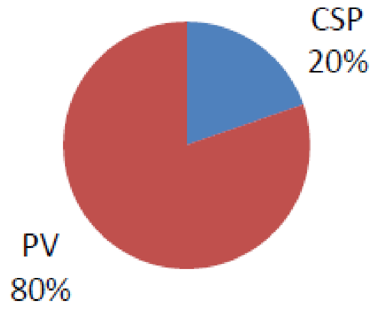
Projects Under Construction



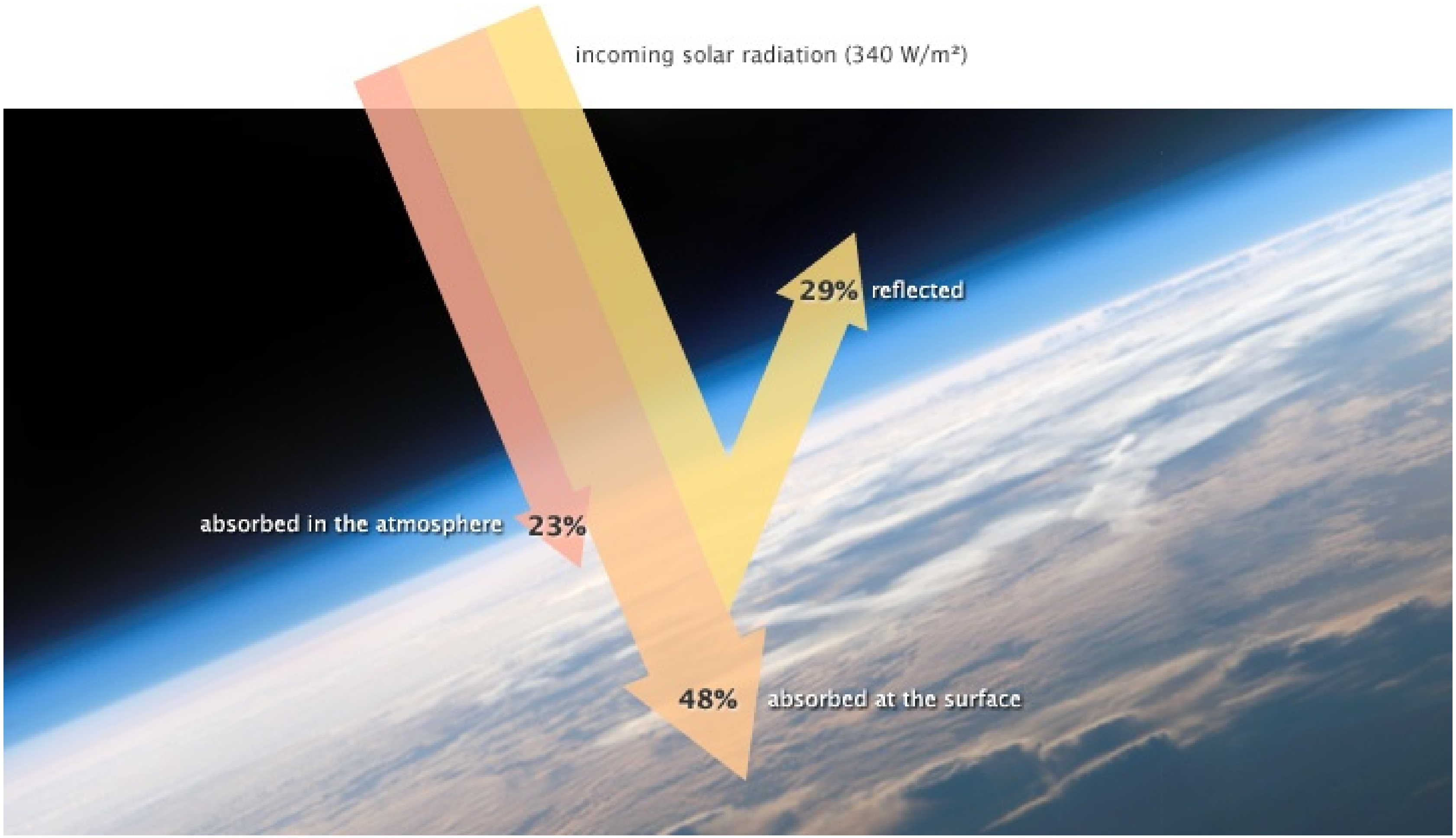
Projects Under Development



Total Project Pipeline

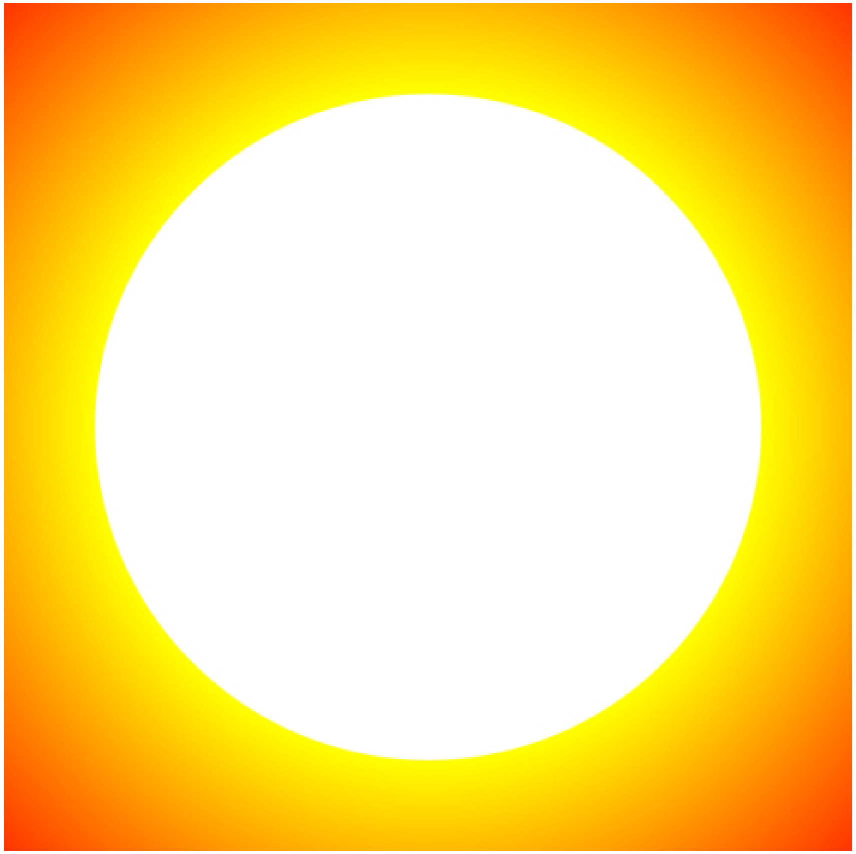


Incoming Solar Energy



Sun at 5670 K (visible): Earth at 255 K (IR) (effective temp)

Radiation balance between two black bodies

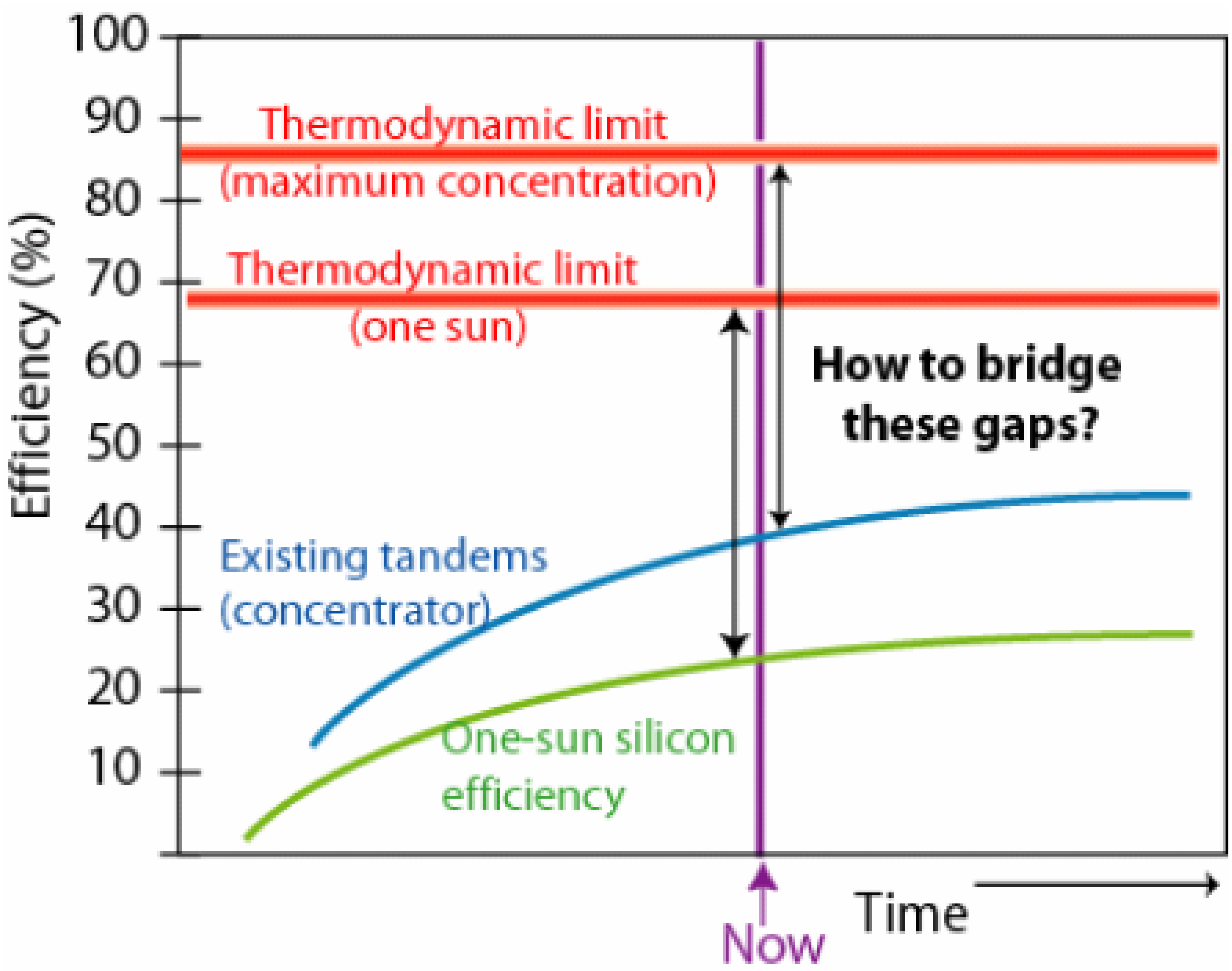


Solar Energy Utilization: CSP vs. PV

Thermal (solar concentration) **Electrical: PV module**

Theoretic limits of photovoltaic cells

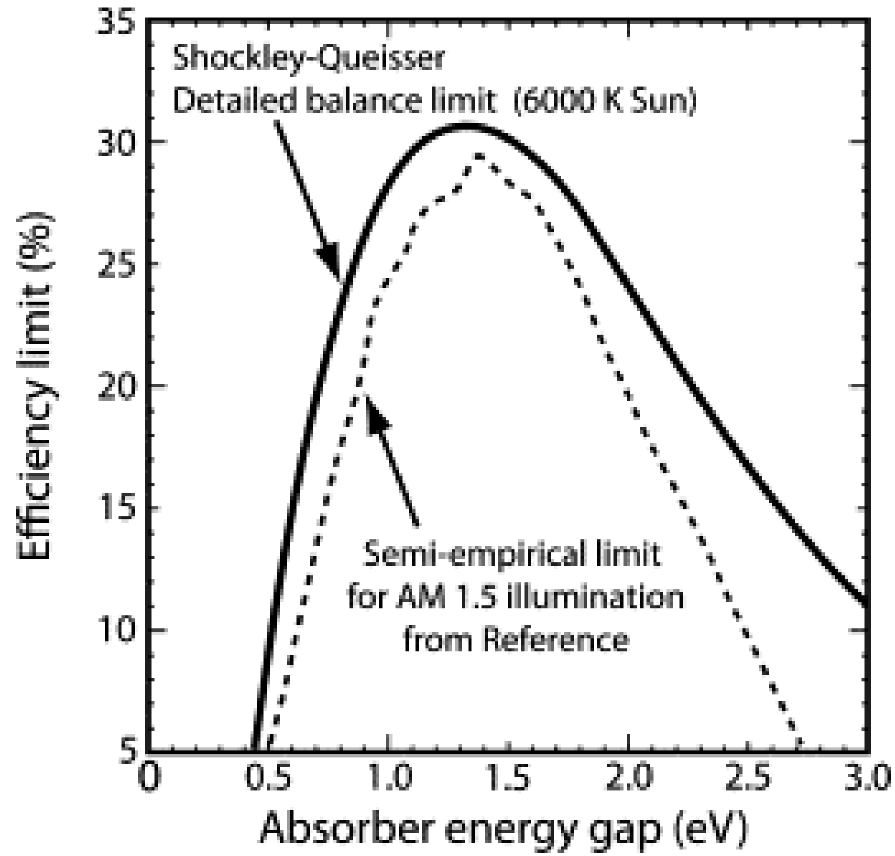
(source: DOE basic research needs (2005)



Solar Cells Thermodynamic efficiencies
(black body approximation)

1. Shockley-Queisser thermodynamic limit (March 1961) established the max theoretical limit of thermal efficiency a single junction solar cell (regardless of technology)
2. Max efficiency: ~30% at 1 x sun

- **Can we push this limit higher?** **(see Eli Yablonovitch's paper of 2011)**

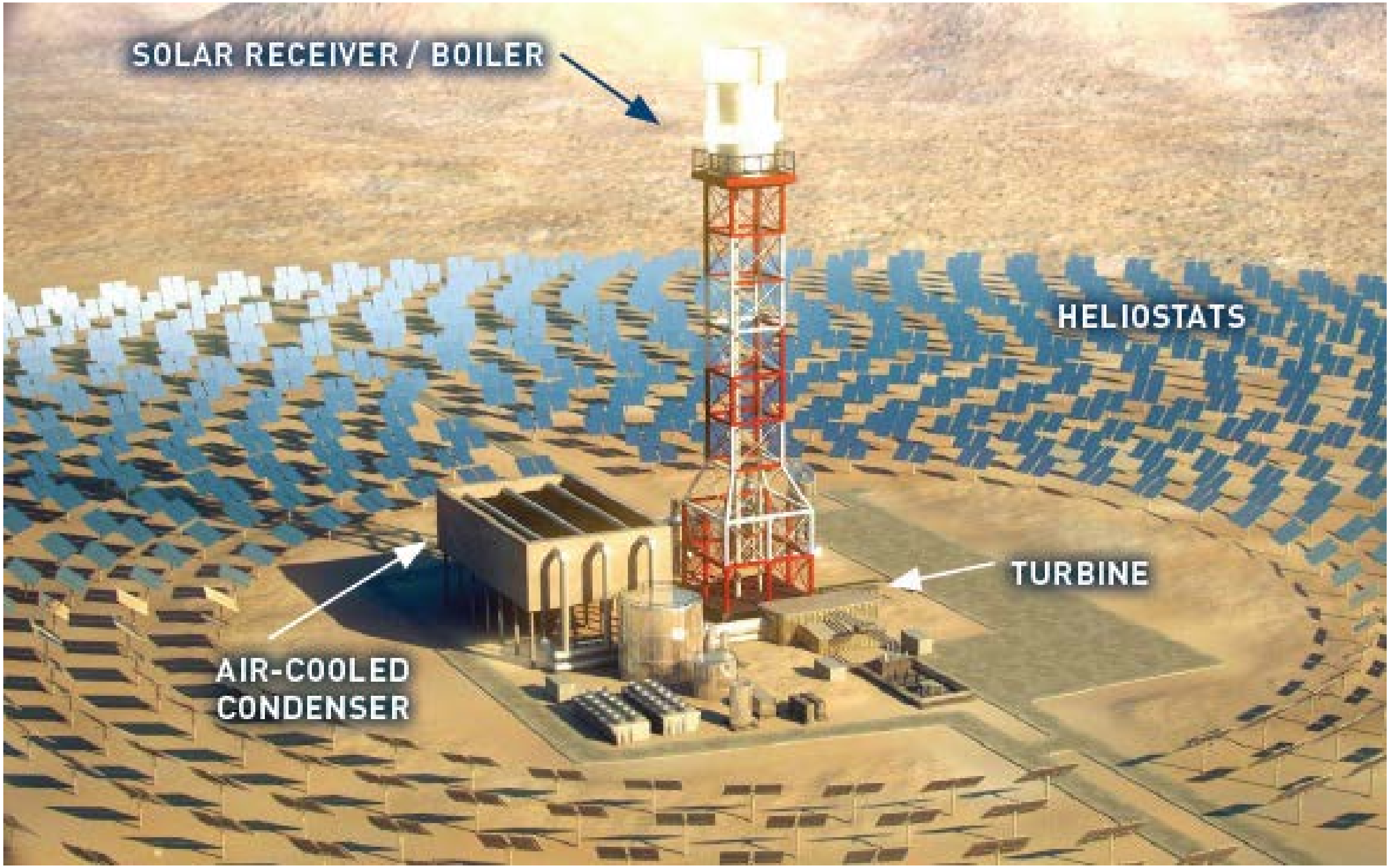


BrightSource Ivanpah, CA (3 x 123 MW)

Ivanpah Solar Plant Key Data

Component	Value
Plant name plate	3 x 123 MW
Turbine	SST-900 dual-casing reheat turbine
Footprint	~3,500 acres (BLM)
Annual generation	~ 1,079 GW hr
Total installed cost	$2.18 billion
Solar technology	Luz power tower 550
Commercial operation	March 2013?

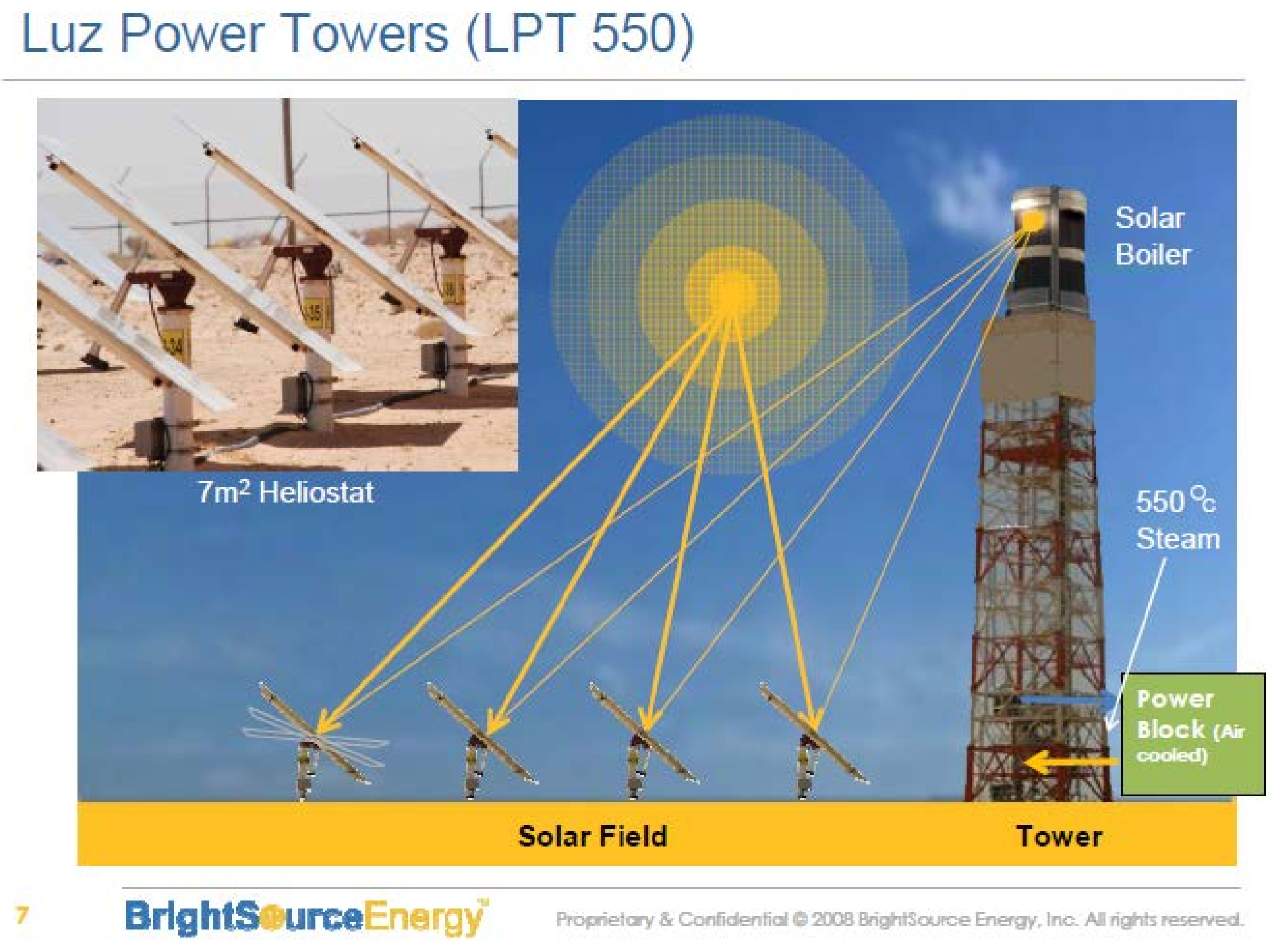
Ivanpah CSP: Power Block



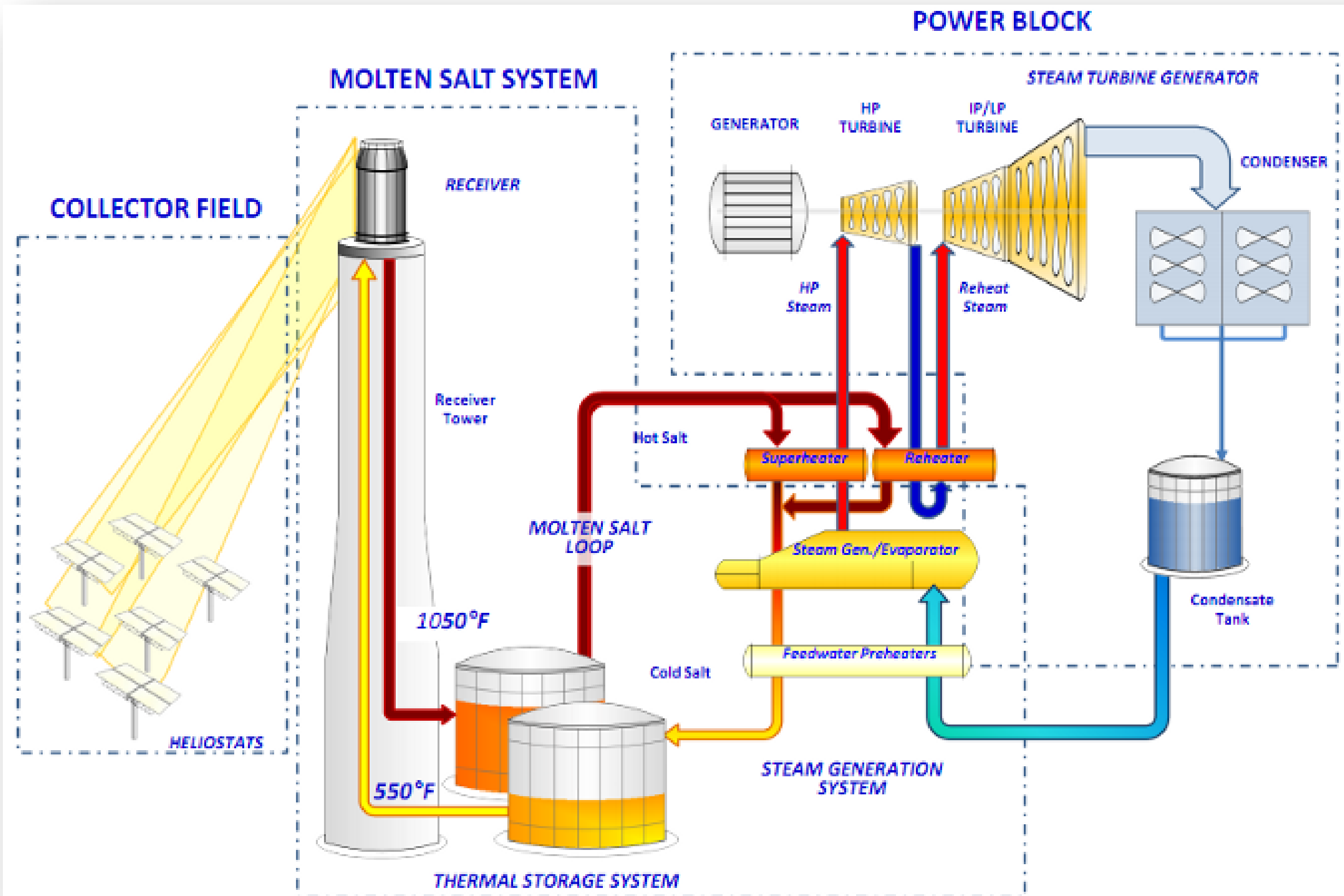
Heliostat Field/BSE CSP

(Negev, Israel, test facility <10 MW)

CSP: Power Tower



(Rocketdyne) Molten Salt Technology (cycle diagram)



SolarReserve Power Tower 150 MW Rice Project, CA
(approved by CEC for construction Feb 2012)

CVSR/ SunPower 250 MW (CA)

California Valley Solar Ranch
Project Site Plan

LEGEND

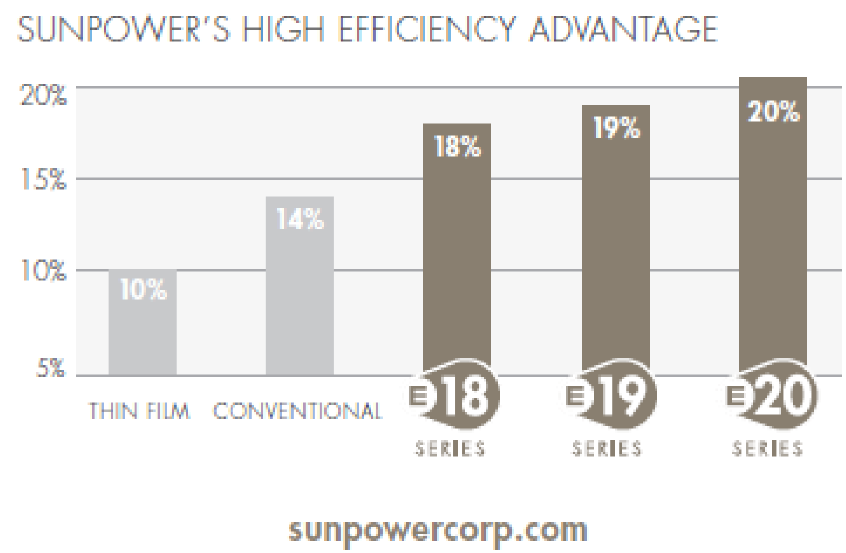
- operations and maintenance building
- solar arrays
- preserved open space
- generation tie-line
- substation/switchyard
- property boundary

CVSR/ Plant Key Data
San Luis Obispo, CA

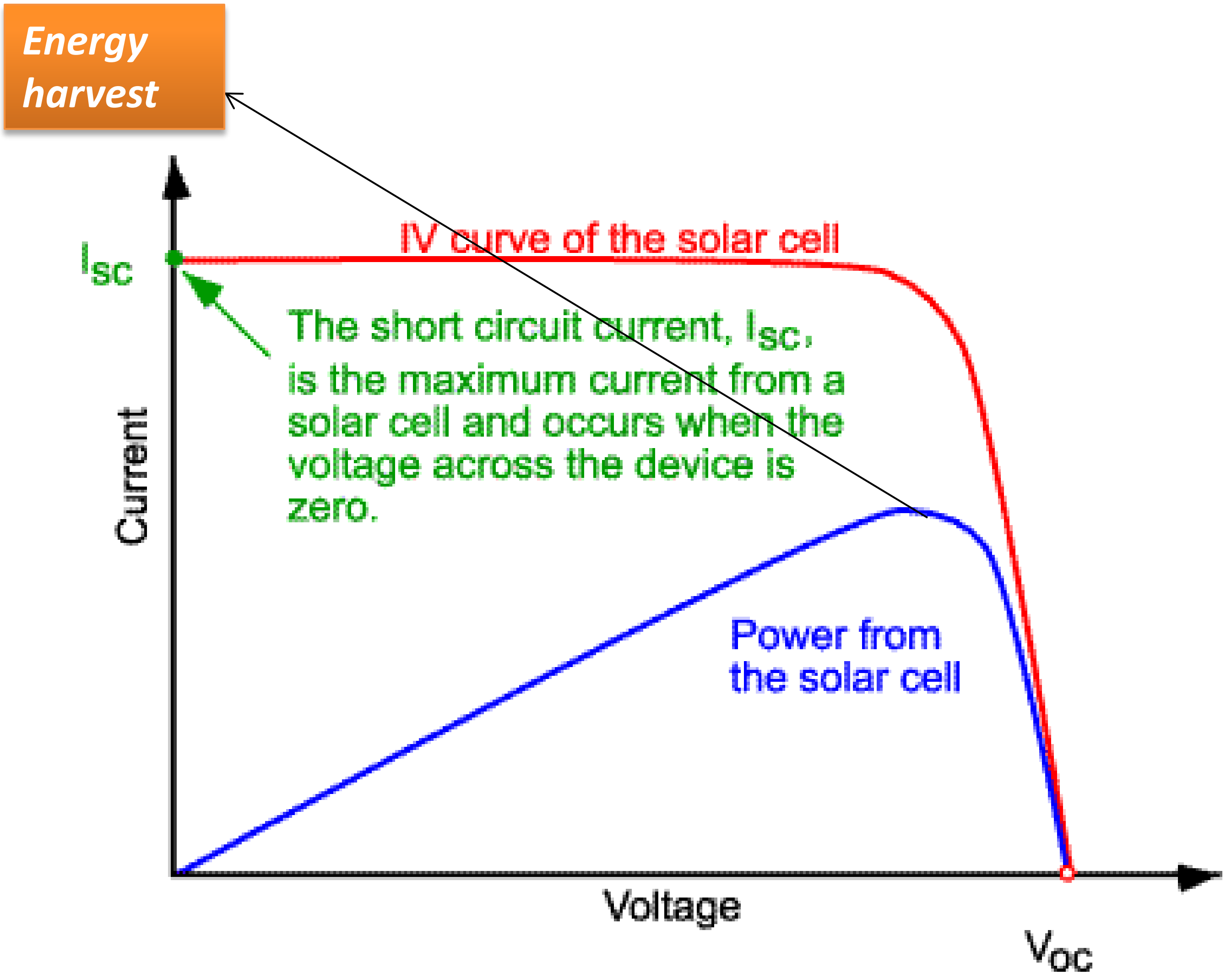
Component	Value
Plant name plate	250 MW
Power Block	1.5 MW ac (Oasis)
PV module	E20, 435 W (STC)
Footprint	~1,500 acres
Annual generation	~ 550 GW hr
Total installed cost	$?
Solar technology	SunPower Oasis power block T0 single axis tracking
Commercial operation	1^{st} phase 2012 (130 MW on grid) Complete : 2013

CVSR/ Oasis power block (partial view of 1 MW)

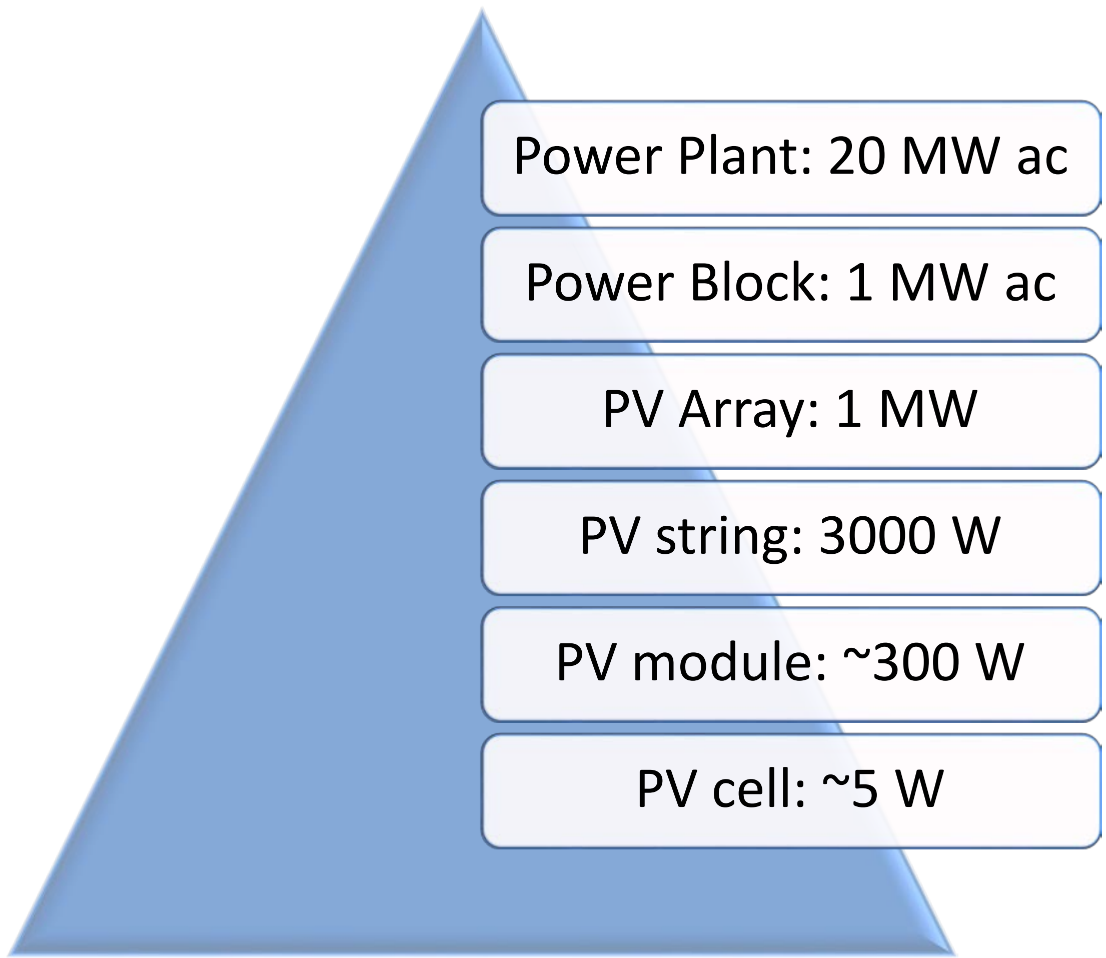
SunPower E 20 module, 327 Wp



Solar Cell: Current-Voltage Map

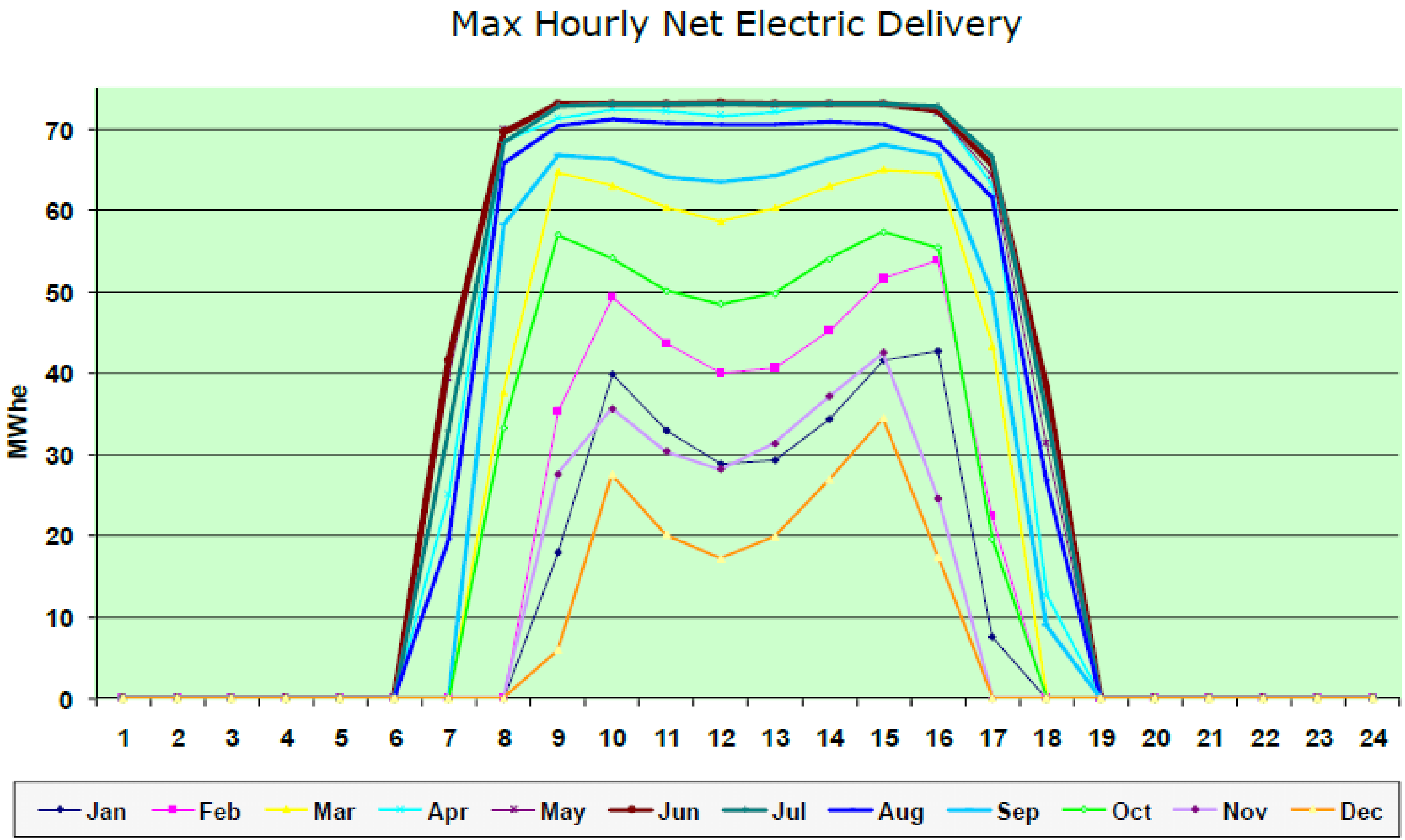


Power profile: PV Power Plant

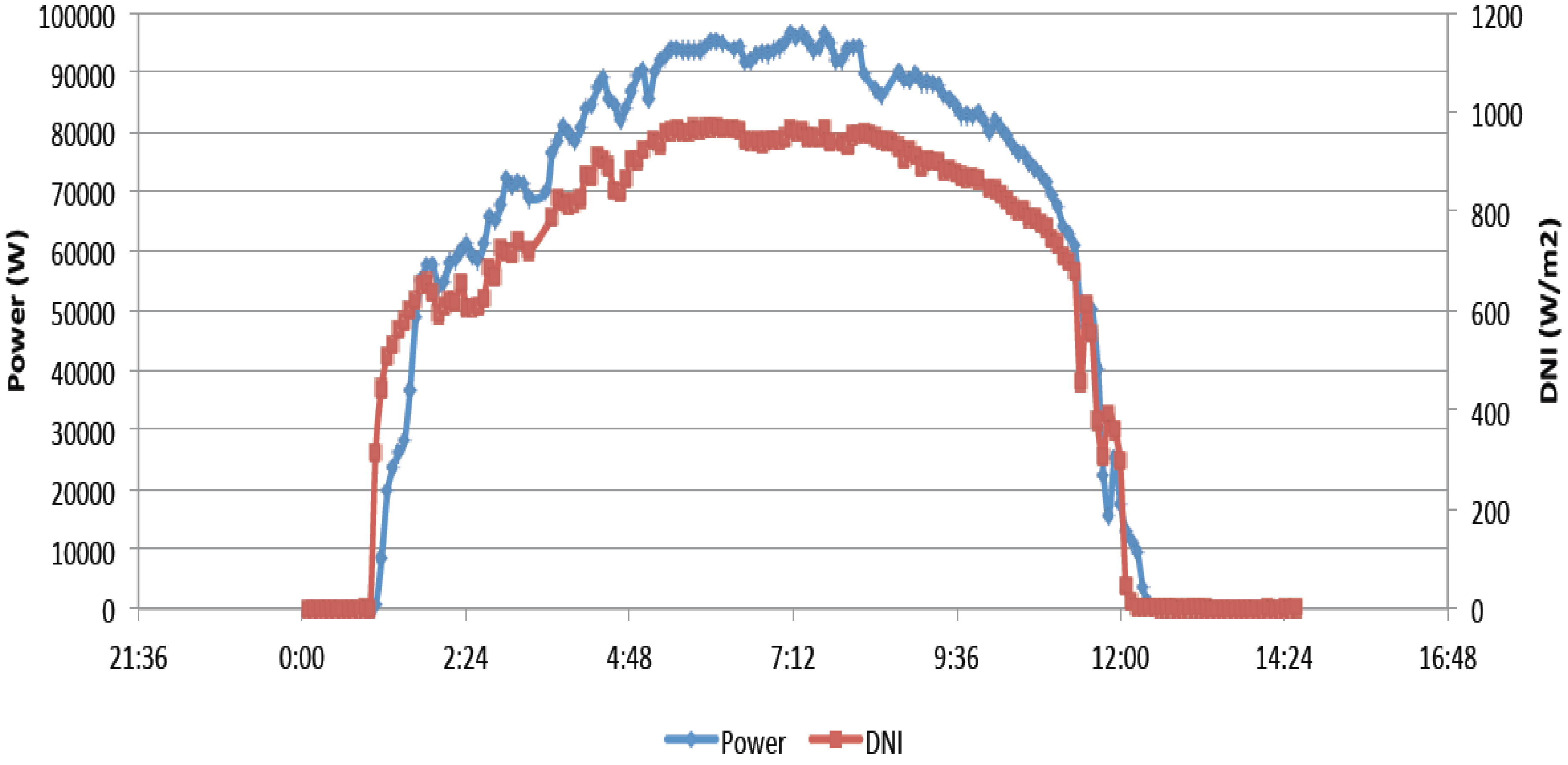


Nevada Solar-1/CSP/(64 MW)

Source: Acciona

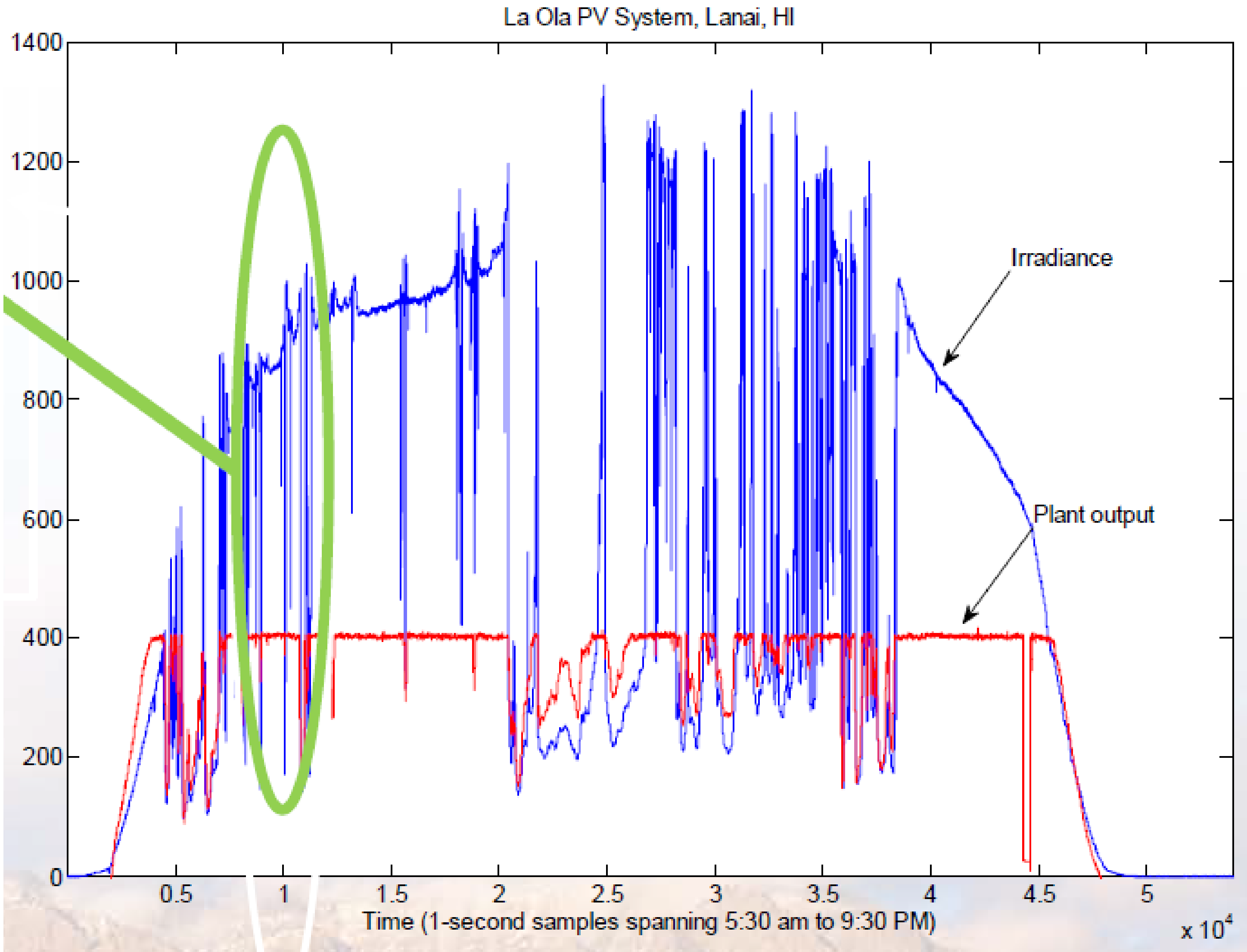


PV power plant operation (100 kWp)



Intermittency: La Ola PV System, HI (1.3 MW)

Sandia Report: Energy Storage, 11/2011



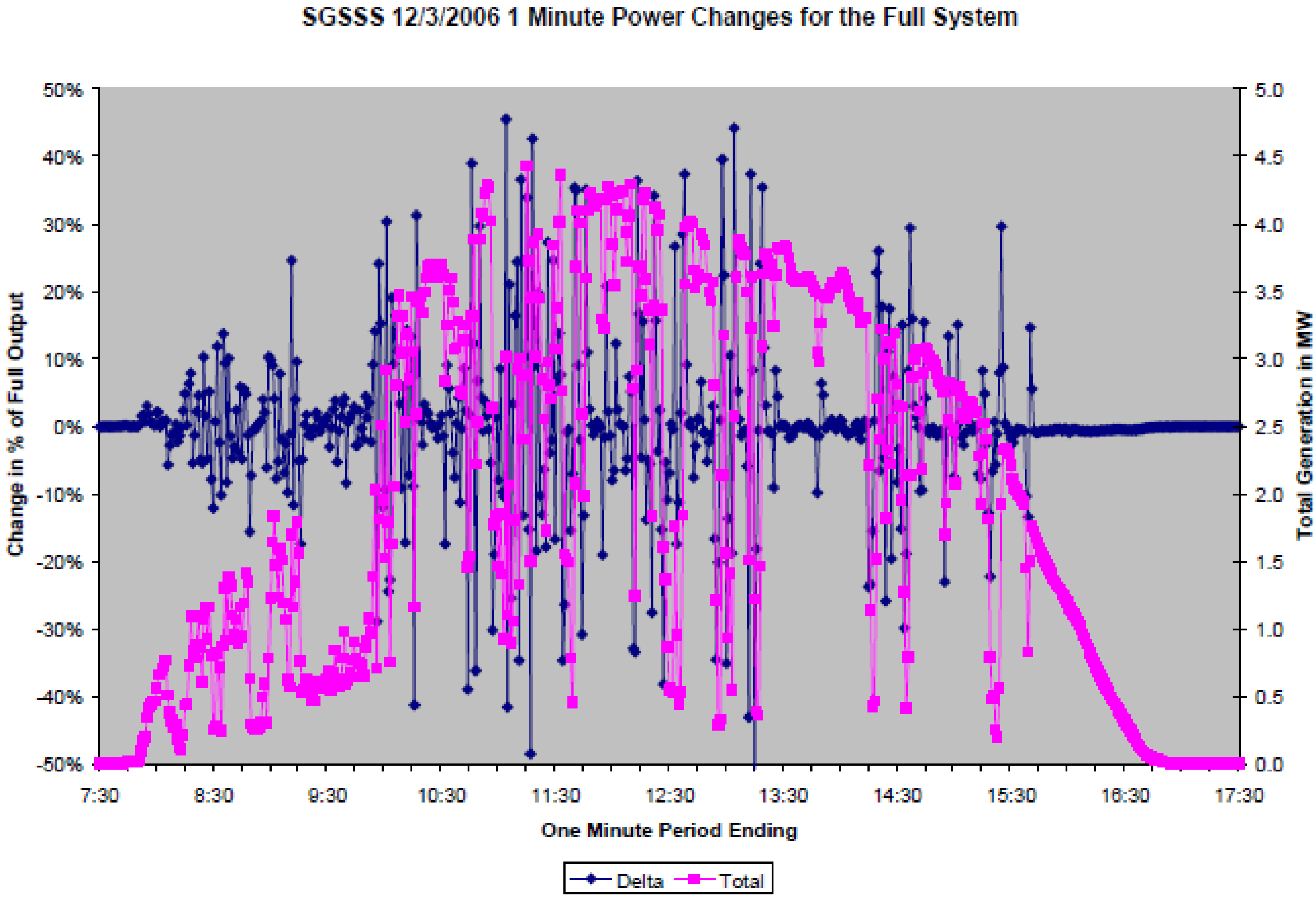
Dealing with intermittency:
Energy (thermal) storage concepts/technologies

- Atmospheric conditions sit between the solar power plants and the clear solar irradiation.
  1. Intermittent operation (cloud passage, rain, snow, etc)
  2. Ability to dispatch (look ahead requirements from transmission system operators, see CAISO guidelines for large solar power projects)
  3. **Variability** (PV power plants have instantaneous mega Watt outputs)
  - **How to deal with 1-3 above?**
    - Thermal storage
    - Energy storage
    - Grid regulation (voltage, frequency, peak shaving, …)

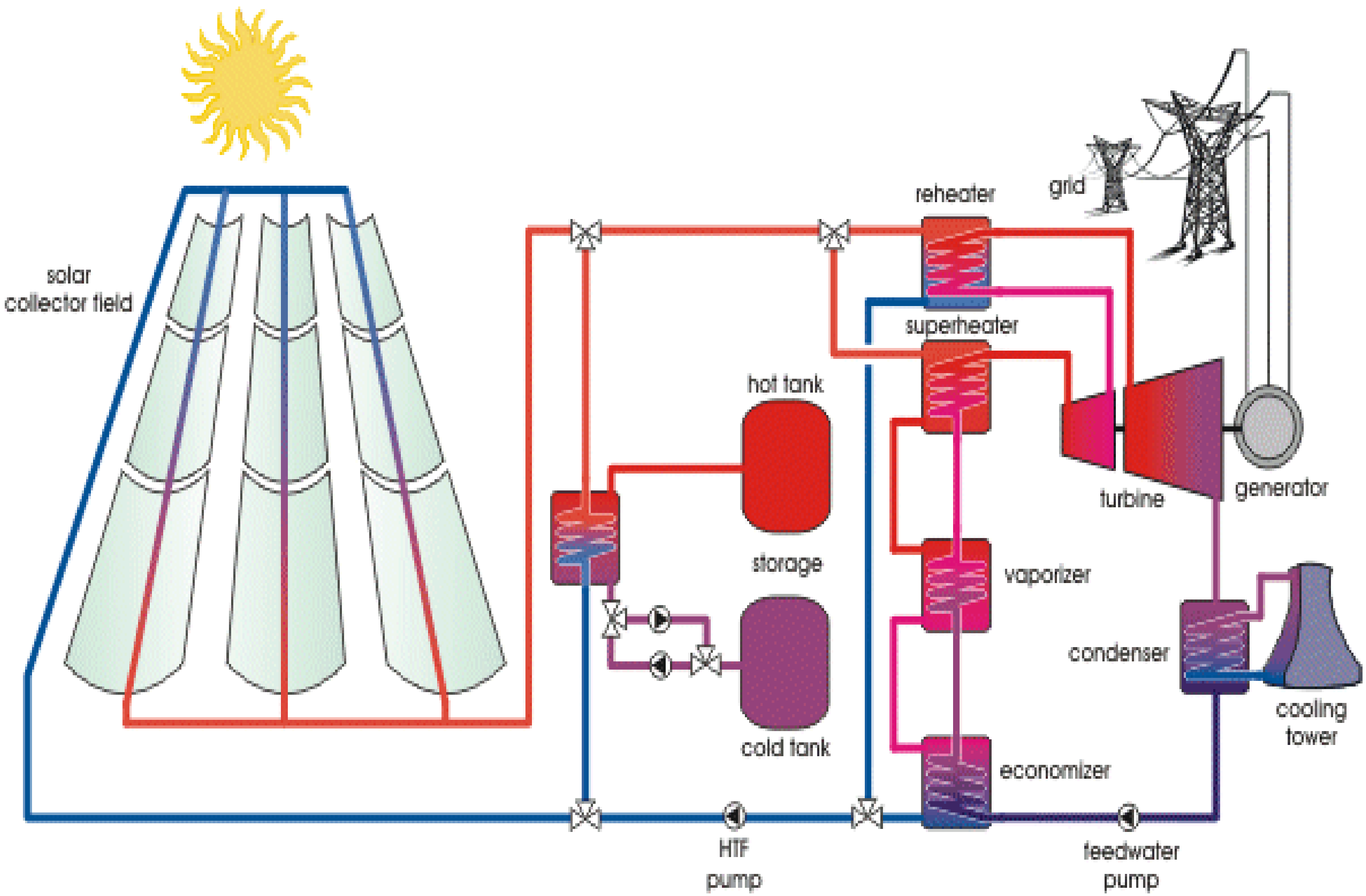
PV variable generation (MW /min)

Source: SEPA 02-08, , Hoff-Perez

Figure 21: Power changes for PV plant in winter using 1 minute time intervals.

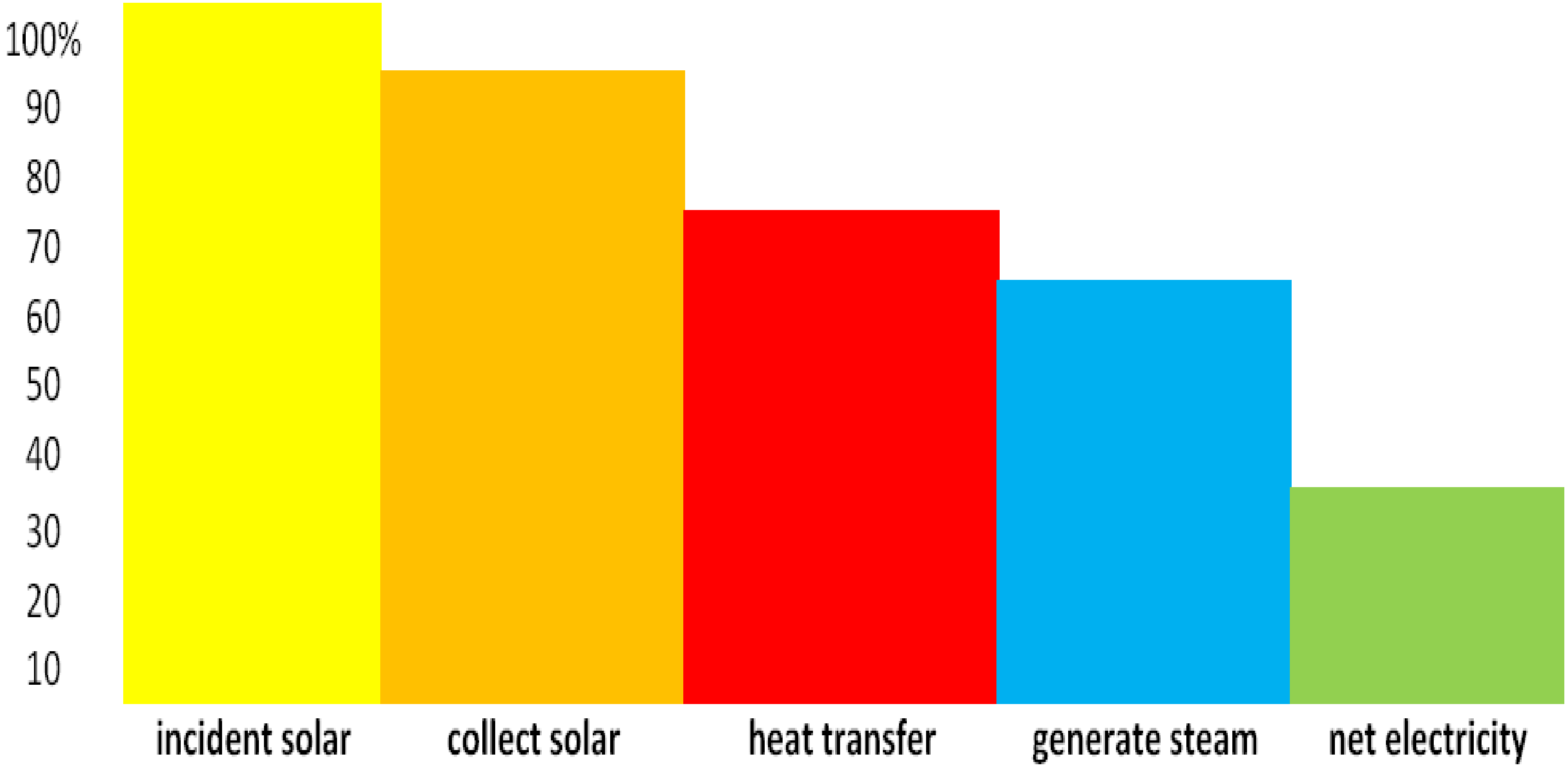


CSP: Tracking Collector Trough



Nevada Solar-1: 65 MW (400 acres)
Built 2007 (Boulder City, NV)

Energy Conversion
Efficiency Cascades: *CSP Representative & Rough*



Andasol 1-2, 50 MW, Spain
Solar Millennium AG

Thermal Storage
source: Solar Millennium/Andasol

Amonix CPV modules/53 kW

Alamosa 30 MW CPV plant, CO

Amonix CPV (500 x SUN)

AMONIX 7700 SOLAR POWER GENERATOR

AMONIX
POWERING THE FUTURE NOW™

Performance	
Name Plate Capacity (AC)*	53 kW(+/- 5%)
Observed System Efficiency (AC, post inverter)	25%
Power Factor	> 0.98
Operating Voltage (AC, 3-Phase)	480 V
Power Temperature Coefficient	-0.16% / K

Physical	
Overall Dimensions	72 ft(w) x 49 ft(h)
Max. Height	50.5 ft
Min. Ground Clearance	2 ft
Pedestal Diameter	3 ft
Foundation Depth	18 ft
Tracking Type	2-Axis
Drive Type	Hydraulic
Sun Tracking Method	Closed Loop Sun Seeker

MegaModule® Warranties	
Limited Product Warranty	5 Year
10 Year Power Output	92%
25 Year Power Output	80%

Environmental	
Max. Operating Wind Speed	28 mph
Max. Wind Loading (ASCE 7-05, Category C)	90 mph
Time to Wind Stow Position	< 1 Min
Operating Temperature Range	- 10°C to + 50°C
Designed Lifetime	> 25 yrs
Hydraulic Fluid	Biodegradable
Land Required per MW	4 to 6 Acres

* Photovoltaics for Utility Scale Applications (PVUSA) test conditions: 850 W/m² DNI, 20°C ambient temperature, 1 m/sec. wind velocity (@ 10 meter height)

Concentrated PV: SP C7

tracker module (mono-Si, 20.1%, (108 x 138W) @C7, 14.7kWp)

PV vs. CPV (energy yield)

Normal production operating hours

SIEMENS

Solar Input versus Energy Output

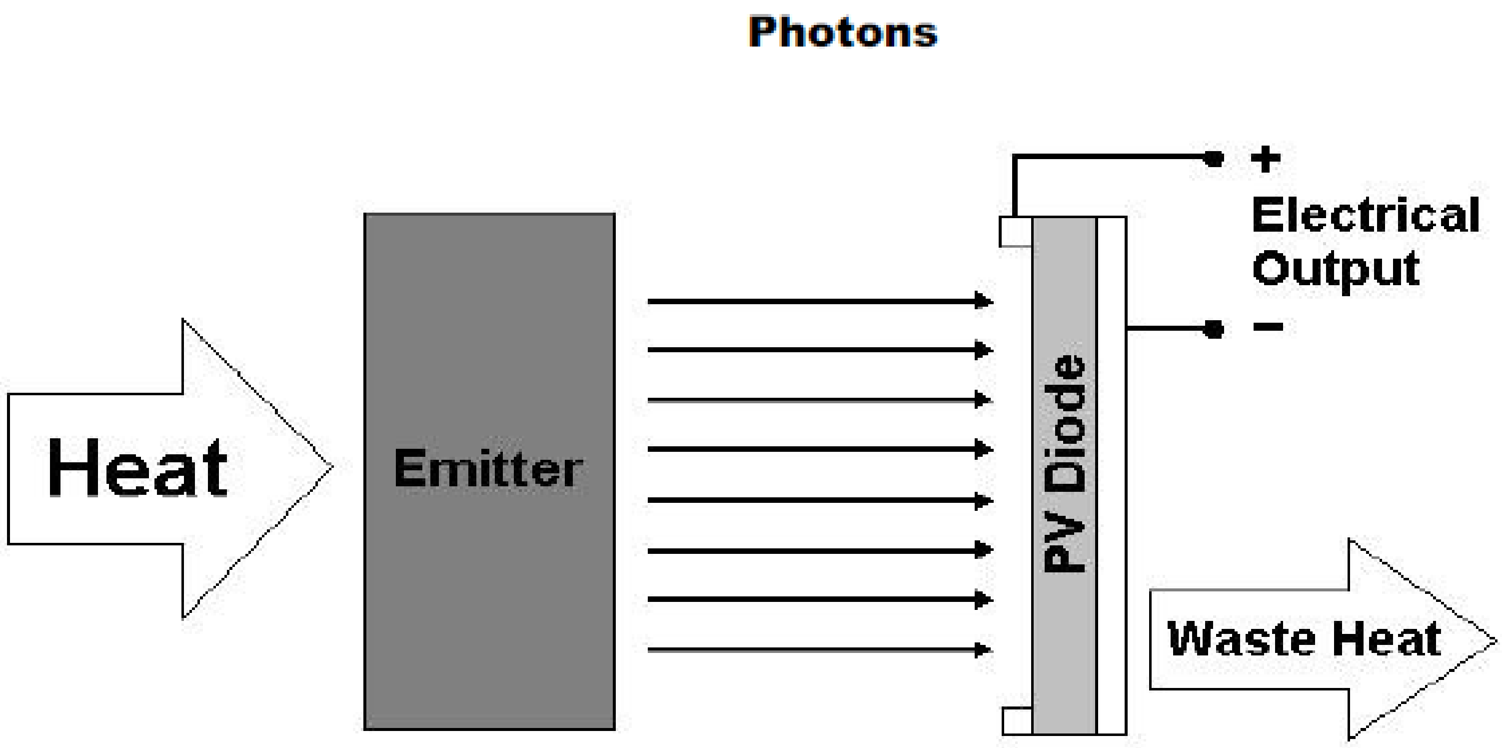
HCPV is competing mainly with single axis PV in the energy output for the same rated STC power plant. Clear conclusion on the required target costs.

Solar Input	fixed PV*	1-axis PV**	HCPV
Global horizontal irradiation (kWh/year.m²)	2090	n.a.	n.a.
Direct normal irradiation (kWh/year.m²)	n.a.	2724	2724
Diffuse horizontal irradiation (kWh/year.m²)	469	469	n.a.
Relevant Irradiation (kWh/year.m²)	*2187*	*2686*	*2723*
Installed Capacity under STC rating (MWp)	1	1	1
Module surface area [m²]	6759	6759	3258
Performance Ratio	78.7%	77.3%	81.3%
Energy Output			
Energy yield in MWh/MWp.year	1722	2077	2214

Example location Daggett, US

*Assuming poly crystalline Si module with 14.9%, 30°tilt
** Assuming a N-S single axis tracking system, 0°tilt, phi range of 90°, backtracking

Thermo-photovoltaic power (MIT TPV)

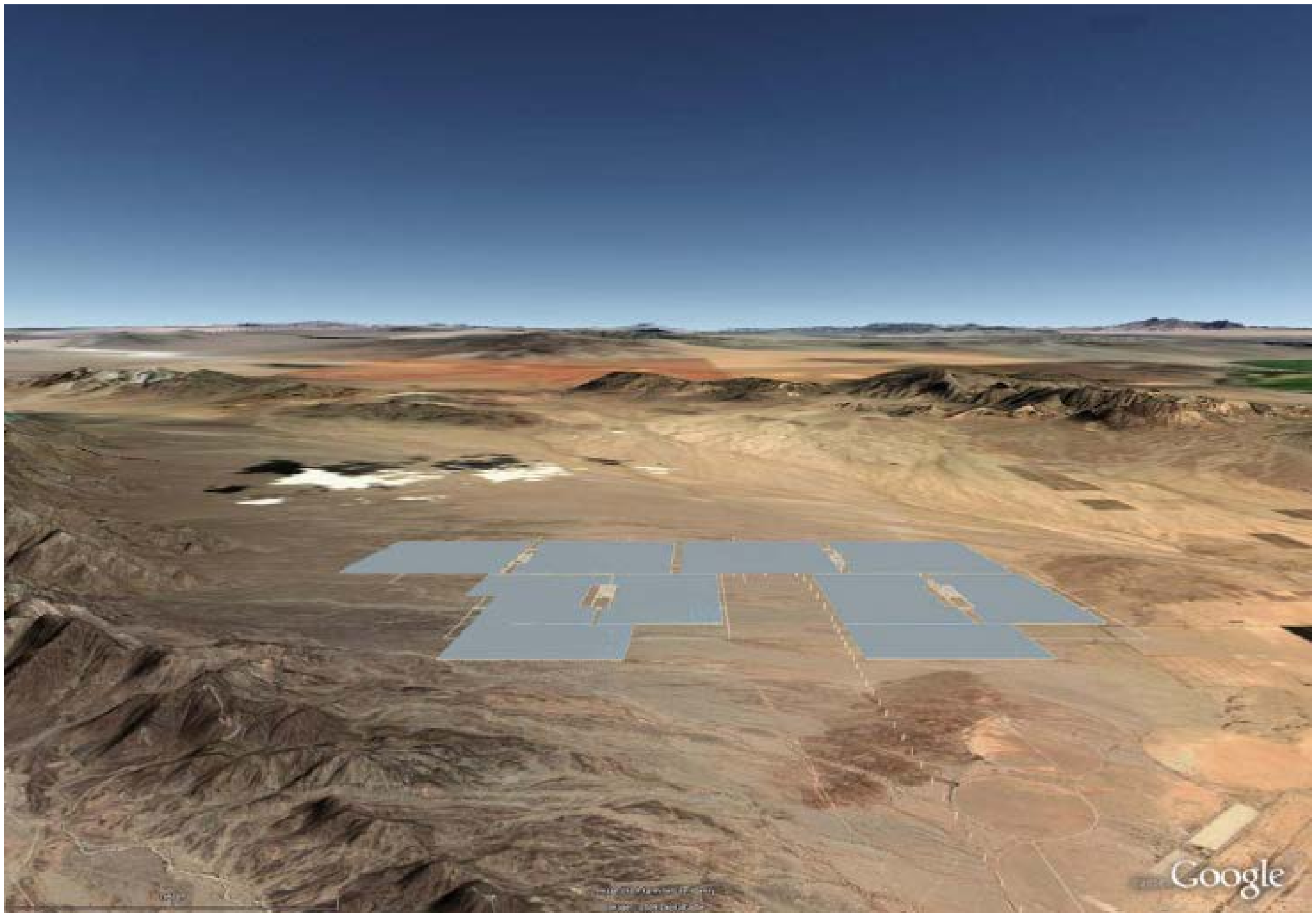


Other Solar Technologies

that were put on hold…

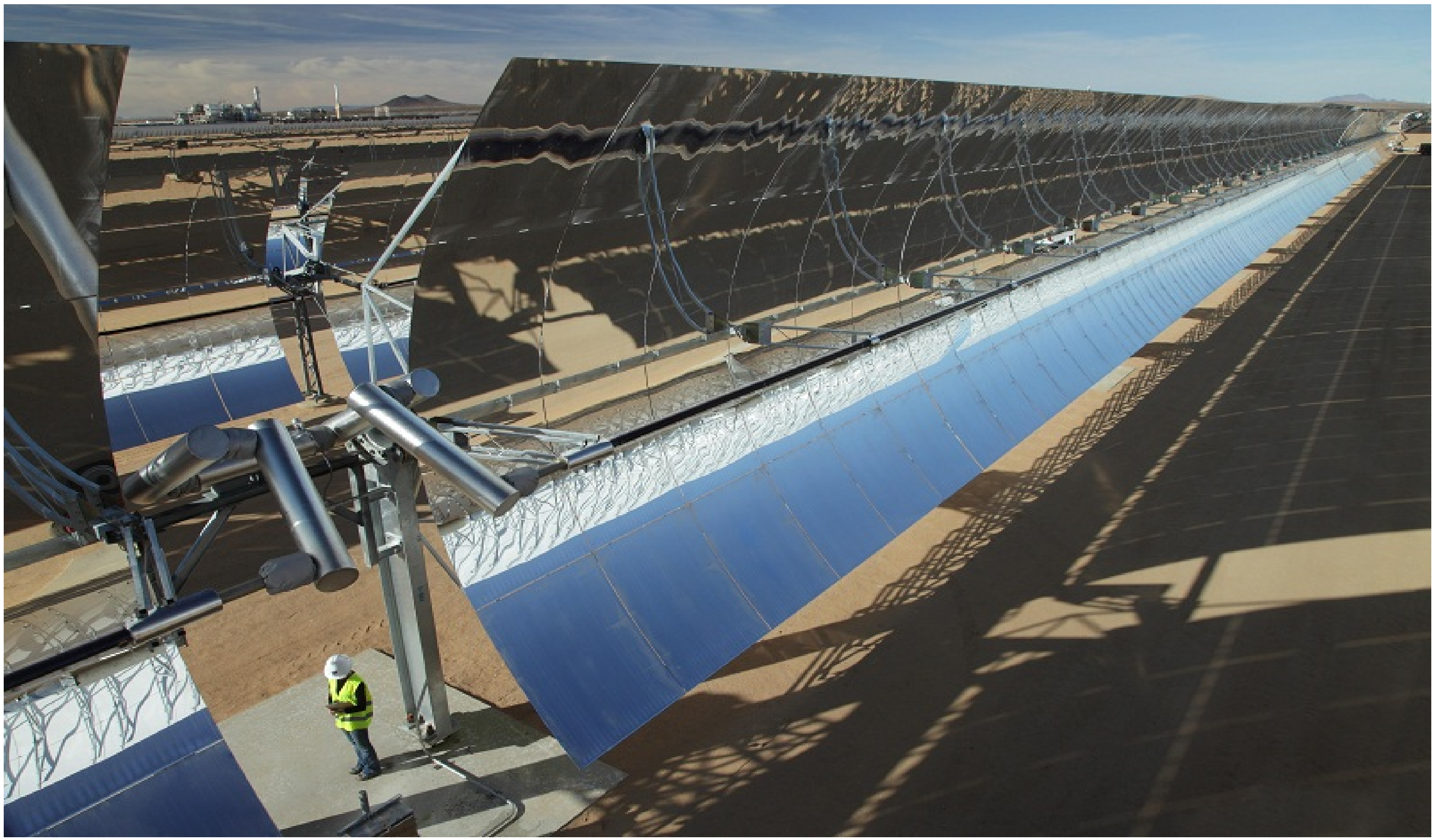
1. Google Energy: solarized gas turbine (<1000 kW)
2. Tessera Sterling Dish (800 MW)
3. Solar Millennium Blythe Super scaled Heliotrough project (Blythe 1000 MW)

Blythe Solar Power Project Site
(4 blocks of 250 MW each), Blythe, CA

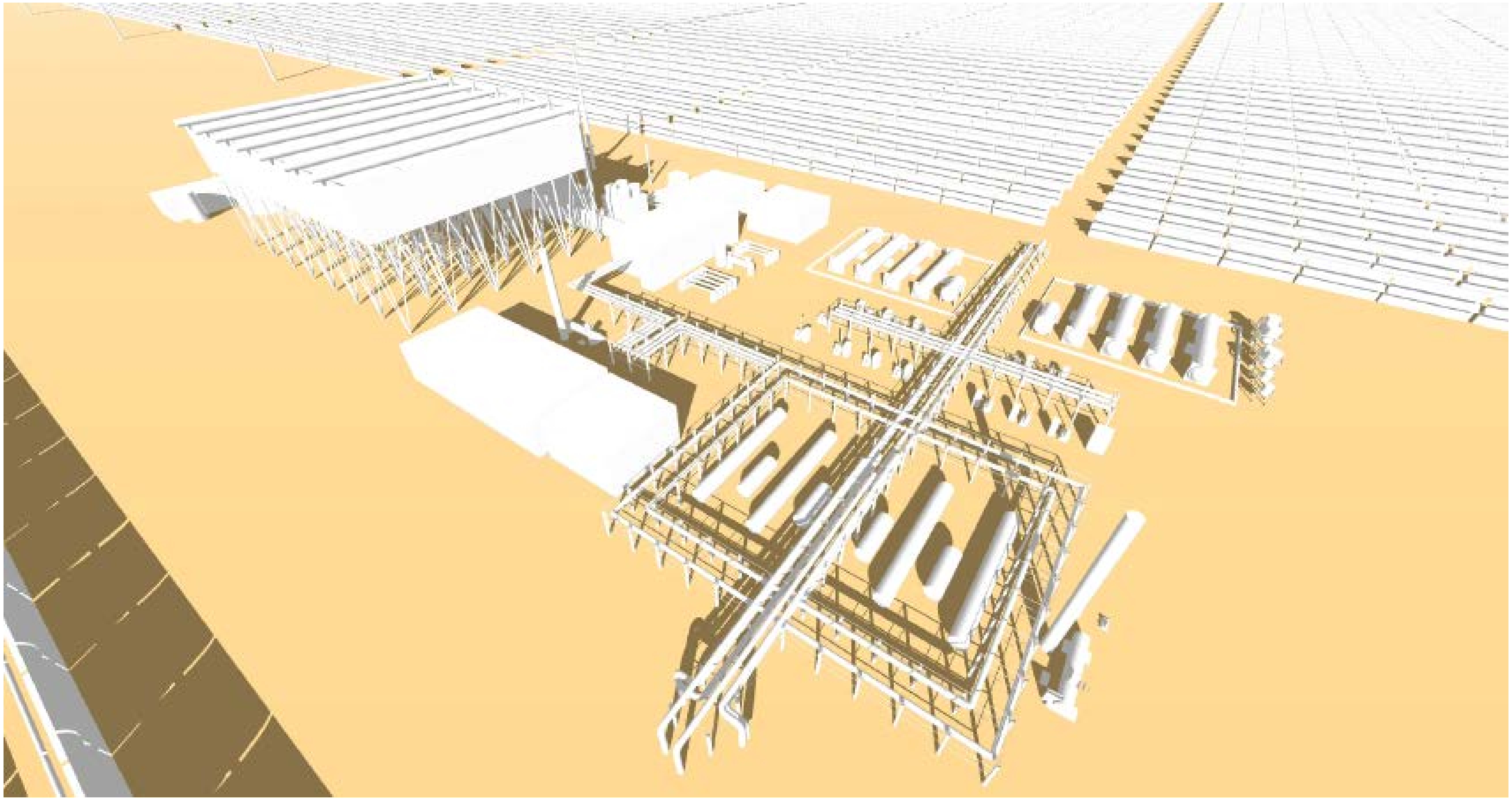


Heliotrough Parabolic Collector Assembly

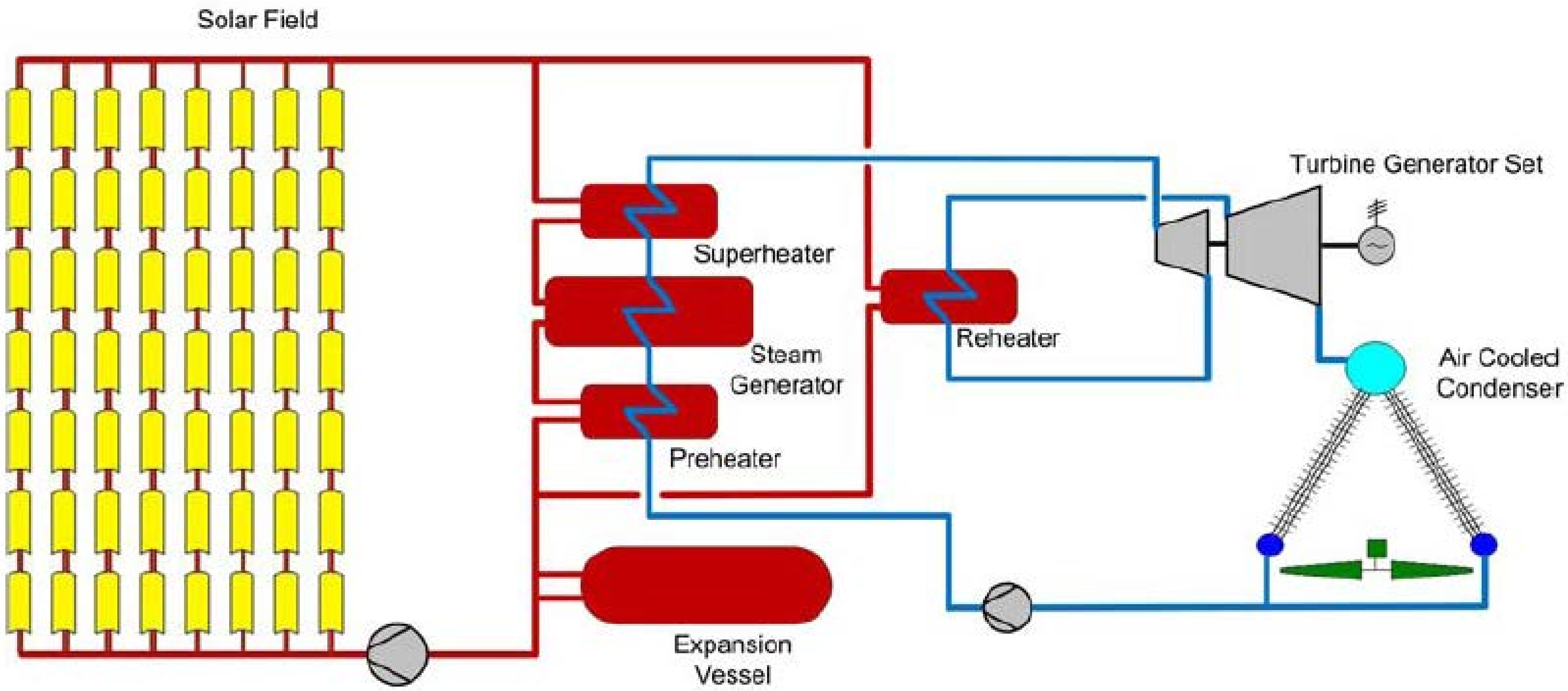
(Kramer Junction Solar Power Plant)



Bythe-1: 3D Model Power Block Area



Blythe Solar Power Plant Process Flow Diagram

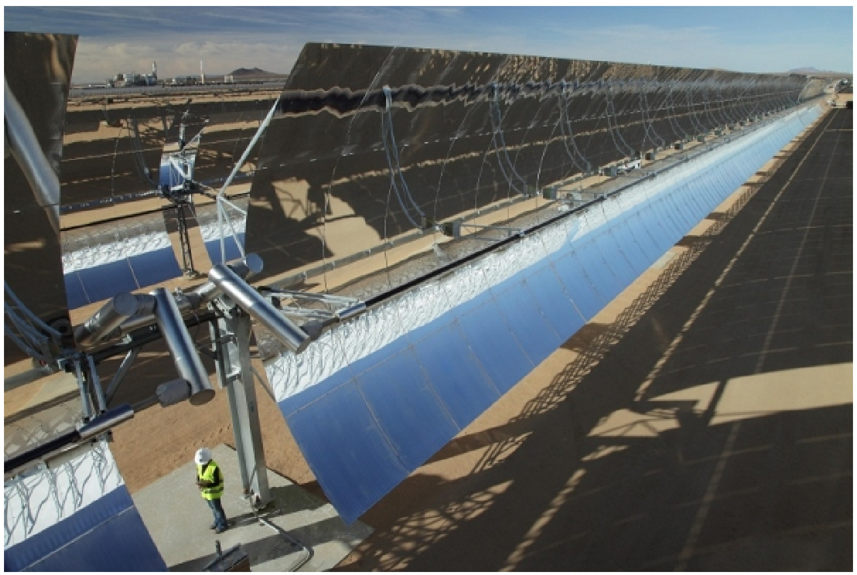


Blythe-1 Solar Field Key Design Data

Parameter	Unit	Value
Solar Field output	**MW th**	**700**
Maximum thermal efficiency	%	75
Maximum optical efficiency	%	83
Solar Concentration		80
Max fluid temp	**F**	**750**
Collector Loops		280
Solar Collector Elements		11,200
Tracking Accuracy	deg	±0.1
Working medium volume	gal	2 million
Solar Field Availability	%	99
Mirrors (RP4) pieces (~5’ x 6’)		499,200
Flow Control: Variable Drive		
Thermal Storage	hr	0
Solar Field Control		SCADA

Heliotrough parabolic trough collector (~ 2.3 MW th *at design point condition*)

SEGS, Kramer Junction, CA



Key Data

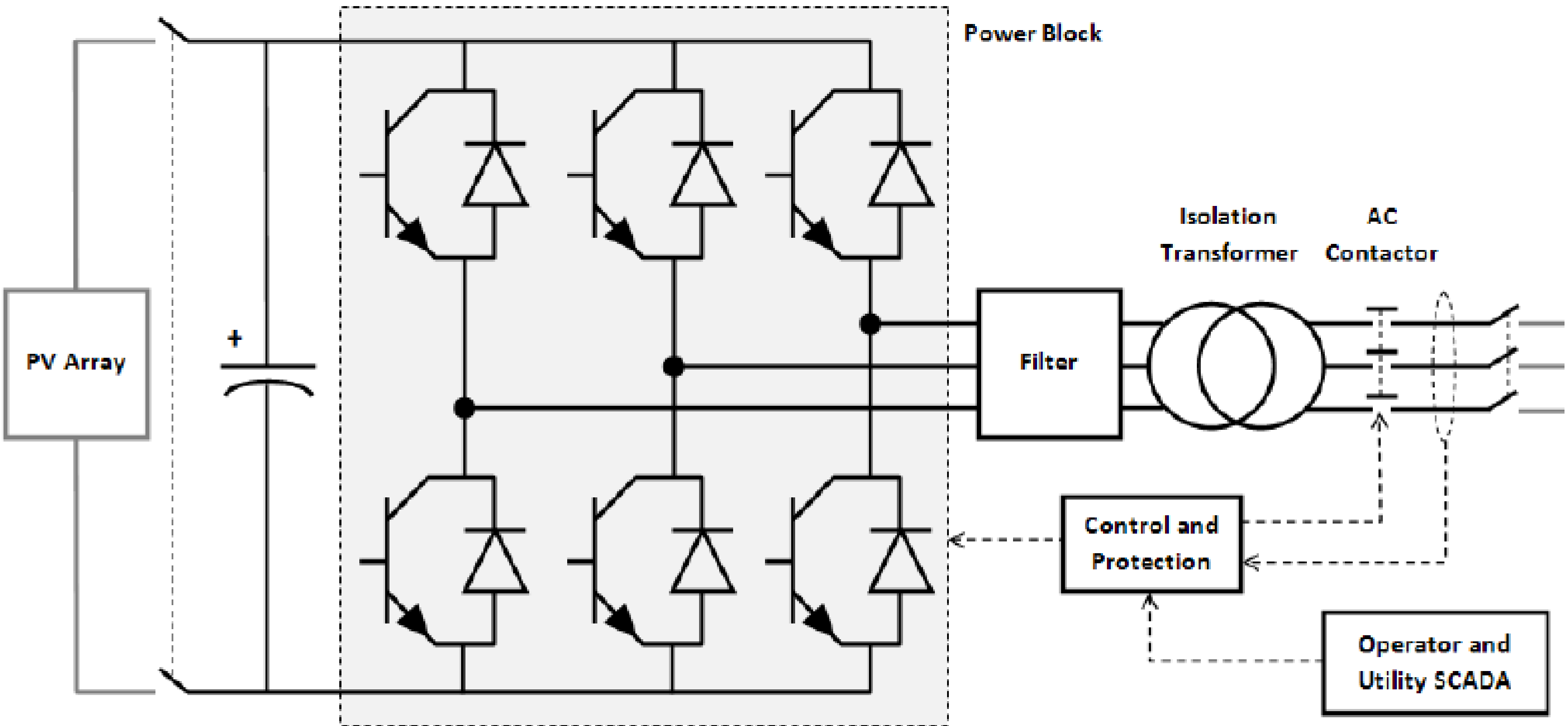
- Optical concentration: 80 x sun
- Optical efficiency: ~<83%
- Thermal efficiency: ~ 74% (at design point condition)
- Aperture: 12,600 ft^2
- # of mirrors: 480
- Alignment: ±0.1 deg arc
- Funded by DOE (SEGS power plant)
- Engineer: *Flagsol-Schlaich Bergermann*

Heliotrough being set on its support pylons

Inherent challenges in CSP solar technology

- A new industry for the new scaled up technologies.
- Need to improve collector optical efficiency.
- Need to improve thermal efficiency heat collecting elements.
- Ability to increase turbine inlet steam temperature.
- Developing advanced air cooling systems.
- Reduce plant parasitic loads (lower below 10% of gross output).
- Configure new emergency power systems for solar field.
- Advanced thermal storage materials and technologies.
- Reducing solar field cost: mirrors, steel frame, bulk commodities.
- Reducing use of water (and mirror wash): ~120 gal/MW-hr
- Better modularized design for collectors (fast construction).

PV power plant equivalent circuit
Utility Scale PV plant/topology



Grid integration of solar power projects:

– Penetration of CSP vs. PV power plants on the electric power system
– Sandia (SEGIS)
– What CAIO is doing? (solar field telemetry)

Cost of Installed Power

levelized cost of electricity (B&V 2012)

Technology	($ /kW) (2010)
Nuclear (1125 MW)	6100
Gas Turbine (211 MW)	651
Combined Cycle (580 MW)	1230
Concentrated Thermal Solar (without thermal storage)	4910
Flat Panel PV (10 MW) tracking	2830
Flat Panel PV (10 MW), fixed tilt	2590

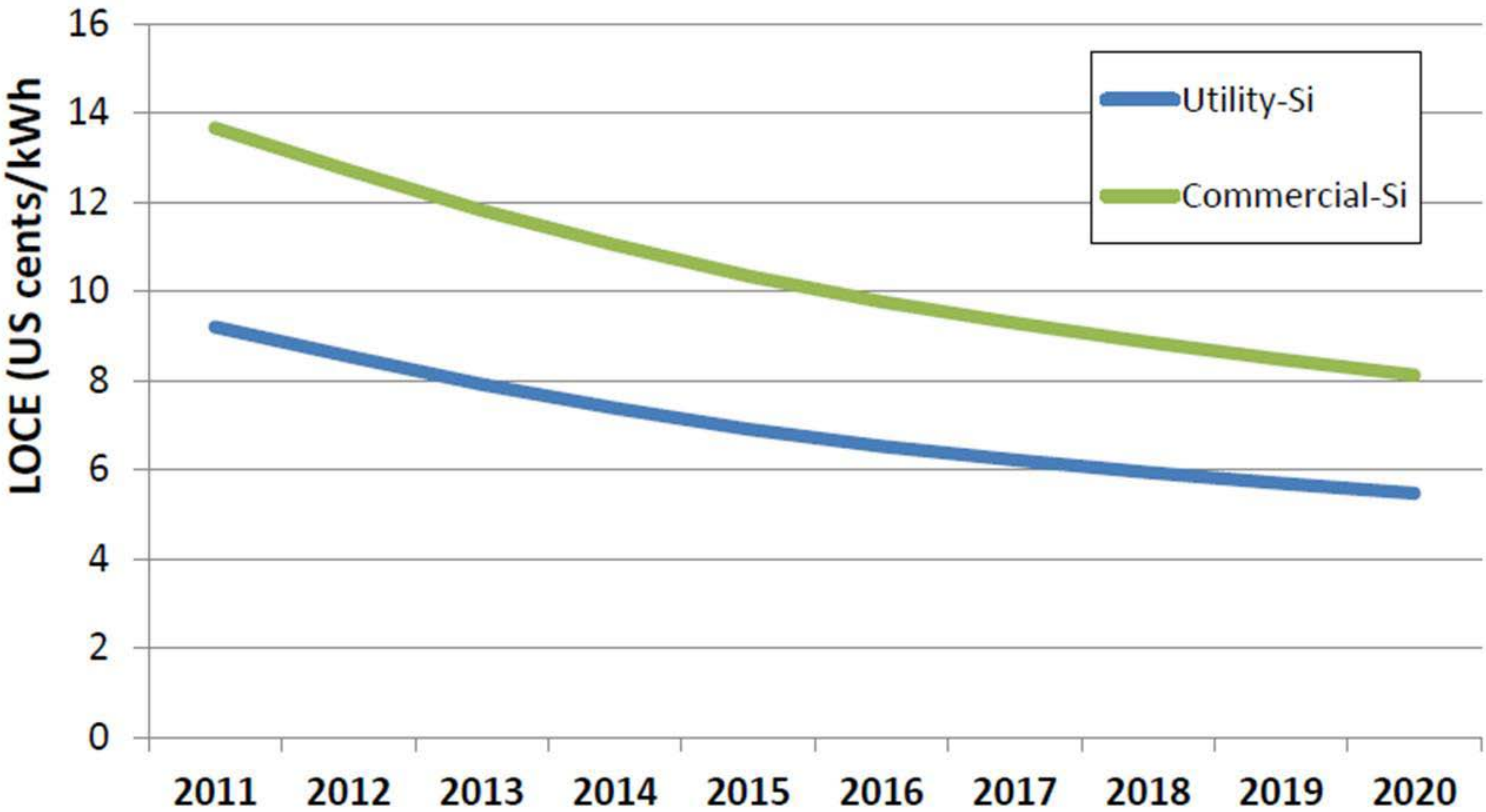
DOE Cost reduction target 2015

$1/Wp work shop summary

PV cost			
Data point	**2010**		**2016**
installed system	$/W	%	
module	$1.7800	51.15%	$1.0500
BOS/installation	$1.4800	42.53%	$0.9700
power electronics	$0.2200	6.32%	$0.1800
Total cost	**$3.4800**	**100.00%**	**$2.2000**
cost of energy			
module	$0.0630	45.32%	$0.0370
BOS/installation	$0.0550	39.57%	$0.0340
power electronics	$0.0080	5.76%	$0.0060
O&M	$0.0130	9.35%	$0.0090
LCOE	**$0.1390**	**100.00%**	**$0.0860**

Projections for levelized cost of electricity

Source: Stefan Reichelstein (2012)



Commercialization: Viability to Bankability

- What constitutes a technology as commercial ready?
  - *Holds a successful proto-type run.*
  - *Has collected enough field operation data.*
  - *Independently reviewed by 3rd Party Engineers*
  - *Reliability*
  - *Possesses demonstrated Quality Assurance program the across R&D and technology development*
  - *Investors*

Solar Project Development

- – Power Purchase Agreement
- – Land (lease or BLM lands)
- – Transmission access (system interconnection):
  - Large Generators or Small Generators
- – Permitting (CEC or local county)
- – EPC Cost (engage an general contractor)
- – EPC contracts
- – Design life: 20 – 25 years

Solar Energy & Water Use

Table 1. Water Consumption Factors for Renewable Technologies (gal/MWh)

Fuel Type	Cooling	Technology	Median	Min	Max	*n*	Sources
PV	N/A	Utility Scale PV	26	0	33	3	[10, 34, 35]
Wind	N/A	Wind Turbine	0	0	1	2	[11, 36]
CSP	Tower	Trough	865	725	1,057	17	[10, 34, 37-46]
		Power Tower	786	740	860	4	[34, 39-41]
		Fresnel	1,000	1,000	1,000	1	[47]
	Dry	Trough	78	43	79	10	[38, 42-44]
		Power Tower	26	26	26	1	[48]
	Hybrid	Trough	338	105	345	3	[42, 47]
		Power Tower	170	90	250	2	[47]
	N/A	Stirling	5	4	6	2	[34, 49]
Biopower	Tower	Steam	553	480	965	4	[49-51]
		Biogas	235	235	235	1	[52]
	Once-through	Steam	300	300	300	1	[50]
	Pond	Steam	390	300	480	1	[50]
	Dry	Biogas	35	35	35	1	[51]
Geothermal[1]	Tower	Dry Steam	1,796	1,796	1,796	1	[10]
		Flash (freshwater)	10	5	19	3	[19, 20, 49]
		Flash (geothermal fluid)	2,583	2,067	3,100	2	[53]
		Binary	3,600	1,700	3,963	3	[10, 54, 55]
		EGS	4,784	2,885	5,147	4	[10, 51, 54, 55]
	Dry	Flash	0	0	0	1	[51]
		Binary	135	0	270	2	[19, 51]
		EGS	850	300	1,778	2	[19, 51]
	Hybrid	Binary	221	74	368	1	[56]
		EGS	1,406	813	1,999	2	[51, 56]
Hydropower	N/A	Aggregated in-stream and reservoir	4,491	1,425	18,000	3	[22, 23]

[1] Most geothermal facilities can use geothermal fluids or freshwater for cooling.